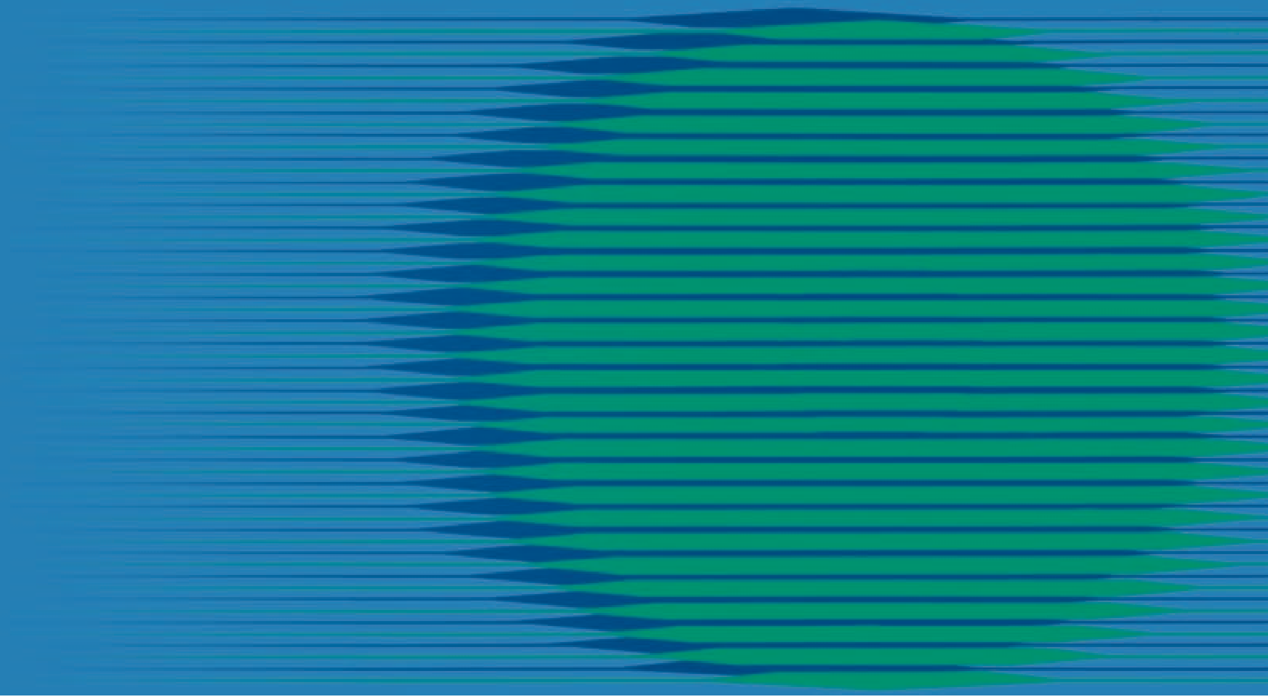
SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCEAR 2008 Report

Volume I: SOURCES

Report to the General Assembly
Scientific Annexes A and B



UNITED NATIONS

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United Nations Scientific Committee on the
Effects of Atomic Radiation

UNSCEAR 2008
Report to the General Assembly
with Scientific Annexes

VOLUME I

UNITED NATIONS
New York, 2010

NOTE

The report of the Committee without its annexes appears as *Official Records of the General Assembly*, Sixty-third Session, Supplement No. 46.

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

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Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report

Volume I

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

Corrigendum

1. **Page 8, figure III**

For the entry for level I (diagnostic medical), *for* 1308 *read* 1332

For the entry for Global (diagnostic medical), *for* 482 *read* 488

2. **Page 9, figure IV**

For the entry for level I, *for* 1.88 *read* 1.92

For the entry for Global, *for* 0.61 *read* 0.62

3. **Page 11, table 4, column headed “Sources of exposure”, subcolumn headed “Nuclear medicine examinations (man Sv)”**

After the entry 82 *insert* [a]
Insert at the foot of the table a footnote *reading*
[a] Refers to health-care levels III-IV.

4. **Page 14, table 6, column headed “1990-1994”**

For the value for the weighted average, *for* 0.8 *read* 1.3

5. **Page 15, paragraph 63**

In the fourth line, *for* 38 *read* 35

In the fifth line, *for* 26 *read* 24

In the sixth line, *for* 38 *read* 35

In the seventh line, *for* 34 *read* 31

In the tenth line, *for* 29 *read* 32

In the eleventh line, *for* 68 *read* 61

6. **Page 15, paragraph 64**

In the fourth line, *for* 85 *read* 80

In the sixth line, *for* Twenty-five *read* Nine

In the seventh line, *for* 164 *read* 120

7. **Page 15, paragraph 65**

In the third line, *for* 29 *read* 34

In the fifth line, *for* 33 *read* 42

8. **Page 15, paragraph 66**

In the fourth line, *for* 29 *read* 32

In the fifth line, *for* 45 *read* 46

In the fifth line, *for* 613 *read* 623

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

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I. INTRODUCTION

1. Exposure to radiation has origins such as medical diagnostic and therapeutic procedures; nuclear weapons production and testing; natural background radiation; nuclear electricity generation; accidents such as the one at Chernobyl in 1986; and occupations that entail increased exposure to artificial or naturally occurring sources of radiation.

2. Since the establishment of the United Nations Scientific Committee on the Effects of Atomic Radiation by General Assembly resolution 913 (X) of 3 December 1955, the mandate of the Committee has been to undertake broad reviews of the sources of ionizing radiation and of the effects of that radiation on human health and the environment. In pursuit of its mandate, the Committee thoroughly reviews and evaluates global and regional exposures to radiation; and it evaluates evidence of radiation-induced health effects in exposed groups, including survivors of the atomic bombings in Japan. The Committee also reviews advances in the understanding of the biological mechanisms by which radiation-induced effects on health or on the environment can occur. Those assessments provide the scientific foundation used, inter alia, by the relevant agencies of the United Nations system in formulating international standards for protection of the public and of workers against ionizing radiation;[1] those standards, in turn, are linked to important legal and regulatory instruments.

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[1] The international basic safety standards for protection against ionizing radiation and for the safety of radiation sources are currently co-sponsored by the International Labour Organization, the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO), the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency of the Organization for Economic Cooperation and Development and the Pan American Health Organization.

II. DELIBERATIONS OF THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION AT ITS FIFTY-SIXTH SESSION

3. The Committee held its fifty-sixth session in Vienna from 10 to 18 July 2008.[2] Norman Gentner (Canada), Wolfgang Weiss (Germany) and Mohamed A. Gomaa (Egypt) served as Chairman, Vice-Chairman and Rapporteur, respectively. The Committee scrutinized and approved for publication five scientific annexes that had last been considered at its fifty-fifth session (21-25 May 2007), as reported to the General Assembly in the report of the Committee on that session.[3] As previously reported,[4] the Committee had originally planned that those documents would be published by 2005.

4. With regard to the report with scientific annexes that it had approved in 2006,[5] the Committee was disappointed that volume I had not been published until July 2008 and that volume II would likely not be published before December 2008, bearing in mind that Member States and some organizations[6] relied on the information contained in that report, to which the Committee members had contributed invaluable expertise. It was observed that the delays were traceable in part to inadequate staffing and to a lack of sufficient, assured and predictable funding.

5. The Committee noted that the General Assembly, in its resolution 62/100 of 17 December 2007, had appealed to the Secretary-General to take appropriate administrative measures so that the secretariat could adequately service the Committee in a predictable and sustainable manner; and had

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[2] The fifty-sixth session of the Committee was attended by members of the Committee and by the official contact points of Belarus, the Russian Federation and Ukraine, for matters related to the Chernobyl accident; observers for Belarus, Finland, Pakistan, the Republic of Korea, Spain and Ukraine; and observers for the United Nations Environment Programme (UNEP), WHO, IAEA, the International Agency for Research on Cancer, the European Commission, the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, the International Organization for Standardization and the International Union of Radioecology.

[3] *Official Records of the General Assembly, Sixty-second Session, Supplement No. 46* (A/62/46), para. 3.

[4] Ibid., *Fifty-sixth Session, Supplement No. 46* (A/56/46), para. 10.

[5] Ibid., *Sixty-first Session, Supplement No. 46* (A/61/46), para. 2.

[6] At its fifty-first regular session, the IAEA General Conference, in its resolution GC(51)/RES/11, entitled “Measures to strengthen international cooperation in nuclear, radiation and transport safety and waste management”, noted that the IAEA Secretariat had commenced revision of the International Basic Safety Standards for Protection against Ionizing Radiation and the Safety of Radiation Sources with the participation of co-sponsors; noted the report of the United Nations Scientific Committee on the Effects of Atomic Radiation on its fifty-fourth session (*Official Records of the General Assembly, Sixty-first Session, Supplement No. 46* (A/61/46)); and urged the IAEA Secretariat to consider carefully and to justify any potential changes to the Basic Safety Standards, ensuring consistency with, inter alia, the Committee’s report.

requested the Secretary-General to provide a comprehensive and consolidated report to the Assembly at its sixty-third session, to be prepared in consultation with the Committee as appropriate, addressing the financial and administrative implications of increased Committee membership, staffing of the professional secretariat and methods to ensure sufficient, assured and predictable funding. The secretariat was requested to facilitate the inclusion in the Secretary-General's report of the views of the Committee on those matters.

6. The Committee decided to hold its fifty-seventh session in Vienna from 25 to 29 May 2009.

III. STRATEGIC PLAN AND PROGRAMME OF WORK OF THE COMMITTEE

7. The Committee had developed a strategic plan[7] to provide vision and direction for all its activities during the period 2009-2013, to facilitate result-based programming by the secretariat, to help foster management of sufficient, assured and predictable resources and to improve planning and coordination among the various parties involved.

8. The Committee considered that its strategic objective for the period was to increase awareness and deepen understanding among authorities, the scientific community and civil society with regard to levels of ionizing radiation and the related health and environmental effects as a sound basis for informed decision-making on radiation-related issues.

9. It was established that the thematic priorities for the period would be medical exposures of patients, radiation levels and effects of energy production, exposure to natural sources of radiation and improved understanding of the effects from low-dose-rate radiation exposure.

10. Several strategic shifts were envisaged in order to better meet the needs of Member States, including: *(a)* streamlining the Committee's scientific evaluation process by preparing short yet wide-ranging summary reports every 4-5 years on the levels and effects of radiation exposure and preparing special reports that respond to emerging issues as the need arises; and establishing standing expert groups to maintain surveillance on emerging issues and networks of centres of excellence to help implement the strategic plan; *(b)* enhancing mechanisms for data collection, analysis and dissemination; *(c)* improving result-based planning, including improving coordination with other stakeholders to develop areas of synergy and avoid inconsistencies; and *(d)* raising awareness and improving outreach by enhancing the website of the Committee and disseminating findings in readily understandable formats to decision makers and the public.

11. It was assumed that, in order to implement the strategic plan, intersessional work by the Committee would increase and action would have to be taken to address both the concern of the Committee that reliance on a single Professional-level post in its secretariat had left the Committee seriously vulnerable and had hampered the efficient implementation of its approved programme of work, and methods to ensure sufficient, assured and predictable funding, as requested in General Assembly resolution 62/100.

12. For its future programme of work, the Committee decided to initiate work immediately on assessments of levels of radiation from energy production and the effects on human health and the environment; uncertainty in radiation risk estimation; attributability of health effects due to radiation exposure (in response to paragraph 6 of General Assembly resolution 62/100); updating its methodology for estimating exposures due to discharges from nuclear installations; a summary of radiation effects; and improving data collection, analysis and dissemination. Depending on the availability of resources, other work might be undertaken on the biological effects of key internal emitters, medical exposures of patients, enhanced exposures to natural sources of radiation due to human activities, public information and development of a knowledge base on radiation levels and effects. The Committee authorized the secretariat to take appropriate action to implement the strategic plan and future programme of work.

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[7] Available on request from the Secretary of the Committee.

IV. SCIENTIFIC REPORT

13. The scientific report and its annexes were elaborated from the fiftieth to the fifty-sixth sessions of the Committee on the basis of documents submitted by the secretariat. Serving as Chairman, Vice-Chairman and Rapporteur at those sessions were:

Session	*Chairman*	*Vice-Chairman*	*Rapporteur*
Fiftieth	J. Lipsztein (Brazil)	Y. Sasaki (Japan)	R. Chatterjee (Canada)
Fifty-first	J. Lipsztein (Brazil)	Y. Sasaki (Japan)	R. Chatterjee (Canada)
Fifty-second	Y. Sasaki (Japan)	R. Chatterjee (Canada)	P. Burns (Australia)
Fifty-third	Y. Sasaki (Japan)	P. Burns (Australia)	N. Gentner (Canada)
Fifty-fourth	P. Burns (Australia)	N. Gentner (Canada)	C. Streffer (Germany)
Fifty-fifth	P. Burns (Australia)	N. Gentner (Canada)	W. Weiss (Germany)
Fifty-sixth	N. Gentner (Canada)	W. Weiss (Germany)	M. Gomaa (Egypt)

14. The names of the members of national delegations who attended those sessions are listed in appendix I. The Committee wishes to acknowledge the contribution of the representatives of specialized agencies of the United Nations system and other organizations to the discussion. The Committee also wishes to recognize a small group of consultants who helped prepare the material (see appendix II). They were responsible for the preliminary assessment of the relevant technical information, on which rested the final deliberations of the Committee.

15. In conducting its work, the Committee applied scientific judgement to the material it reviewed and took care to assume an independent and neutral position in reaching its conclusions. Following established practice, the findings are presented in the present report. The supporting scientific annexes are aimed at the scientific community and will be issued separately as a United Nations sales publication.

Overview

16. For as long as they have been on the planet, humans have been exposed to ionizing radiation from natural sources, although exposure may be modified by human activity. In addition, new, artificial sources of exposure have developed over the past century or so. The Committee last made estimates of radiation exposure levels and trends in its 2000 report.[8] The present report updates and extends those estimates; table 1 summarizes the updated values for average annual doses and ranges of exposure from all sources.[9]

17. The main natural sources of exposure are cosmic radiation and natural radionuclides found in the soil and in rocks. Cosmic radiation is significantly higher at the cruising altitudes of jet aircraft than on the Earth's surface. External exposure rates due to natural radionuclides vary considerably from place to place, and can range up to 100 times the average. An important radionuclide is radon, a gas that is formed during the decay of natural uranium in the soil and that seeps into homes. Exposures due to inhalation of radon by people living and working indoors vary dramatically depending on the local geology, building construction and household lifestyles; this mode of exposure accounts for about half of the average human exposure to natural sources.

18. The Committee evaluated the additional radiation exposures introduced by military and peaceful activities. Nuclear test explosions in the atmosphere had been conducted at a number of sites, mostly in the northern hemisphere, the most active testing being in the periods 1952–1958 and 1961–1962. The radioactive fallout from those tests represents a source of continuing exposure even today, albeit at very low levels. There is concern regarding the return of residents to nuclear test areas, because radioactive residue levels are considerable at some sites. People living near sites where nuclear materials and weapons had been produced are also exposed to radiation. Military use of depleted uranium, especially in armour-piercing munitions, has raised concerns about residual contamination; however, radiation exposures are generally negligible.

19. With regard to the peaceful uses of radiation, medical exposures were by far the dominant form. Medical exposure is almost always voluntary and provides a direct benefit to the exposed individual. Irrespective of the level of health care in a country, the medical uses of radiation continue to increase as techniques develop and become more widely disseminated;

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

[9] See paragraph 26 below for a discussion of the concept of radiation dose.

about 3.6 billion radiological examinations are conducted worldwide every year. In countries with high levels of health care, exposure from medical uses is on average now equal to about 80 per cent of that from natural sources.

Table 1. Annual average doses and ranges of individual doses of ionizing radiation by source
(Millisieverts[a])

Source or mode	*Annual average dose (worldwide)*	*Typical range of individual doses*	*Comments*
Natural sources of exposure			
Inhalation (radon gas)	1.26	0.2–10	The dose is much higher in some dwellings.
External terrestrial	0.48	0.3–1	The dose is higher in some locations.
Ingestion	0.29	0.2–1	
Cosmic radiation	0.39	0.3–1	The dose increases with altitude.
Total natural	**2.4**	**1–13**	**Sizeable population groups receive 10-20 millisieverts (mSv).**
Artificial sources of exposure			
Medical diagnosis (not therapy)	0.6	0-several tens	The averages for different levels of health care range from 0.03 to 2.0 mSv; averages for some countries are higher than that due to natural sources; individual doses depend on specific examinations.
Atmospheric nuclear testing	0.005	Some higher doses around test sites still occur.	The average has fallen from a peak of 0.11 mSv in 1963.
Occupational exposure	0.005	~0–20	The average dose to all workers is 0.7 mSv. Most of the average dose and most high exposures are due to natural radiation (specifically radon in mines).
Chernobyl accident	0.002[b]	In 1986, the average dose to more than 300,000 recovery workers was nearly 150 mSv; and more than 350,000 other individuals received doses greater than 10 mSv.	The average in the northern hemisphere has decreased from a maximum of 0.04 mSv in 1986. Thyroid doses were much higher.
Nuclear fuel cycle (public exposure)	0.000 2[b]	Doses are up to 0.02 mSv for critical groups at 1 km from some nuclear reactor sites.	
Total artificial	**0.6**	**From essentially zero to several tens**	**Individual doses depend primarily on medical treatment, occupational exposure and proximity to test or accident sites.**

[a] Unit of measurement of effective dose.

[b] Globally dispersed radionuclides. The value for the nuclear fuel cycle represents the maximum per caput annual dose to the public in the future, assuming the practice continues for 100 years, and derives mainly from globally dispersed, long-lived radionuclides released during reprocessing of nuclear fuel and nuclear power plant operation.

20. The generation of electrical energy by nuclear power plants has grown steadily since 1956. The nuclear fuel cycle includes the mining and milling of uranium ore; fuel fabrication; production of energy in the nuclear reactor; storage or reprocessing of irradiated fuel; and the storage and disposal of radioactive wastes. The doses to which the public is exposed vary widely from one type of installation to another, but they are generally small and they decrease markedly the further the distance from the facility. Doses from nuclear power reactors to local and regional populations decrease over time because of lower discharge levels.

21. In the area of occupational exposure, attention had traditionally focused on artificial sources of radiation; however, it is now recognized that a very large number of workers are exposed to natural sources. Occupational exposures at commercial nuclear power plants have been falling steadily over the past three decades, albeit with significant differences between reactor types. Estimates for exposure related to the nuclear fuel cycle are generally more robust and comprehensive than for other uses of radiation. By contrast, the monitoring and reporting of occupational exposures in the medical and industrial sectors is less comprehensive. While

the average dose to workers in all occupational groups has dropped substantially over the past two decades, occupational exposures from natural radiation sources have changed little.

22. A small number of accidents have occurred in association with the nuclear fuel cycle and have attracted widespread publicity. However, more than 100 accidents have occurred with industrial and medical sources, especially in settings termed “orphaned” (i.e. outside regulatory control), and those accidents have caused injury to workers and the public. Accidents can also occur during medical uses of radiation, usually involving human or machine error in radiotherapy. While it is known that accidents involving orphan sources and medical uses of radiation have become more frequent, the current figures are likely to be underestimates, and possibly significantly so, because of underreporting.

23. The accident at the Chernobyl nuclear power plant in 1986 was the most severe such accident in the history of civilian nuclear power. Two workers died in the immediate aftermath, and 134 plant staff and emergency personnel suffered acute radiation syndrome, which proved fatal for 28 of them. Several hundred thousand workers were subsequently involved in recovery operations. Among the persons exposed to the highest radiation doses in 1986 and 1987, there are some reports of increased incidence of leukaemia and of cataracts; there is no other consistent evidence to date of other radiation-related health effects. The radioactive cloud created by the accident deposited substantial amounts of radioactive material over large areas of the former Soviet Union and other parts of Europe, contaminating land, water and biota and causing particularly serious social and economic disruption to large segments of the population in the countries known today as Belarus, the Russian Federation and Ukraine. Among the people who were children or adolescents in 1986 in affected areas of the former Soviet Union, more than 6,000 cases of thyroid cancer have been reported (to date only a small number of them fatal), of which a substantial portion could be attributed to drinking milk contaminated with the short-lived radionuclide iodine-131. In the longer term, the general population too was exposed to radiation (of the low-level chronic type) but there has been no consistent evidence yet of any other radiation-related health effects in the general population.

24. In its 1996 scientific report, the Committee evaluated the rates of exposure below which effects on populations of species other than humans were unlikely. The Committee has since reviewed the approaches to evaluating radiation doses to species other than humans, together with new scientific information on the radiobiological effects on plants and animals (in particular information from the continuing follow-up of the environmental consequences of the Chernobyl accident). That review has revealed no evidence to support changing the conclusions of the 1996 report according to which no effects are expected at chronic dose rates below 0.1 milligrays per hour or at acute doses below 1 gray to the most highly exposed individuals in the exposed population.

A. Sources of radiation exposure

25. All matter is made up of atoms. Some atoms are naturally stable, others are unstable. Radioactivity is a natural phenomenon that occurs when an atom with an unstable nucleus spontaneously transforms, releasing energy in the form of ionizing radiation. These unstable elements are known as radionuclides and they are radioactive. The released radiation may take the form of particles (including electrons, neutrons and alpha particles) or of electromagnetic gamma radiation or X-rays, all with different amounts of energy. Radiation can also be generated artificially by machines.

26. When ionizing radiation passes through matter, including living tissue, it deposits energy that ultimately produces ionization and excitation in the matter. The amount of energy deposited divided by the mass of tissue exposed is called the absorbed dose and is usually measured in units known as milligrays. The biological damage caused by radiation is related to the amount of energy deposited. However, to estimate the potential biological effect, allowance is made for the fact that different kinds of radiation have different biological effects for the same amount of energy deposited and the fact that tissues also react differently. A weighted quantity called the effective dose is used in radiation protection, and is the most commonly used indicator of the potential biological effects associated with exposure to ionizing radiation in humans. The effective dose (here simply “dose”) is usually expressed in millisieverts (mSv). The total exposure of a group of people to radiation is called the collective dose and is expressed in man-sieverts (man Sv). As a reference for subsequent comparisons, the annual global average per caput dose from natural background radiation is 2.4 mSv, while the corresponding annual collective dose to the global population from natural background radiation is about 16 million man Sv.

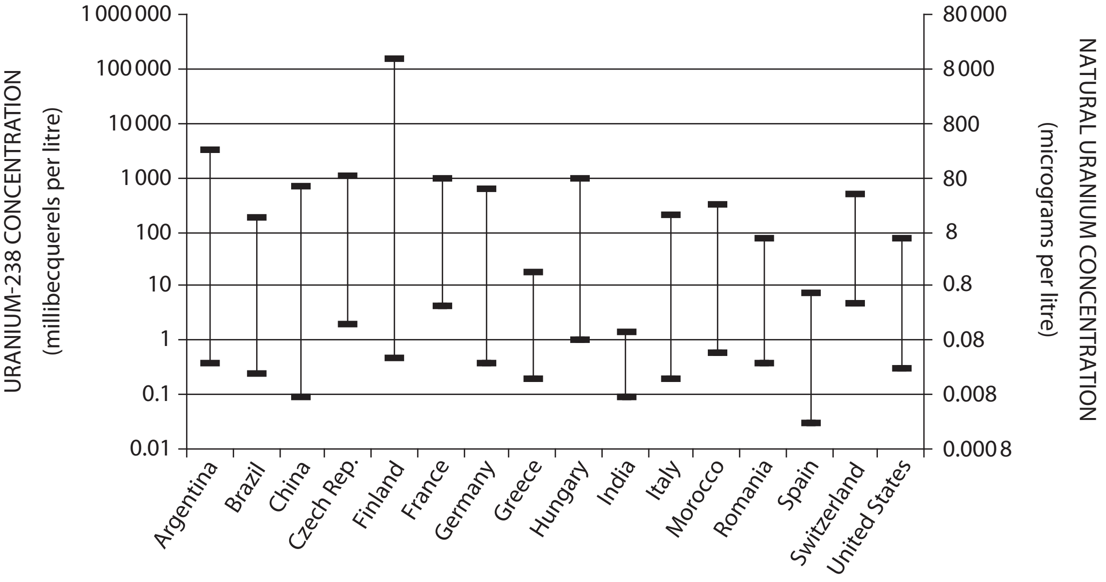
1. Natural sources

27. For most individuals, exposure to natural background radiation is the largest component of their total radiation exposure. Although the sources of radiation are natural, exposures are affected by human activity, of which the simplest example is living in a house. Building materials provide shielding against radiation from the ground but may themselves contain radionuclides that increase exposure. In addition, buildings may trap radon gas and thus increase exposures vis-à-vis those occurring in the open air.

28. Cosmic radiation (i.e. radiation originating in outer space) is significantly attenuated by the Earth’s atmosphere. At sea level it contributes about 15 per cent of the total dose from natural radiation sources; however, at higher altitudes and especially in outer space, it is the dominant radiation source. At cruising altitudes of commercial aircraft, the average dose rates are 0.003–0.008 mSv per hour, some two orders of magnitude higher than at sea level.

29. Everything in and on the Earth contains radionuclides. The so-called primordial radionuclides found in the ground (potassium-40, uranium-238 and thorium-232), together with the radionuclides into which they decay, emit radiation. Estimates of external exposure[10] vary considerably from one location to another. Some specific locations have such high concentrations of these radionuclides that the dose rates may be 100 times the global average value. These radionuclides and some formed by the interaction of cosmic rays with the Earth's atmosphere are also present in food and drink and so become incorporated into the body. Environmental concentrations of natural radionuclides are highly variable (see figure I). Most of the dose from such internal exposure[10] is due to potassium-40.

Figure I. Variability of natural uranium concentrations observed in drinking water



Note: The vertical lines express the range of values observed in the country. Note that the scales on the vertical axes increase by factors of 10.

30. One radionuclide produced from the uranium-238 decay series is radon-222 (or simply "radon"). This gas is a normal constituent of soil gas and seeps into buildings. When radon is inhaled, some of its short-lived decay products are retained in the lungs and irradiate cells in the respiratory tract. Radon levels vary dramatically depending on the underlying local geology and other factors such as the permeability of the soil, construction of the building, climate and household lifestyles. Very extensive measurement programmes have been conducted and have formed the basis for implementing measures to reduce indoor radon concentrations. Radon accounts for about half of the average exposure to natural sources of radiation.

31. The estimates of annual average and individual doses of ionizing radiation from exposure to all natural radiation sources are shown above in table 1.

2. Artificial sources

(a) Exposures from military activities

32. Nuclear test explosions in the atmosphere were conducted at a number of sites, mostly in the northern hemisphere, between 1945 and 1980, the most active testing being in the periods 1952–1958 and 1961–1962. In all, 502 tests were conducted, with a total yield of 434 megatons of trinitrotoluene (TNT) equivalent. The estimated annual per caput effective dose of ionizing radiation due to global fallout from atmospheric nuclear weapons testing was highest in 1963, at 0.11 mSv, and subsequently fell to its present level of about 0.005 mSv (see figure II). This source of exposure will decline only very slowly in the future as most of it is now due to the long-lived radionuclide carbon-14.

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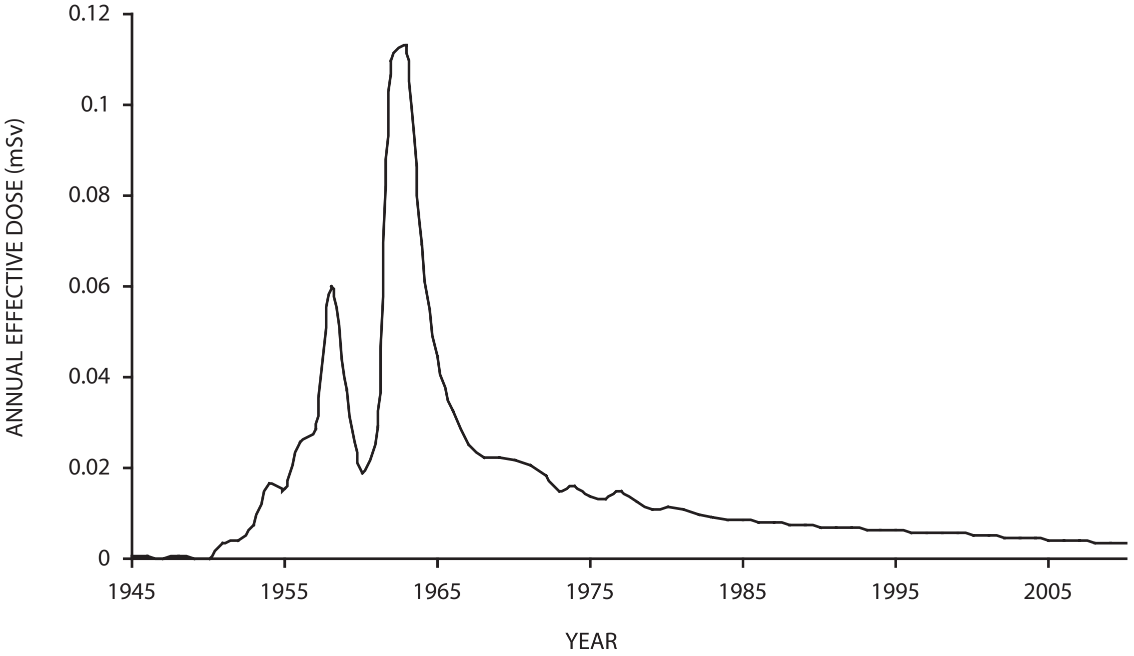
[10] External exposure is exposure to radiation that originates from outside the body, whereas internal exposure is exposure to radiation that originates from radioactive material inside the body.

Figure II. Estimated annual per caput effective dose of ionizing radiation worldwide from atomic bomb tests, 1945–2005



33. People living near test sites were also exposed to local fallout. Because the sites and the characteristics of the tests differed substantially, doses can only be estimated separately after very detailed studies at each site. Many of those studies were carried out in the late 1990s and the early years of the present decade and are still continuing. It is clear that some people living near the sites at the time of testing received very large doses. Presently there is concern regarding the return to use of nuclear test areas, since radioactive residue in some environments may be considerable.

34. From 1962 to 1990, following the signature of the 1963 Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water,[11] typically up to 50 or more explosions were conducted underground annually; a few tests were also conducted after that. Most underground tests had a much lower yield than atmospheric tests, and any radioactive debris was usually contained unless gases were vented or leaked into the atmosphere. The tests generated a very large quantity of radioactive residue, but that residue is not expected to expose the public to radiation because it is located deep underground and essentially is fused with the host rock.

35. In addition to the weapons tests themselves, the installations where nuclear materials were produced and nuclear weapons were manufactured were another source of radionuclide releases leading to radiation exposure of local populations.

36. A by-product of uranium enrichment is depleted uranium, which is less radioactive than natural uranium. Its chemical toxicity is its most hazardous property. Except for a few specific scenarios (such as long-term handling), radiation exposures should be negligible.

(b) Exposures from peaceful activities

(i) Radiation exposures of patients

37. The exposure of patients to ionizing radiation relates to diagnostic radiology, nuclear medicine and radiotherapy. The Committee conducted a survey of medical exposures for the period 1997–2007. There are some limitations on the survey data, with the majority of the responses being received from relatively more developed countries. Explicit comparison of doses resulting from medical exposures with those from other sources is inappropriate, as patients receive a direct benefit from their exposure and, moreover, they may be sick or older than the general population. In fact, increasing medical exposure is likely associated with increased health benefits to the population.

Diagnostic medical exposures

38. Since the previous survey (covering the period 1991–1996), the total number of diagnostic medical examinations (both medical and dental) is estimated to have risen from 2.4 billion to 3.6 billion—an increase of approximately 50 per cent. As in previous reports of the Committee, data are grouped according to a country's health-care level (I, II, III or IV—I being the highest, IV the lowest—based on the number of physicians per population). Figure III shows, for the period 1997-2007, the annual frequency of

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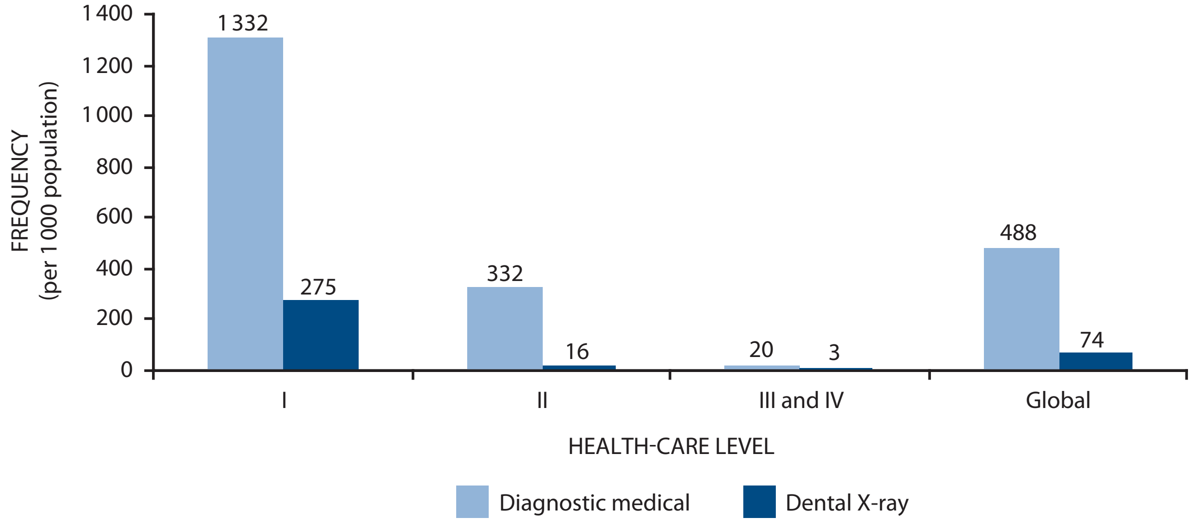
[11] United Nations, *Treaty Series*, vol. 480, No. 6964.

medical X-ray examinations by health-care level. As can be seen from the figure, such examinations were over 65 times more frequent in level I countries (which account for 24 per cent of the global population) than in level III and IV countries (which account for 27 per cent of the global population). The wide imbalance in health-care provision is also reflected in the availability of X-ray equipment and of physicians.

Figure III. Average annual frequency of diagnostic medical and dental X-ray examinations, by health-care level, 1997–2007



39. Table 2 shows the trend in the use of diagnostic radiology and the associated exposures.

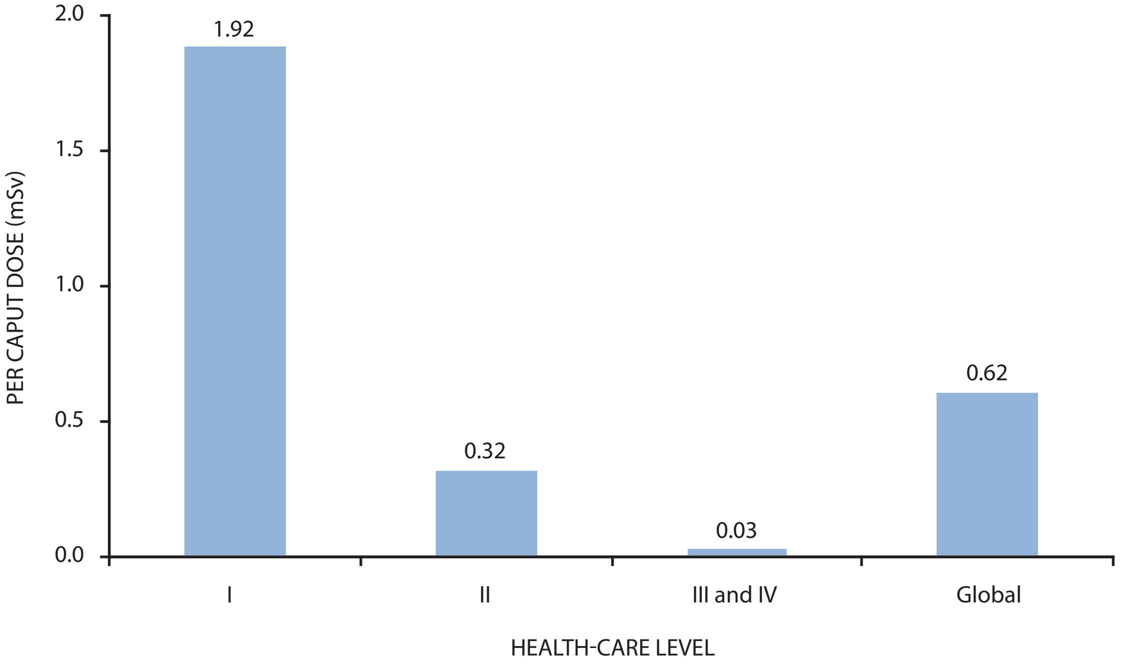
Table 2. Trend in radiation exposure from diagnostic radiology

Year of Committee report in which survey data were analysed	*Number of examinations (millions)*	*Collective effective dose (man Sv)*	*Annual per caput dose (mSv)*
1988	1 380	1 800 000	0.35
1993	1 600	1 600 000	0.3
2000	1 910	2 300 000	0.4
2008	3 100	4 000 000	0.6

40. As part of that trend, new, high-dose X-ray technology (particularly computed tomography scanning) is causing extremely rapid growth in the annual number of procedures performed in many countries and, by extension, a marked increase in collective doses. For several countries, this has resulted, for the first time in history, in a situation where the annual collective and per caput doses of ionizing radiation due to diagnostic radiology have exceeded those from the previously largest source (natural background radiation).

41. Since the last survey analysed by the Committee, the total collective effective dose from medical diagnostic examinations is estimated to have increased by 1.7 million man Sv, rising from about 2.3 million to about 4 million man Sv, an increase of approximately 70 per cent. Figure IV shows, for the period 1997–2007, the annual average per caput effective dose of radiation by health-care level and for the global population due to diagnostic medical and dental X-ray examinations.

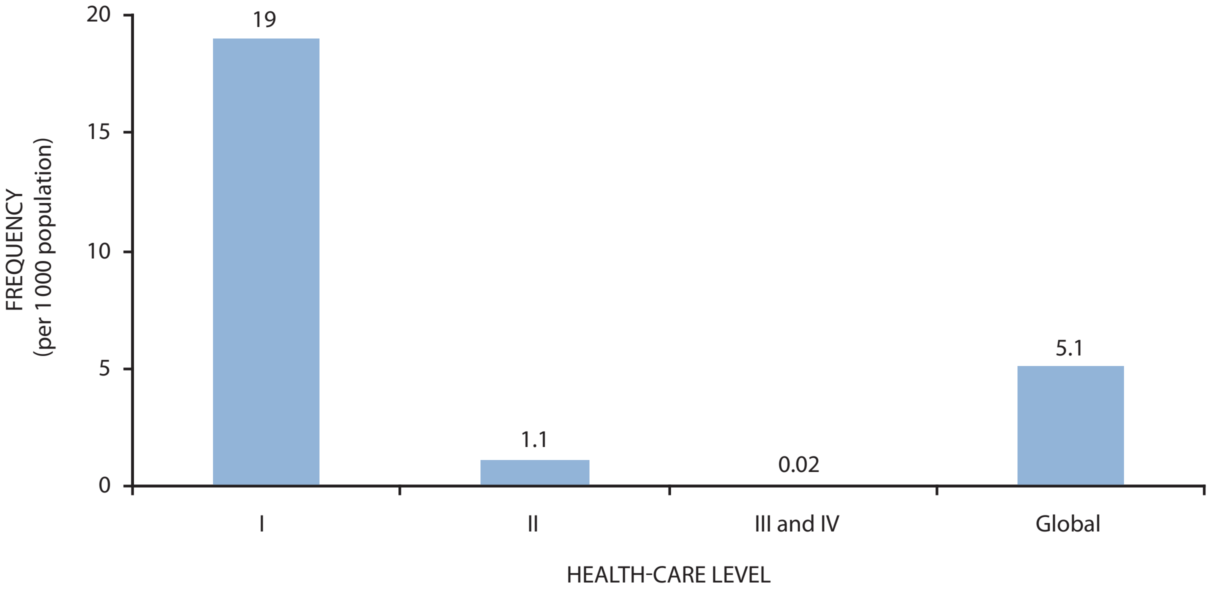
Figure IV. Annual average per caput effective dose of ionizing radiation due to diagnostic medical and dental X-ray examinations, by health-care level, 1997–2007



Nuclear medicine

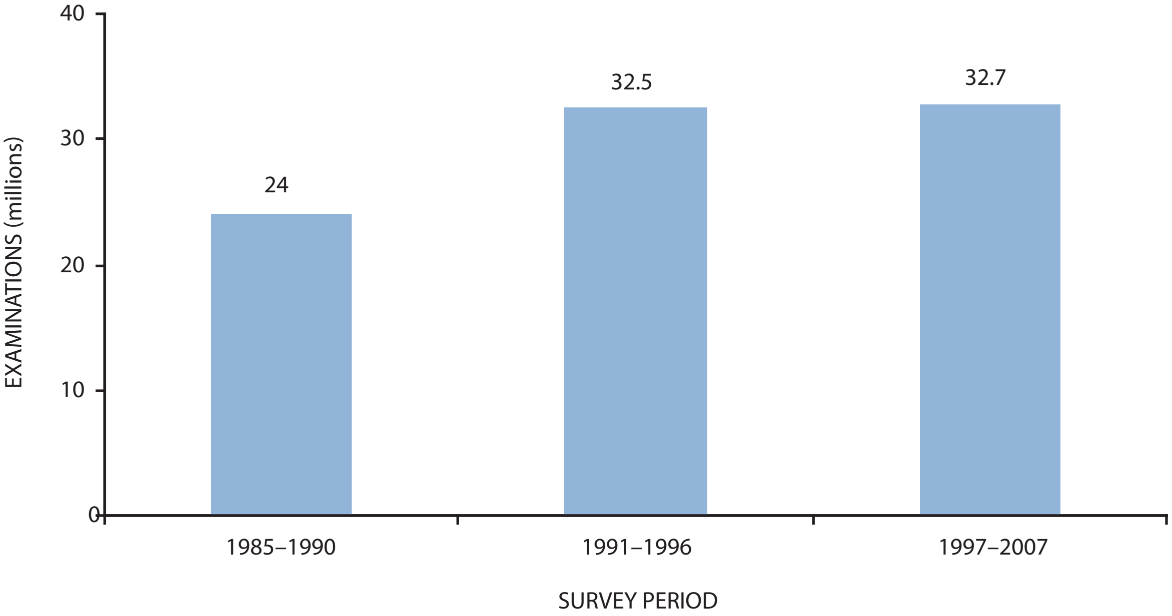
42. An estimated 32.7 million diagnostic nuclear medicine examinations are presently performed annually worldwide, which represents an increase of 0.2 million examinations per year or under 1 per cent since the 1991–1996 survey. Over that same period, the collective effective dose due to nuclear medicine examinations rose from 150,000 to 202,000 man Sv, representing an increase of 52,000 man Sv or about 35 per cent. People living in health-care level I countries account for about 90 per cent of all nuclear medicine examinations. Figure V presents, for the period 1997–2007, a summary of the annual frequency of diagnostic nuclear medicine examinations by health-care level.

Figure V. Annual frequency of diagnostic nuclear medicine examinations, by health-care level, 1997–2007



43. The estimated number of diagnostic nuclear medicine examinations conducted annually has grown over the past three survey periods (1985–1990, 1991–1996 and 1997–2007), as shown in figure VI.

Figure VI. Estimated number of diagnostic nuclear medicine examinations conducted annually, 1985–1990, 1991–1996 and 1997-2007



Radiation therapy

44. Estimated annual data on the most common types of radiotherapy treatment during the period 1997-2007 are shown for each health-care level in table 3. As can be seen, the level I countries accounted for about 70 per cent of all radiotherapy treatments. An estimated 5.1 million courses of radiotherapy treatment were administered annually between 1997 and 2007, up from an estimated 4.3 million in 1988. About 4.7 million of those treatments involved teletherapy and 0.4 million brachytherapy.

Table 3. Estimated annual data on radiotherapy treatments[a] worldwide, 1997–2007

Health-care level	*Population (millions)*	*Teletherapy*		*Brachytherapy[b]*		*All radiotherapy treatments*	
		Treatments administered each year (millions)	*Treatments administered per 1 000 population*	*Treatments administered each year (millions)*	*Treatments administered per 1 000 population*	*Treatments administered each year (millions)*	*Treatments administered per 1 000 population*
I	1 540	3.5	2.2	0.18	0.12	3.6	2.4
II	3 153	1.2	0.4	0.20	0.06	1.4	0.4
III	1 009	0.06	0.06	(<0.05)[c]	(<0.01)[c]	0.1	0.06
IV	744	(0.03)[c]	(<0.01)[c]	(<0.01)[c]	(<0.005)[c]	(0.03)[c]	(0.01)[c]
World[d]	6 446	4.7	0.73	0.4	0.07	5.1	0.8

Source: Committee survey on medical radiation usage and exposures, 1997–2007.

[a] Complete courses of treatment.

[b] Excluding treatments with radiopharmaceuticals.

[c] Assumed value in the absence of data.

[d] Global data include several countries not represented by levels I-IV.

Summary

45. Table 4 summarizes the estimated annual collective effective dose of ionizing radiation due to medical exposures for the period 1997–2007. Almost 75 per cent of the worldwide collective effective dose due to medical exposures is accounted for by health-care level I countries (those that are relatively more developed).

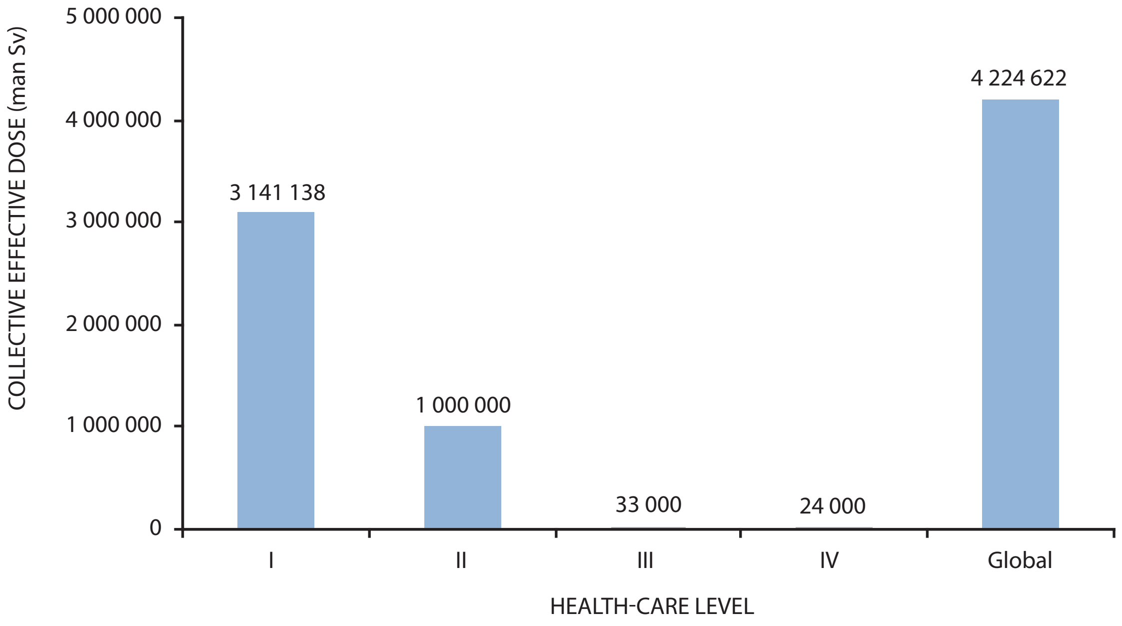
Table 4. Estimated annual collective effective dose of ionizing radiation due to medical exposures, 1997–2007
(Totals may not add precisely because of rounding)

Health-care level	*Population (millions)*	*Source of exposure*			*Total (man Sv)*
		Diagnostic medical examinations (man Sv)	*Dental X-ray examinations (man Sv)*	*Nuclear medicine examinations (man Sv)*	
I	1 540	2 900 000	9 900	186 000	3 100 000
II	3 153	1 000 000	1 300	16 000	1 000 000
III	1 009	33 000	51	82[a]	33 000
IV	744	24 000	38	. .	24 000
World	6 446	4 000 000	11 000	202 000	4 200 000

[a] Refers to health-care levels III-IV.

46. Medical exposure remains by far the largest artificial source of exposure to ionizing radiation and continues to grow at a remarkable rate. Medical exposures account for 98 per cent of the contribution from all artificial sources and are now the second largest contributor to the population dose worldwide, representing approximately 20 per cent of the total. About 3.6 billion medical radiation procedures were performed annually during the survey period, compared with 2.5 billion in the previous survey period; that is an increase of 1.1 billion procedures, or over 40 per cent, in the last decade. The total annual collective effective dose due to medical exposures (excluding radiotherapy) stood at approximately 4.2 million man Sv, an increase of 1.7 million man Sv (or just over 65 per cent) over the previous period. The distribution of medical procedures and of doses is markedly uneven among country groups (see figure VII).

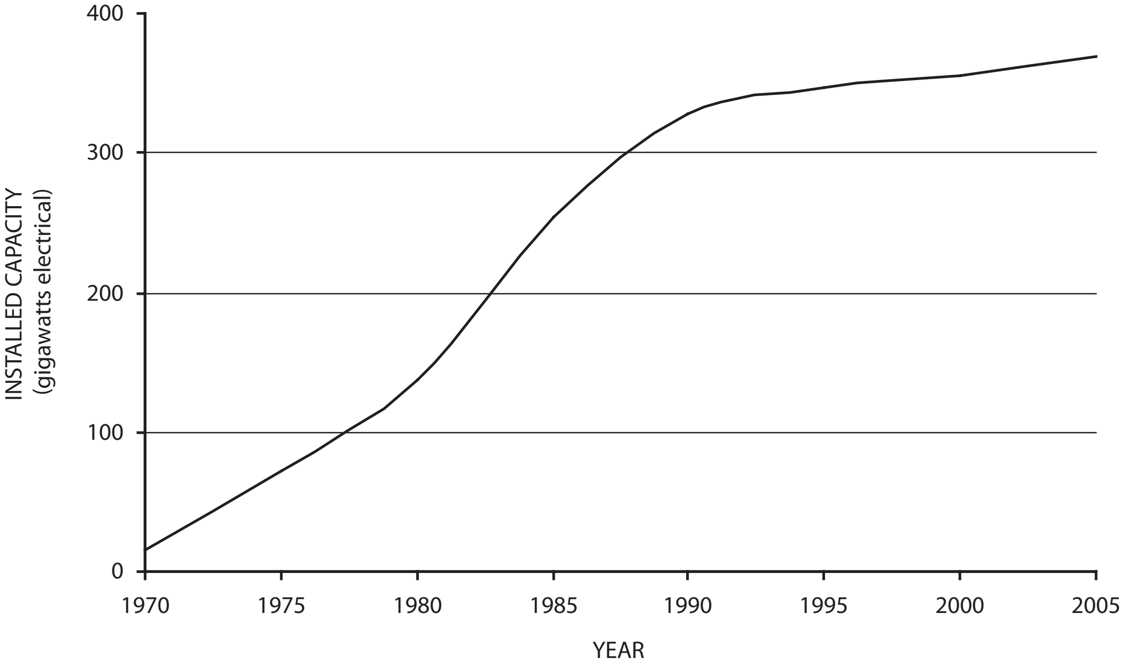
Figure VII. Total annual collective effective dose of radiation due to medical exposures (excluding radiotherapy)



(ii) Radiation exposures of the general public

47. The generation of electrical energy by nuclear power plants has grown steadily since the industry began in 1956. Despite the increase in the decommissioning of older reactors, electrical energy production from nuclear sources continues to grow (see figure VIII). The nuclear fuel cycle has the following stages: mining and milling of uranium ore and its conversion to nuclear fuel; fabrication of fuel elements; production of energy in a nuclear power plant; storage or reprocessing of irradiated fuel; transport between the various stages; and the storage and disposal of radioactive wastes. The doses of ionizing radiation to exposed individuals vary widely from one type of facility to another, between different locations and over time.

Figure VIII. Installed nuclear electricity-generating capacity worldwide, 1970–2005



48. Uranium mining and milling produces substantial quantities of residues in the form of tailings. Until 2003, the total world production of uranium was about 2 million tonnes while the resultant tailings totalled over 2 billion tonnes. Current tailing piles are well maintained, but many old, abandoned sites exist and only a few have been remediated. The Committee estimates the current annual collective dose of ionizing radiation to local and regional population groups around mine and mill sites and tailing piles at about 50–60 man Sv, similar to its previous estimates.

49. Most power reactors are of the light-water moderated and cooled type, although other designs are used in some countries. The average annual collective dose of ionizing radiation to local and regional population groups (combined) due to environmental releases from reactors is now estimated to be 75 man Sv. This is lower than previous estimates.

50. In the nuclear fuel cycle, spent fuel is reprocessed to recover uranium and plutonium for reuse in reactors. Most spent fuel is retained in interim storage but about one third of that so far produced has been reprocessed. The estimate of the annual collective dose of ionizing radiation due to reprocessing is still in the range of 20–30 man Sv.

51. The low-level and some of the intermediate-level waste from fuel cycle operations is currently disposed of in near-surface facilities, although waste was sometimes dumped at sea in the past. Both the high-level waste from reprocessing and the spent fuel (if not reprocessed) are stored but will eventually need to be disposed of. The public is expected to be exposed to radiation from disposed waste only in the distant future, if at all, so assessment of the radiological impact has to rely on mathematical modelling. Overall, an annual collective dose of about 200 man Sv is estimated for all operations related to electrical energy production. The dominant component of those operations is mining. The annual per caput dose to representative local and regional populations around nuclear power plants is less than 0.0001 mSv (about equivalent to the dose received from cosmic radiation in a few minutes of air travel).

52. There are several types of facility around the world that, while unrelated to the use of nuclear energy, may all the same expose the public to radiation because of enhanced concentrations of naturally occurring radionuclides in their industrial products, by-products and waste. The most important such facilities involve mining and minerals processing. Besides these, naturally occurring radioactive material can expose

people to ionizing radiation as a result of various normal human practices, such as the agricultural use of sludge from water treatment or the use of residue as landfill or building material. Although doses to the public are low, on the order of less than a few thousandths of a millisievert, some especially vulnerable groups could receive doses approaching 1 mSv. A major effort is under way, at both the national and international levels, to assess exposure to naturally occurring radioactive material and to develop strategies to address situations that give rise to increased radiation exposure.

(iii) Radiation exposures of workers

53. Until the 1990s, attention in the area of occupational exposure—apart from the practices related to the nuclear fuel cycle—focused on artificial sources of radiation. Now, however, it is realized that a very large number of workers are exposed occupationally to natural sources of radiation as well, and the current estimate of the resulting collective dose is about three times that indicated in the Committee's 2000 report. The total number of workers exposed to ionizing radiation is currently estimated to be about 22.8 million, of whom about 13 million are exposed to natural sources of radiation and about 9.8 million to artificial sources. Medical workers comprise the largest proportion (75 per cent) of workers exposed to artificial sources of radiation.

54. Radiation exposure of workers involved in military activities occurs during the production and testing of weapons, the operation of reactors for propulsion of naval vessels and other uses similar to those in the civilian sector. The Committee estimates that the worldwide average annual collective dose of ionizing radiation from such sources was about 50–150 man Sv and the average annual worker dose was about 0.1–0.2 mSv. However, there is a large degree of uncertainty in this estimate.

55. The extraction and processing of radioactive ores that may contain significant levels of natural radionuclides is a widespread activity. The mining sector accounts for the vast majority of occupationally exposed workers, and radon is the main source of radiation exposure in underground mines of all types. Table 5 summarizes the exposure to radon in the workplace.

Table 5. Exposure to radon in the workplace

Workplace	*Number of workers (millions)*	*Collective dose (man Sv)*	*Average effective dose (mSv)*
Coal mines	6.9	16 560	2.4
Other mines[a]	4.6	13 800	3.0
Other workplaces	1.25	6 000	4.8
		Weighted average	2.9

[a] Excluding uranium mines.

56. The annual collective dose of ionizing radiation to airline flight crews is about 900 man Sv. The estimated annual average effective dose is 2–3 mSv. Dose measurements have also been made available for a number of space missions. The reported doses for short space missions were in the range of 1.9–27 mSv.

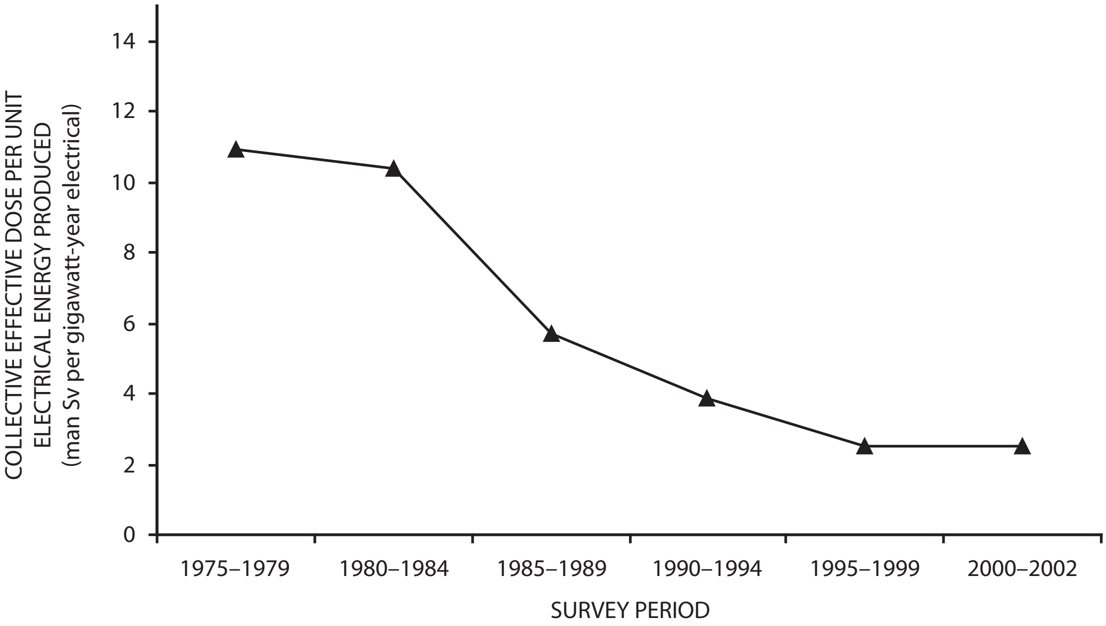
57. The annual collective dose of ionizing radiation to workers involved in the nuclear fuel cycle is estimated to be about 800 man Sv. For the fuel cycle overall, the average annual effective dose is about 1.0 mSv. The average annual dose to monitored workers in the nuclear fuel cycle has gradually declined since 1975, from 4.4 mSv to 1.0 mSv at present. Much of this decline is because of the significant reduction in uranium mining coupled with more advanced mining techniques; concurrently, the total occupational exposure at commercial nuclear power plants divided by the energy produced has also fallen steadily over the past three decades (see figure IX).

58. Between 1975 and 1989 the annual collective effective dose averaged over five-year periods for all operations in the nuclear fuel cycle varied little from the average value of 2,500 man Sv despite the three- to four-fold increase in electrical energy generated by nuclear means. The energy generated has continued to increase, but the average annual collective effective dose has fallen by almost half, from 1,400 man Sv in the period 1990–1994 to 800 man Sv in the period 2000–2002.

59. The annual collective dose to workers involved in the medical use of radiation is estimated to be about 3,540 man Sv; the average annual effective dose is about 0.5 mSv. The average annual dose to monitored workers involved in medical

uses of radiation increased by a factor of 1.7 from 1994 to 2002. However, workers involved in interventional procedures have high effective doses; and extremity doses can reach the regulatory limits. As the number of interventional procedures has increased significantly, the number of workers involved in the medical use of radiation increased by a factor of seven in the period from 1975 to 2002, and the estimated number was about 7.4 million for 2002.

Figure IX. Annual occupational collective dose of ionizing radiation at reactors, normalized to unit electrical energy produced, 1975– 2002



60. The annual collective dose to workers involved in industrial uses of radiation is estimated to be about 289 man Sv, and the average annual effective dose is about 0.3 mSv. This represents a decrease from the level of 1.6 mSv in 1975. The number of workers involved in industrial uses of radiation increased by a factor of 1.6 in the period from 1975 to 2002; the estimated number was about 0.9 million for 2002.

61. The trends in average annual occupational effective doses of ionizing radiation are shown in table 6 for the periods 1980–1984, 1990–1994 and 2000–2002. A decrease in the average effective dose can be seen for all categories of exposure to artificial sources; the sharp decrease in dose for the nuclear fuel cycle was due mainly to changes in uranium mining. However, the overall weighted average effective dose increased because of the increased exposure to natural sources of radiation.

Table 6. Trends in average annual occupational effective doses of ionizing radiation, 1980–1984, 1990–1994 and 2000–2002
(Millisieverts)

Source of exposure	*1980–1984*	*1990–1994*	*2000–2002*
Natural sources	. .	1.8	2.9
Military activities	0.7	0.2	0.1
Nuclear fuel cycle	3.7	1.8	1.0
Medical uses	0.6	0.3	0.5
Industrial uses	1.4	0.5	0.3
Miscellaneous	0.3	0.1	0.1
Weighted average	**1.3**	**1.3**	**1.8**

(c) Exposures in accidents

62. Early acute effects of radiation exposure occur only as the result of accidents (or malicious acts). Some serious accidents have led to significant population exposures owing to dispersion of radioactive material in the environment. Radiation exposures from accidents have been discussed in several past reports of the Committee, including specific evaluations of the Chernobyl accident. The Committee has categorized and summarized reported radiation accidents that resulted in early acute health effects, deaths or major environmental contamination over the past 60 years.

63. Accidents associated with the nuclear fuel cycle included a small number of serious accidents that received extensive publicity and whose consequences were reported in detail. Between 1945 and 2007, 35 serious radiation accidents occurred in nuclear facilities, 24 of them in facilities related to nuclear weapons programmes. Of those 35 accidents, 31 resulted in employee deaths or injury and 7 caused off-site releases of radioactive materials and significant population exposures. Excluding the 1986 accident at Chernobyl (which is discussed in section B below), 32 deaths (including 4 deaths caused by trauma) and 61 cases of radiation-related injuries requiring medical care are known to have occurred as a result of accidents associated with the nuclear fuel cycle.

64. Large radiation sources are in widespread use in industry (industrial irradiation facilities or accelerators) and have been involved in a number of accidents, usually attributable to operator error. All of the 80 accidents covered in the present report involved sufficient levels of exposure to cause radiation-related injuries to workers. Nine deaths and 120 worker injuries were reported in connection with those accidents.

65. Orphan sources are radioactive sources that were originally subject to regulatory control but were then abandoned, lost or stolen. The 34 reported serious accidents involving orphan sources caused radiation-related injuries to the public; altogether, 42 people, including a number of children, died in those accidents. In the accident in Goiânia, Brazil, in 1987, several hundred people were contaminated.

66. In radiation medicine, accidents generally involve errors in the delivery of radiotherapy that are often detected only after many patients have been overexposed. The Committee has reviewed only 32 reported accidents—involving 46 deaths and 623 injuries—since 1967. It is likely that some deaths and many injuries in the medical use of radiation have not been reported. Nevertheless, the reported accidents alone appear to have injured more people than accidents in any other category.

67. Of the accidents that caused exposures of ionizing radiation to the general population, the 1986 Chernobyl accident was by far the most serious one. The collective dose from that accident was many times greater than the combined collective dose from all other accidents causing exposures to the general population.

68. The trends in these accidents vary considerably. Criticality accidents were more common during the early periods of nuclear weapons programmes. Operational events related to the nuclear fuel cycle are sporadic. Accidents in industry and in academic or research establishments appear to have peaked in the late 1970s, falling off to only a few isolated occurrences in industry since 2000. The extensive and worldwide transport of radioactive materials for non-military purposes over the past many years has not resulted in any radiation-related injuries at all. Accidents with orphan sources and those related to medical uses of radiation have shown an increase over recent periods but the data may suffer from underreporting.

(d) Comparison of exposures

69. Although it is clear from the data presented that doses vary substantially by location, group, health-care level and so on, it is nonetheless helpful and customary to summarize the findings on a global basis (see table 1 above). Exposure to natural radiation does not change significantly over time, although individual exposures, particularly to radon, can vary significantly. One of the most striking changes over the past decade or so has been the sharp increase in medical exposures, owing for example to the rapid expansion in the use of computed tomography scanning. In several countries, this has meant that medical exposure has displaced exposure due to natural sources of radiation as the largest overall component. The residual doses from atmospheric testing and from the Chernobyl accident continue to decline slowly. Although occupational exposure shows a low value when averaged across the whole population, the estimated level has increased substantially owing to the recognition of exposure to natural radionuclides in mining. Doses from the nuclear fuel cycle continue to be very small despite the gradual expansion of that sector.

B. Chernobyl accident

70. The 1986 accident at the Chernobyl nuclear power plant in the former Soviet Union was the most severe such accident in the history of civilian nuclear power. Two workers died in the immediate aftermath, and 134 plant staff and emergency personnel suffered acute radiation syndrome, which proved fatal for 28 of them. Several hundred thousand workers were subsequently involved in recovery operations.

71. The accident caused the largest uncontrolled radioactive release into the environment ever recorded for any civilian operation; large quantities of radioactive substances were released into the atmosphere for about 10 days. The radioactive cloud created by the accident dispersed over the entire northern hemisphere and deposited substantial amounts of radioactive material over large areas of the former Soviet

Union and other parts of Europe, contaminating land, water and biota and causing particularly serious social and economic disruption to large segments of the population in the countries known today as Belarus, the Russian Federation and Ukraine. Two radionuclides, the short-lived iodine-131 (with a half-life of 8 days) and the long-lived caesium-137 (with a half-life of 30 years), were particularly significant because of the radiation dose they delivered to the public. However, the doses delivered were quite different for the two radionuclides: the thyroid doses from iodine-131 ranged up to several grays within a few weeks after the accident, while the whole-body doses from caesium-137 ranged up to a few hundred millisieverts over the following few years.

72. The contamination of fresh milk with iodine-131 and the lack of prompt countermeasures led to high thyroid doses, particularly among children, in the former Soviet Union. In the longer term, mainly due to radiocaesium, the general population was also exposed to radiation, both externally from radioactive deposits and internally from consuming contaminated foodstuffs. However, the resulting long-term radiation doses were relatively low (the average additional dose over the period 1986–2005 in "contaminated areas"[12] of Belarus, the Russian Federation and Ukraine was 9 mSv, approximately equivalent to that from a medical computed tomography scan), and should not lead to substantial health effects in the general population that could be attributed to radiation. The foregoing notwithstanding, the severe disruption caused by the accident resulted in a major social and economic impact and great distress for the affected populations.

73. Since the accident, the international community has made unprecedented efforts to assess the magnitude and characteristics of its radiation-related health effects. Many initiatives, including those by the United Nations Educational, Scientific and Cultural Organization (UNESCO), the World Health Organization (WHO), the International Atomic Energy Agency (IAEA) and the European Commission, were launched to better understand the consequences of the accident and assist in their mitigation. The results of those initiatives were synthesized at an international conference on the theme "One decade after Chernobyl: summing up the consequences of the accident", which was held in Vienna from 8 to 12 April 1996. The conference was co-sponsored by WHO, IAEA and the European Commission in cooperation with the United Nations, the United Nations Scientific Committee on the Effects of Atomic Radiation, the Food and Agriculture Organization of the United Nations, UNESCO and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development. In the international scientific assessments, broadly similar conclusions were reached on the extent and character of the consequences of the accident.

74. The Committee first considered the initial radiological consequences of the accident in its 1988 report.[13] In its 2000 report, the Committee provided a detailed account of the situation as it was known at that time. Subsequent to the publication of that report, eight organizations and bodies of the United Nations system[14] (including the Committee) and the three affected States launched the Chernobyl Forum, which was to generate authoritative consensual statements on the environmental and health consequences attributable to radiation exposure and to provide advice on issues such as environmental remediation, special health-care programmes and research activities. The work of the Chernobyl Forum was appraised at an international conference on the theme "Chernobyl: looking back to go forwards; towards a United Nations consensus on the effects of the accident and the future", which was held in Vienna on 6 and 7 September 2005. At that conference, all the previous assessments of the scale and character of the radiation-related health consequences of the accident were essentially reconfirmed.

75. The objective of the Committee in the present evaluation is to provide an authoritative and definitive review of the health effects observed to date that are attributable to radiation exposure due to the accident and a clarification of the projection of potential effects, taking into account the levels, trends and patterns of radiation dose to the exposed populations. To that end the Committee evaluated relevant information that became available since its 2000 report and ascertained that observations were not inconsistent with assumptions used previously to assess radiological consequences. It also recognized that some outstanding details merited further scrutiny and that its work to provide the scientific basis for a better understanding of the radiation-related health and environmental effects of the accident needed to continue.

76. Although a considerable volume of new research data has become available, the major conclusions regarding the scale and nature of the health consequences of the Chernobyl accident are essentially consistent with the Committee's 1988 and 2000 reports. Those conclusions are as follows:

(a) A total of 134 plant staff and emergency workers received high doses of radiation that resulted in acute radiation syndrome (ARS), many of them also incurring skin injuries due to beta irradiation;

(b) The high radiation doses proved fatal for 28 of those people in the first few months following the accident;

(c) Although 19 ARS survivors had died by 2006, those deaths had different causes that usually were not associated with radiation exposure;

(d) Skin injuries and radiation-related cataracts were among the main sequelae of ARS survivors;

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[12] The "contaminated areas" were defined arbitrarily by the former Soviet Union as areas where the soil levels of caesium-137 were greater than 37 kilobecquerels per square metre.

[13] *Official Records of the General Assembly, Forty-third Session, Supplement No. 45* (A/43/45).

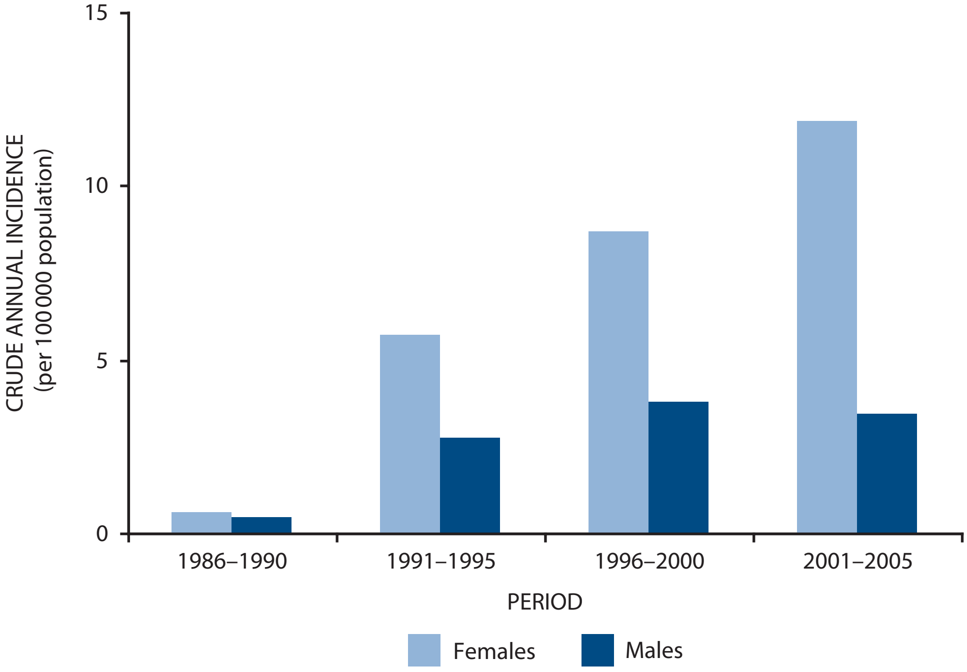
[14] UNEP, Office for the Coordination of Humanitarian Affairs of the Secretariat, the United Nations Development Programme, the United Nations Scientific Committee on the Effects of Atomic Radiation, FAO, WHO, the World Bank and IAEA.

(e) Aside from the emergency workers, several hundred thousand people were involved in recovery operations but, apart from indications of an increase in incidence of leukaemia and of cataracts among those who received higher doses, there is to date no consistent evidence of health effects that can be attributed to radiation exposure;

(f) A substantial increase in thyroid cancer incidence among persons exposed to the accident-related radiation as children or adolescents in 1986 has been observed in Belarus, Ukraine and four of the more affected regions of the Russian Federation. For the period 1991–2005, more than 6,000 cases were reported, of which a substantial portion could be attributed to drinking milk in 1986 contaminated with iodine-131. Although thyroid cancer incidence continues to increase for this group (see figure X for the trend in Belarus), up to 2005 only 15 cases had proved fatal;

(g) Among the general public, to date there has been no consistent evidence of any other health effect that can be attributed to radiation exposure.

Figure X. Thyroid cancer incidence among people in Belarus who were children or adolescents at the time of the Chernobyl accident, 1986–1990, 1991–1995, 1996–2000 and 2001–2005



77. Although model-based predictions have been published about possible increases in solid cancer incidence among the general population, for all the population groups considered the doses are relatively small and are comparable to doses resulting from exposure to natural background radiation. The Committee has decided not to use models to project absolute numbers of effects in populations exposed to low doses because of unacceptable uncertainties in the predictions. However, the Committee considers that it is appropriate to continue surveillance.

78. Based on 20 years of studies, it is possible to reconfirm the conclusions of the Committee's 2000 report. Essentially, persons who were exposed as children to radioiodine from the Chernobyl accident and the emergency and recovery operation workers who received high doses of radiation are at increased risk of radiation-induced effects. Most area residents were exposed to low-level radiation comparable to or a few times higher than the annual natural background radiation levels and need not live in fear of serious health consequences.

79. The Committee considers its most recent evaluation an important point of reference for the United Nations Coordinator of International Cooperation on Chernobyl in responding to the request by the General Assembly pursuant to paragraph 16 of its resolution 62/9 of 20 November 2007, that the Coordinator continue his work in organizing, in collaboration with the Governments of Belarus, the Russian Federation and Ukraine, a further study of the health, environmental and socio-economic consequences of the Chernobyl disaster, consistent with the recommendations of the Chernobyl Forum, and to improve the provision of information to local populations.

C. Effects on non-human biota

80. All species present on the Earth have existed and evolved in environments where they have been exposed to ionizing radiation from the natural background. More recently, however, organisms are also being exposed to artificial sources of radiation, such as global fallout from atmospheric nuclear weapons tests and, in certain locations, controlled discharges of radionuclides or accidental releases of radioactive material.

81. In its 1996 report,[15] the Committee evaluated those doses and dose rates of ionizing radiation below which effects on populations of non-human biota were unlikely. It considered that the individual responses to radiation exposure that were likely to be significant at the population level were in the areas of mortality, fertility, fecundity and the induction of mutations. The Committee also considered that reproductive changes were a more sensitive indicator of radiation effects than mortality, and that mammals were the most sensitive of all animal organisms. On that basis, the Committee derived the dose rates to the most highly exposed individuals that would be unlikely to have significant effects on most populations.

82. Since then, new data on the effects of ionizing radiation have been obtained from follow-up observations of non-human biota in the area around the Chernobyl site. Various organizations have carried out comprehensive reviews of the scientific literature and, in some cases, have developed new approaches for assessing the potential effects on non-human biota. There is a considerable range of end points and corresponding effect levels presented in the literature and also considerable variation in how different researchers evaluate those data. Table 7 provides a brief summary of the relevant data for aggregated categories of organisms.

83. The Committee concluded that, overall, there was no evidence to support changing the conclusions of its 1996 report according to which chronic dose rates of less than 0.1 milligrays per hour to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities and chronic dose rates of less than 0.4 milligrays per hour to any individual in aquatic populations of organisms would be unlikely to have any detrimental effect at the population level. For acute exposures, studies of the Chernobyl accident experience had confirmed that significant effects on populations of non-human biota were unlikely at doses below about 1 gray.

84. Since the time of the Committee's 1996 report, a great deal of work has been done to investigate and improve data and methods for evaluating pathways through which biota are exposed to radiation in their environment; there have also been many improvements in assessing doses to biota. It is important to note that many opportunities remain for improving current understanding and methods in those areas. An improved understanding of such aspects will improve the overall understanding of the relationship between levels of radiation and radioactivity in the environment and the potential effects on biota.

Table 7. Some effects of ionizing radiation on selected categories of non-human biota

Chronic dose rate (milligrays per hour)	*Category*	*Effect*	*End point*
0.1-1	Plants Fish	Death of pine needles: reduced numbers of herbaceous plants Reduction in sperm production, delayed spawning	Mortality, morbidity Reproductive damage
About 0.1	Mammals	No detrimental end points described	Morbidity, mortality, reproductive damage

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[15] *Official Records of the General Assembly, Fifty-first Session, Supplement No. 46* (A/51/46).

APPENDIX I

MEMBERS OF NATIONAL DELEGATIONS ATTENDING THE FIFTIETH TO FIFTY-SIXTH SESSIONS OF THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, AT WHICH THE 2008 SCIENTIFIC REPORT WAS ELABORATED

Argentina	A. J. González (Representative), D. Beninson (Representative), P. Gisone (Representative), M. del Rosario Pérez
Australia	P. A. Burns (Representative), S. Solomon, P. Thomas
Belgium	H. Vanmarcke (Representative), H. Bosmans, A. Debauche, H. Engels, J. Lembrechts, J. R. Maisin (Representative), P. Smeesters, J. M. Van Dam, A. Wambersie, H. Bijwaard, R. O. Blaauboer, M. J. Brugmans
Brazil	O. Dias Gonçalves (Representative), J. L. Lipsztein (Representative), M. C. Lourenço, M. Nogueira Martins, D. R. Melo (Representative), E. R. Rochedo
Canada	N. E. Gentner (Representative), R. P. Bradley, K. Bundy, D. B. Chambers, R. M. Chatterjee (Representative), R. J. Cornett, R. Lane, C. Lavoie, S. Vlahovich (Representative), D. Whillans
China	Pan Z. (Representative), He Q., Hou P., Jia J., Li K., Li J., Liu S., Liu Q., Lu J., Pan S., Shang B., Shi J., Su X., Sun J., Sun Q., Wang F., Xiu B., Xuan Y., Yang G., Yang H., Yang X., Yu J., Zhang J., Zhu M.
Egypt	M.A.M. Gomaa (Representative), A. M. el-Naggar (Representative)
France	A. Flüry-Hérard (Representative), E. Ansoborlo, A. Aurengo, D. Averbeck, M. Benderitter, M. Bourguignon, C. Forestier, J. F. Lacronique (Representative), J. Lallemand, J. J. Leguay, C. Luccioni, R. Maximilien, A. Rannou, M. Tirmarche
Germany	W. Weiss (Representative), A. Friedl, P. Jacob, A. Kellerer, J. Kiefer, G. Kirchner, W. Köhnlein, R. Michel, W. U. Müller, C. Streffer (Representative)
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SECRETARY OF THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION

N. E. Gentner (fiftieth to fifty-second sessions)

M. J. Crick (fifty-third to fifty-sixth sessions)

APPENDIX II

SCIENTIFIC STAFF AND CONSULTANTS COOPERATING WITH THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION IN THE PREPARATION OF THE 2008 SCIENTIFIC REPORT OF THE COMMITTEE

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May 2011

Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report to the General Assembly, with Scientific Annexes—Volume I

Corrigendum

1. Annex A (“Medical radiation exposures”), page 172, figure D-II

The title *should read*

Representative isodose distributions: Intensity-modulated radiation therapy plan for a prostate tumour, showing superior conformation of the 50 Gy isodose line to the planning target volume

2. Annex B (“Exposures of the public and workers from various sources of radiation”), paragraph 155

The paragraph *should read*

155. *Effluents and solid waste*. Mining operations have been carried out in open pits, in underground mines and by in situ leaching. Uranium mill tailings are generated at about one tonne per tonne of ore extracted, and they generally retain 5–10% of the uranium and 85% of the total activity [V4]. The estimated amounts of tailings worldwide are shown in figure XVII; they total about 2.35×10^9 t. Besides the tailings, waste rock piles may also become a source of public exposure. For open-pit mining, the amount of debris produced is from 3 to 30 tonnes per tonne of extracted ore. For underground mining, about ten times less debris is produced. On the basis of information provided for 13 mining sites in Argentina [R13], Canada [M28], Germany [F2] and Spain [S29], the amount of waste rock varies from 40 to 6,000 times the amount of tailings, with an average value of about 1,600 tonnes of waste rock per tonne of tailings [I38].

ANNEX A

MEDICAL RADIATION EXPOSURES

CONTENTS

MEDICAL EXPOSURE TO IONIZING RADIATION

I. INTRODUCTION

1. The objective of the past reports of the Scientific Committee [U3, U4, U6, U7, U9, U10] with respect to medical exposures has been to establish the annual frequency of medical examinations and procedures involving the use of radiation, as well as their associated doses. Reviews have been performed of practice in diagnostic radiology, in the use of nuclear medicine and in radiation therapy. Data have been analysed to deduce temporal trends, to evaluate the collective population dose due to medical exposure, and to identify procedures for which the doses are major contributors to the total collective dose. In earlier UNSCEAR reports on doses from medical irradiation [U10, U11], the annual frequency of medical exposures was estimated on the basis of a very limited series of surveys, mainly but not exclusively performed in developed countries. Initially information was obtained under broad headings such as diagnostic radiography or diagnostic fluoroscopy [U11].

2. The purpose of this annex is to assess the magnitude of use of medical exposures around the globe in the period 1997–2007, to determine the relative contribution to dose from various modalities and procedures, and to assess trends. It is not within the mandate of the Committee to assess potential benefits from medical exposure. Documented detrimental effects resulting from medical exposures have been covered in other reports of the Committee and their associated scientific annexes, for example those on carcinogenesis (annex A, “Epidemiological studies of radiation and cancer”, of the UNSCEAR 2006 Report [U1]) and accidental exposure (annex C, “Radiation exposures in accidents”, of the UNSCEAR 2008 Report).

3. Exposure of the public resulting from contact with patients undergoing either treatment or a diagnostic procedure that uses sealed or unsealed radionuclides is considered in annex B, “Exposures of the public and workers from various sources of radiation”, of the UNSCEAR 2008 Report. That annex also addresses exposures of the public arising from the disposal of radioactive waste from hospitals and the production of radionuclides for medicine.

4. Occupational exposure resulting from work involving the medical use of radiation occurs for persons administering the radiation to the patient or in some circumstances for persons nearby. Annex B also examines such occupational exposure in detail.

5. This annex presents a comprehensive up-to-date review of medical exposures to ionizing radiation. This review is based in part on an analysis of the responses to the UNSCEAR Global Survey of Medical Radiation Usage and Exposures and a critical assessment of the published literature on medical exposures. The purpose of this annex is to estimate the annual frequency (number of examinations per fixed number of people) of diagnostic and therapeutic medical procedures and the doses associated with them.

II. SCOPE AND BASIS FOR THE ANALYSIS

6. Medical exposures include [I3]: *(a)* the exposure of patients as part of their medical diagnosis or treatment; *(b)* the exposure of individuals as part of health screening programmes; *(c)* the exposure of healthy individuals or patients voluntarily participating in medical, biomedical, diagnostic or therapeutic research programmes.

7. There are substantial and distinct differences between medical exposure to radiation and most other exposures to radiation. Medical exposure is almost always voluntary and is generally accepted to bring more benefits than risks. In many developing countries, increasing the availability of appropriate medical procedures that use ionizing radiation results in a net health benefit.

8. Medical exposures typically involve only a portion of the body, whereas many other exposures involve the whole body. In addition, many persons who are exposed are not typical of the general population. Their average age is usually somewhat higher and they have medical conditions that may significantly affect the trade-off between the benefits and the risks of using radiation. In contrast, the introduction of new imaging technologies has in some instances resulted in increased use of paediatric radiology, influencing the age profile for the examinations performed. As a result of the above considerations, while the magnitude of medical exposures can be examined, it is very difficult or impossible to estimate the risks of adverse effects due to medical uses, still less to defensibly compare such estimates with those for other sources of exposure to radiation.

III. MEDICAL RADIATION EXPOSURE

9. There are three general categories of medical practice involving exposure to ionizing radiation: diagnostic radiology (and image-guided interventional procedures), nuclear medicine and radiation therapy.

10. Diagnostic radiology generally refers to the analysis of images obtained using X-rays. These include plain radiographs (e.g. chest X-rays), images of the breast (i.e. mammography), images obtained using fluoroscopy (e.g. with a barium meal or barium enema) and images obtained by devices using computerized reconstruction techniques such as computed tomography (CT). In addition to their use for diagnosis, interventional or invasive procedures are also performed in hospitals (e.g. placing a catheter in a blood vessel to obtain images). For the purposes of this annex, such uses are considered to be diagnostic exposures. Some of the procedures mentioned above are not always performed by diagnostic radiologists but may also be performed by others, including general medical physicians, cardiologists and orthopaedic surgeons, whose training in radiation protection may not be as thorough as that of diagnostic radiologists. Physicians also use imaging technologies that do not employ ionizing radiation, such as ultrasound and magnetic resonance imaging (MRI). Dental radiology has been included in the analysis conducted here of diagnostic radiology practice; however the terms “diagnostic dental radiology” and “diagnostic medical radiology” (mutatis mutandi) are used to distinguish dental exposures from other diagnostic exposures.

11. Nuclear medicine refers to the introduction of unsealed radioactive materials into the body, most commonly to obtain images that provide information on either structure or organ function. The radioactive material is usually given intravenously, orally or by inhalation. A radionuclide is usually modified to form a radiopharmaceutical that will be distributed in the body according to physical or chemical characteristics (for example, a radionuclide modified as a phosphate will localize in the bone, making a bone scan possible). Radiation emitted from the body is analysed to produce diagnostic images. Less commonly, unsealed radionuclides are administered to treat certain diseases (most frequently hyperthyroidism and thyroid cancer). There is a clear trend towards increased therapeutic applications in modern nuclear medicine.

12. Radiation therapy refers to the use of ionizing radiation to treat various diseases (usually cancer). Sometimes radiation therapy is referred to as radiation oncology; however, benign diseases also may be treated. External radiotherapy refers to treatment of the patient using a radiation source that is outside the patient. This may be a machine containing a highly radioactive source (usually cobalt-60) or a high-voltage machine that produces radiation (e.g. a linear accelerator). Treatment can also be performed by placing metallic or sealed radioactive sources within the patient (brachytherapy). These may be placed either temporarily or permanently.

IV. METHODOLOGY AND SOURCES OF DATA

13. Evaluation of medical exposures consists of assessing the annual frequency and types of procedure being undertaken, as well as an evaluation of the radiation doses for each type of procedure. Annual frequency and dose data are derived from three main sources: the peer-reviewed scientific literature, official reports provided by member States, and the Surveys of Medical Radiation Usage and Exposures conducted by the secretariat on behalf of the Committee. As in previous reports, annual frequency data on procedures are stratified by health-care level (level I, II, III or IV), which are based on the number of physicians per head of population. The number of physicians per head of population has been shown to correlate well with the number of medical examinations performed using ionizing radiation [M39, M40]. This allows extrapolation to those countries for which the Committee has limited or no data.

14. The UNSCEAR 1982 Report [U9] was the first to use a survey, developed by WHO in cooperation with UNSCEAR, to obtain information on the availability of diagnostic radiology equipment and the annual frequency of diagnostic X-ray examinations in various countries. Examination frequency data in previous reports had been based upon surveys in a limited number of countries. Data from five continents were presented in the UNSCEAR 1982 Report [U9], which was also the first UNSCEAR survey to include an assessment of exposures from CT.

15. The four-level health-care model for the analysis of medical exposures was introduced in the UNSCEAR 1988 Report [U7] and has been used in the Committee’s subsequent reports. In this model, countries were stratified according to the number of physicians per head of population. Level I countries were defined as those in which there was at least one physician for every 1,000 people in the general population; in level II countries there was one physician for every 1,000–2,999 people; in level III countries there was one physician for every 3,000–10,000 people; and in level IV countries there was less than one physician for every 10,000 people [U7].

16. The Committee also explored other approaches to the classification of health-care levels, for example by health-care expenditure or number of hospital beds. However, it

was found that there was a poor correlation between values for these parameters and the number of medical radiation procedures. Subsequent reports have therefore continued to use the four-level health-care model based upon the number of physicians per head of population [U3, U6]. Over the years this model has proved to be robust in estimating medical radiation exposures. One of the main advantages of the model is that it provides a consistent basis for the extrapolation of practice in a small sample of countries to the entire world. It also facilitates the comparison of trends in medical exposures over time [U7]. Consequently this health-care model has been used in the present analysis of worldwide exposure.

17. In order to evaluate the level of medical exposures worldwide, the UNSCEAR secretariat conducted a Survey of Medical Radiation Usage and Exposures by circulating a questionnaire to all Member States of the United Nations. The Committee bases its estimation of medical exposures upon an analysis of the questionnaire returns. Most of the responses have been received from countries defined by the Committee as health-care level I countries, which represent under a quarter of the world's population.

18. As annual frequency data were only available from those countries that undertake surveys of practice, the analysis of medical exposures has necessarily been based on extrapolating data from the fraction of countries where data were reported to all other countries in a given health-care level. Data on doses were also collected by survey and compared with those in the published literature. For each procedure, the number of procedures per head of population is multiplied by the effective dose per procedure and the relevant population size (i.e. population size for the respective health-care level). The collective effective dose (or population dose) for the global population is then deduced by performing the above calculation for all procedures across all health-care levels and summing the result for all procedures. The Committee also examines trends over time for various procedures, as well as trends over time in the global collective effective dose.

V. ASSESSMENT OF GLOBAL PRACTICE

A. Diagnostic radiology

19. The medical use of ionizing radiation remains a rapidly changing field. This is in part because of the high level of innovation by equipment supply companies [W1] and the introduction of new imaging techniques such as multislice CT and digital imaging.

20. In the UNSCEAR 2000 Report [U3] it was noted that 34% of the collective dose due to medical exposures arose from CT examinations. As a consequence, the increasing trend in annual CT examination frequency and the significant dose per examination have an important impact on the overall population dose due to medical exposures. The contribution of CT examinations to the population dose has continued to increase rapidly ever since the practice was introduced in the 1970s. In the area of CT examinations, the introduction of helical and multislice scanning has reduced scan times [I28]. As a consequence, it is now possible to perform more examinations in a given time, to extend the scope of some examinations, and to introduce new techniques and examinations. The ease of acquisition of images could result in unnecessary exposures of patients to radiation. This, combined with the increase in the number of machines, has a significant impact on population doses, particularly for countries with health-care systems at level I. An accurate assessment of medical exposures due to CT scanning is therefore particularly important.

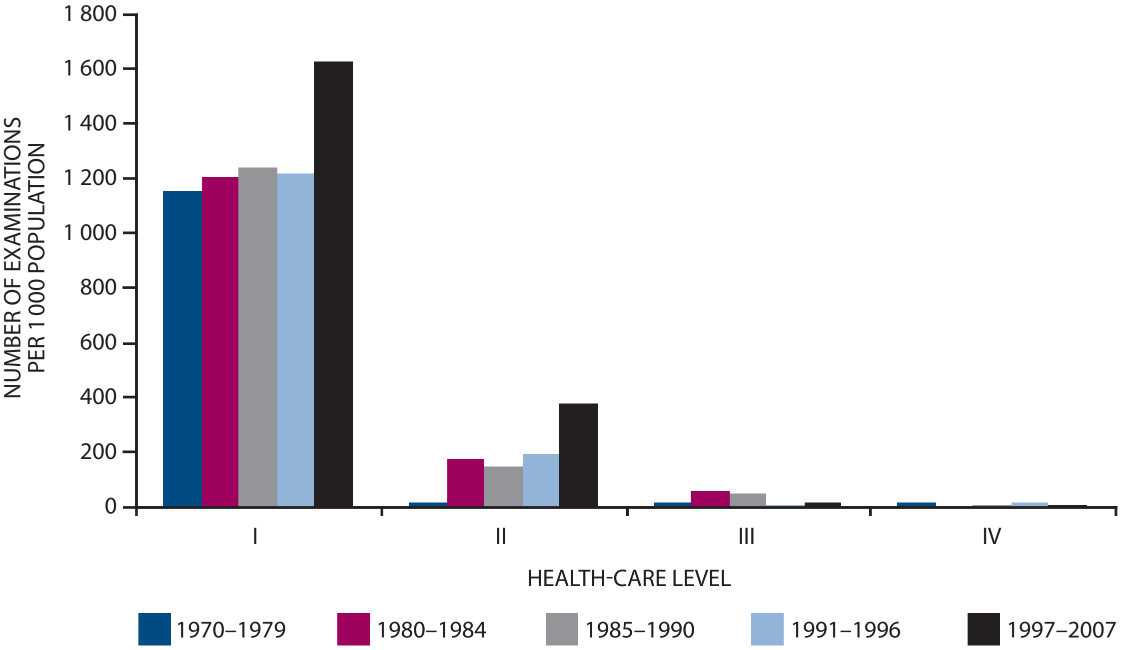
21. Digital imaging is another area of diagnostic radiology that has seen striking changes [I8]. Digital imaging using photostimulable storage phosphor devices was introduced into clinical practice in the 1980s. Since its introduction, there has been a gradual increase in its use. New types of digital imaging device are being introduced to the marketplace. These systems utilize a large-area direct digital detector for imaging and offer many advantages, one of which in principle is a lower dose per image compared with other devices. Thus there could be another era of rapidly changing practice in diagnostic radiology over the course of the next UNSCEAR Global Survey of Medical Radiation Usage and Exposures. This will initially influence population doses in health-care level I countries for radiographic and fluoroscopic examinations before the practice widely influences population doses in countries at other health-care levels. Population doses due to digital radiology will probably increase as a result of an increasing frequency of digital imaging examinations and procedures.

22. According to the current analysis, there are approximately 3.6 billion diagnostic radiology X-ray examinations (including diagnostic medical and dental examinations) undertaken annually in the world. Figure I presents trends in the annual frequency of diagnostic medical and dental radiological examinations for each health-care level.

23. The 24% of the population living in health-care level I countries receive approximately two thirds of these examinations. The annual frequency of diagnostic medical examinations alone (defined here as excluding dental radiology) in health-care level I countries is estimated to have increased from 820 per 1,000 population in 1970–1979 to 1,332 per 1,000 population in this survey. Comparative values for health-care level II countries exhibit an even greater relative increase, from 26 per 1,000 in 1970–1979 to 332 per 1,000 in 1997–2007. Most of the increase for level I and II countries

occurred in the period 1997–2007. The estimated annual frequency of diagnostic medical examinations in health-care level III/IV countries has remained fairly constant over this period, although since there were limited data for these countries, there is considerable uncertainty associated with this estimate.

Figure I. Trends in the annual frequency of diagnostic medical and dental radiological examinations for each health-care level

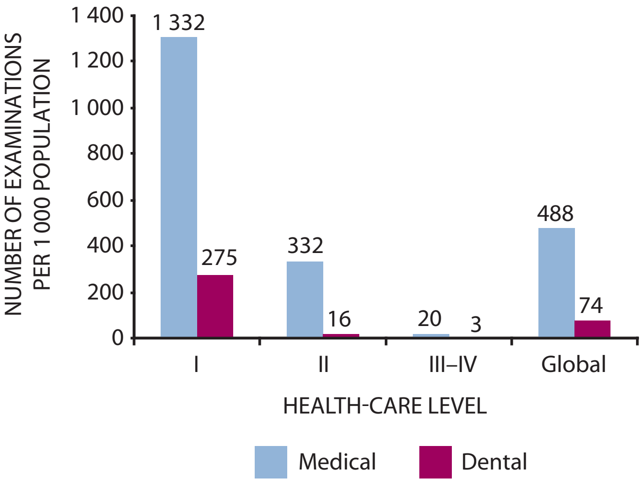


24. CT scanning accounts for 7.9% of the total number of diagnostic medical examinations in health-care level I countries, just over 2.0% in health-care level II countries and just under 14% in health-care level III/IV countries. However, the contribution of CT scanning to the total collective effective dose due to diagnostic medical examinations is approximately 47% in health-care level I countries, and 15% and 65% in health-care level II and III/IV countries, respectively (there is great uncertainty in the doses and frequencies for health-care level III/IV countries). According to this UNSCEAR Global Survey of Medical Radiation Usage and Exposures, CT scanning accounts for 43% of the total collective effective dose due to diagnostic medical radiology.

25. For diagnostic dental examinations, the annual frequency has remained fairly constant for health-care level I countries, being 275 per 1,000 population in this survey, compared with 320 per 1,000 population in the 1970–1979 survey. Over this period, there has been a substantial increase in the annual frequency of diagnostic dental examinations in health-care level II countries, rising from 0.8 per 1,000 population in 1980–1984 to 16 per 1,000 population in the current survey.

26. Figure II summarizes the variation in annual frequency of diagnostic medical and dental radiological examinations for each health-care level, as found in the current UNSCEAR Global Survey of Medical Radiation Usage and Exposures. Also shown in figure II are the global averages. There are wide variations in the frequency of diagnostic medical and dental examinations. For example, diagnostic medical examinations are over 66 times more frequent in health-care level I countries (where 24% of the global population live) than in health-care level III and IV countries (where 27% of the global population live). The change in annual frequency of diagnostic medical examinations reflects changes in population demographics, as most medical exposures are performed on older individuals. Globally, on average there are just over 488 diagnostic medical examinations and 74 dental examinations per 1,000 population. The wide imbalance in health-care provision is also reflected in the availability of X-ray equipment and of physicians.

Figure II. Variation in the annual frequency of diagnostic medical and dental radiological examinations for the respective health-care levels and the global average (1997–2007)



27. The variation in the annual collective effective dose between health-care levels for diagnostic medical and dental radiological examinations is summarized in figure III. Dental exposures account for less than 1% of the collective dose. On average, over 70% of the total collective effective dose is received by the 1.54 billion individuals living in health-care level I countries. The annual collective effective dose to the population of health-care level I countries from diagnostic medical examinations is estimated to be 2,900,000 man Sv, with 1,000,000 man Sv to the population of health-care level II countries, 33,000 man Sv to the population of health-care level III countries and 24,000 man Sv to the population of health-care level IV countries. The total annual collective effective dose to the global population from diagnostic medical exposures is estimated to be 4,000,000 man Sv.

Figure III. Variation in the annual collective effective dose from diagnostic medical and dental radiological examinations for the respective health-care levels and the global total (1997–2007)

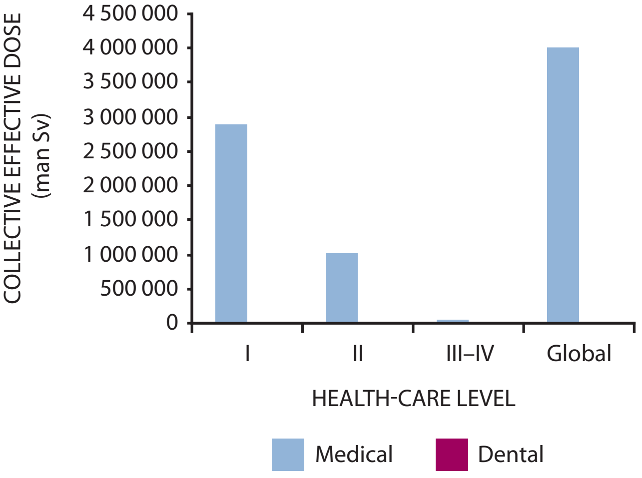
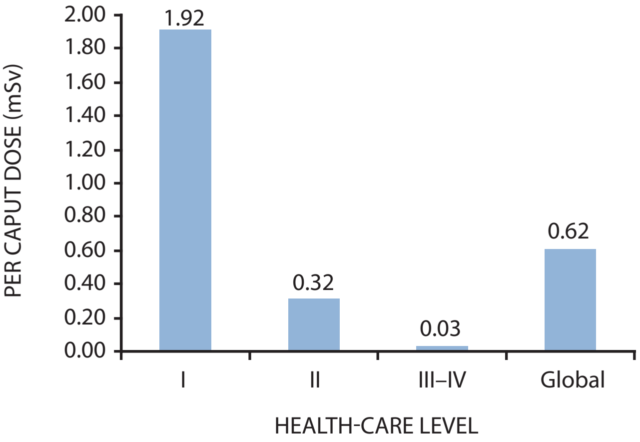
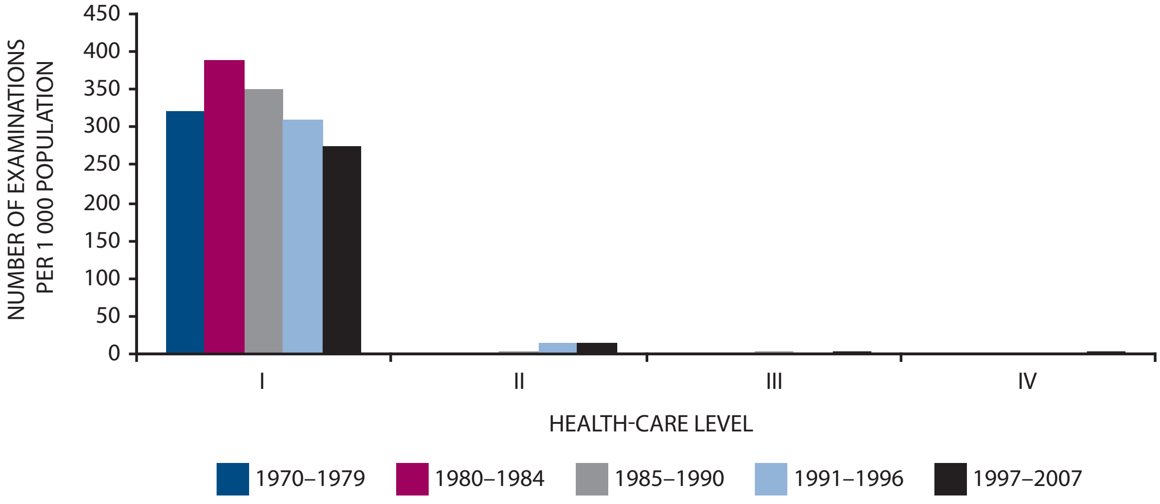


Figure IV. Variation in the annual per caput effective dose from diagnostic medical and dental radiological examinations for the respective health-care levels and the global average (1997–2007)



28. Figure IV shows the annual per caput effective dose for the various health-care levels and the average value across the global population (0.62 mSv) from diagnostic medical and dental radiological examinations. Temporal trends in the annual frequency of diagnostic dental radiological examinations have been obtained and are shown in figure V. Worldwide there are an estimated 480 million diagnostic dental examinations performed annually. Almost all of these are undertaken in level I countries. The contribution of dental examinations to annual per caput or collective effective dose is very small (much less than 1%). However, the number of dental examinations and the availability of equipment may be under-reported in many countries.

Figure V. Trends in the annual frequency of dental radiological examinations for each health-care level



29. For diagnostic dental radiology the collective effective dose to the population of health-care level I countries is estimated to be 9,900 man Sv, with 1,300 man Sv, 51 man Sv and 38 man Sv being received by the populations of health-care level II, III and IV countries, respectively. The total annual collective effective dose to the global population from diagnostic dental radiology is 11,000 man Sv.

30. In the period 1997–2007 covered by the 2008 UNSCEAR Report, the estimated annual collective effective dose to the world population from diagnostic medical and dental radiological examinations is estimated to be 4,000,000 man Sv (see table 1). Since the previous survey [U3], there has been a rise of approximately 1,700,000 man Sv. This increase results in part from an increase in the annual frequency of diagnostic medical and dental radiological examinations (from 1,230 per 1,000 population to 1,607 per 1,000 population in health-care level I countries; from 168 per 1,000 population to 348 per 1,000 population in health-care level II countries; and from 20 per 1,000 population to 23 per 1,000 population in health-care level III/IV countries), an increase in the per caput effective dose per examination (from 0.4 to 0.62 mSv) and an increase in the global population (from 5,800 million to 6,446 million).

Table 1. Estimated annual per caput dose and annual effective dose to the world population from diagnostic medical and dental radiological examinations (1997–2007)

Health-care level	*Population (millions)*	*Annual per caput dose (mSv)*		*Annual collective effective dose (man Sv)*	
		Medical	*Dental*	*Medical*	*Dental*
I	1 540	1.91	0.006 4	2 900 000	9 900
II	3 153	0.32	0.000 4	1 000 000	1 300
III	1 009	0.03	0.000 051	33 000	51
IV	744	0.03	0.000 051	24 000	38
Global	6 446	0.62	0.002	4 000 000	11 000

31. Trends in dose for selected diagnostic medical examinations are shown in table 2. It is clear that doses for two typical radiological examinations (chest radiography and mammography) have been decreasing significantly. On the other hand, the dose from a CT examination, which is a relatively high-dose procedure, has decreased only slightly since the previous survey. However, the nature of CT scanning has changed over the years. In the 1970–1974 survey, only head scans were included; now most CT examinations are of other parts of the body.

Table 2. Trends in average effective doses resulting from selected diagnostic medical examinations in countries of health-care level I

Examination	*Average effective dose per examination (mSv)*			
	1970–1979	*1980–1990*	*1991–1996*	*1997–2007*
Chest radiography	0.25	0.14	0.14	0.07
Abdomen X-ray	1.9	1.1	0.53	0.82
Mammography	1.8	1	0.51	0.26
CT scan	1.3	4.4	8.8	7.4
Angiography	9.2	6.8	12	9.3

B. Nuclear medicine

32. There are approximately 33 million diagnostic nuclear medicine examinations performed annually worldwide. The 24% of the global population living in level I countries receive about 90% of all nuclear medicine examinations. The annual frequency of diagnostic nuclear medicine examinations in health-care level I countries is estimated to have increased from 11 per 1,000 population in 1970–1979 to 19 per 1,000 in this survey. Comparative values for health-care

level II countries also exhibit an increase, from 0.9 per 1,000 population in 1970–1979 to 1.1 per 1,000 in 1997–2007. For therapeutic nuclear medicine procedures, according to the global model, the annual frequency of nuclear medicine treatments in health-care level I countries has increased from 0.17 per 1,000 population in 1991–1996 to 0.47 per 1,000 in this survey, consistent with the trend towards more therapeutic applications. Comparative values for health-care level II countries exhibit an increase from 0.036 per 1,000 population in 1991–1996 to 0.043 per 1,000 in 1997–2007. Figures VI and VII present summaries of the annual frequencies of nuclear medicine examinations for the respective health-care levels and average annual numbers of examinations for each time period considered, respectively.

Figure VI. Annual frequency of diagnostic nuclear medicine examinations for the respective health-care levels and the global average (1997–2007)

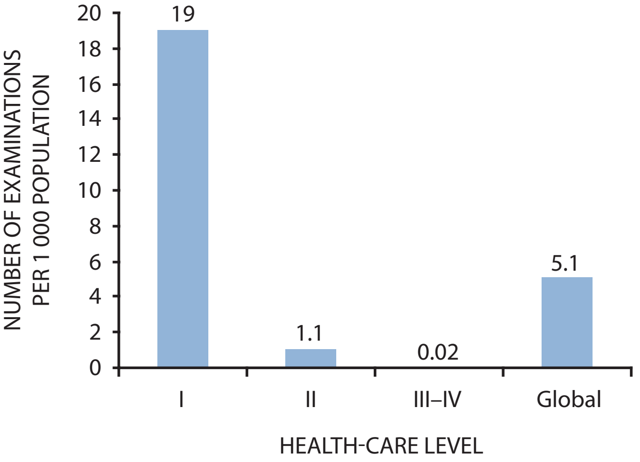
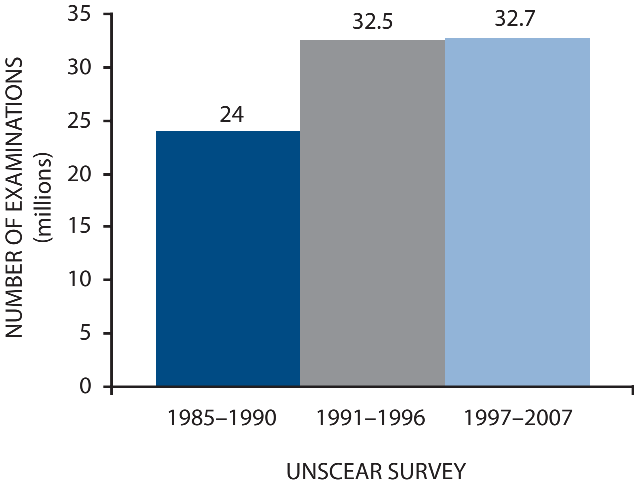


Figure VII. Annual number of diagnostic nuclear medicine examinations



33. In the period covered by the 2008 UNSCEAR Report, the annual collective effective dose to the world population due to diagnostic nuclear medicine examinations is estimated to be 202,000 man Sv. The trend in the annual collective effective dose from diagnostic nuclear medicine examinations over the last three surveys is summarized in figure VIII. There has been an increase in collective dose of nearly 50,000 man Sv, a rise of just over a third since the last report. The increase in the global collective effective dose from diagnostic nuclear medicine examinations results from three factors: an increase of nearly a third in the average effective dose per procedure (from 4.6 mSv in the UNSCEAR 2000 Report to the present estimate of 6.0 mSv) and an increase in the annual number of diagnostic nuclear medicine examinations to the world population. The annual collective effective dose for the respective health-care levels is shown in figure IX.

Figure VIII. Trend in the annual collective effective dose from diagnostic nuclear medicine examinations

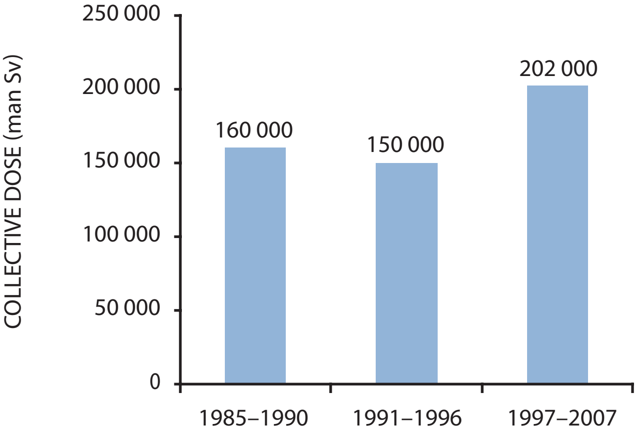
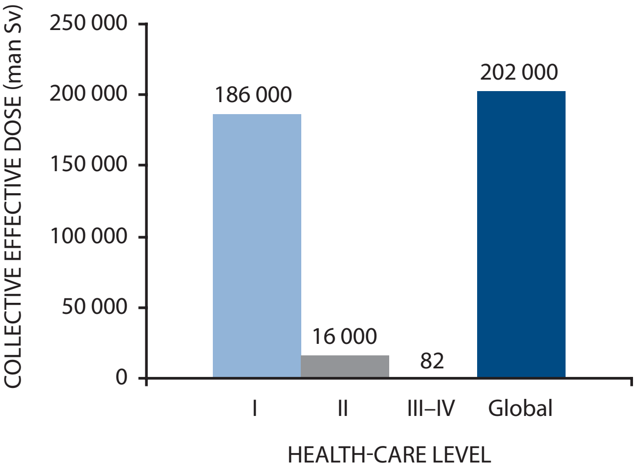


Figure IX. Annual collective effective dose from diagnostic nuclear medicine examinations for the respective health-care levels and the global total (1997–2007)



C. Radiation therapy

34. Worldwide in 1991–1995, approximately equal numbers of radiation therapy patients were treated using X-ray machines, radionuclide units and linear accelerators [U3]. Insufficient data were received for the period 1997–2007 to estimate the numbers of patients treated with each type of treatment device. The availability of linear accelerators worldwide was about 1.6 machines per million population. The availability of X-ray machines and of cobalt units was about equal, 0.4 per million population. In level I countries, however, the availability of treatment equipment was considerably greater than the world average (for example, there were 5.4 linear accelerators per million population). The total number of treatment machines also varied from one health-care level to another. The numbers of patients treated in different countries varied in approximate proportion to the availability of treatment equipment. The annual number of various types of treatment for each health-care level is shown in table 3. The 24% of the world population in the level I countries received approximately three-quarters of all radiation therapy treatments.

35. In the period 1997–2007, the global use of radiation therapy increased to 5.1 million treatments, from 4.7 million treatments in 1991–1996. About 4.7 million patients were treated with external beam radiation therapy, while 0.4 million were treated with brachytherapy. The number of linear accelerator treatment units increased to about 10,000 worldwide, from about 5,000 in the previous period. A large increase was seen in level I countries. Level II countries appeared to show a decrease, but this is likely to be an artefact of the limited data received from the survey. At the same time, the number of brachytherapy treatments and the number of afterloading brachytherapy units appeared to have changed very little.

Table 3. Estimated annual number of radiation therapy treatments[a] in the world (1997–2007)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Population (millions)*	*Annual number of teletherapy treatments*		*Annual number of brachytherapy treatments[b]*		*Annual number of all radiotherapy treatments*	
		Millions	*Per 1 000 population*	*Millions*	*Per 1 000 population*	*Millions*	*Per 1 000 population*
I	1 540	3.5	2.2	0.18	0.12	3.6	2.4
II	3 153	1.2	0.4	0.20	0.06	1.4	0.4
III	1 009	0.06	0.06	(<0.05)[c]	(<0.01)[c]	0.1	0.06
IV	744	(0.03)[c]	(<0.01)[c]	(<0.01)[c]	(<0.005)[c]	(0.03)[c]	(0.01)[c]
World[d]	6 446	4.7	0.73	0.4	0.07	5.1	0.8

[a] Complete courses of treatment.
[b] Excluding treatments with radiopharmaceuticals.
[c] Assumed value in the absence of data.
[d] Global data include several countries not represented by levels I–IV.

VI. IMPLICATIONS FOR THE FUTURE ANALYSIS OF MEDICAL EXPOSURES

36. Because of the introduction of new techniques and equipment and the ever-increasing use of radiation in medicine, it is important to continue to assess the doses resulting from medical exposure to radiation [O2]. At present it appears that the world is entering another period of major technological changes, where the impact of these changes on the population dose worldwide in the future will be very difficult to predict. The introduction of the new technologies may also affect the age profile of the exposed population.

37. The present questionnaire that the Committee has used to collect information is quite detailed and asks for much more information than most countries routinely collect, and this may have discouraged some responses. For future surveys it would probably be useful to design a simpler questionnaire, taking into account feedback from those collecting, analysing or using the data. Comprehensive data from less industrialized countries are difficult to obtain, but given the large populations of these areas, the Committee would encourage those countries to develop their programmes to assess medical uses and exposures.

38. Just under half of the collective effective dose due to diagnostic radiology arises from three procedures: CT, angiographic examinations and interventional radiology. Therefore accurate comprehensive data on these procedures would improve the estimation of population dose. For diagnostic nuclear medicine, the main contributions to the collective effective dose arise from ^{99m}Tc bone scans, ^{201}Tl cardiovascular studies and iodine thyroid scans.

VII. SUMMARY AND CONCLUSIONS

39. Medical exposure remains by far the largest human-made source of exposure to ionizing radiation and continues to grow at a substantial rate. There are now about 3.6 billion medical radiation procedures performed annually. There is a markedly uneven distribution of medical radiation procedures (including both diagnostic medical and dental procedures) among countries, with about two-thirds of these procedures being received by the 24% of the world's population living in health-care level I countries. For level I and II countries, where 75% of the world's population resides, medical uses of radiation have increased from year to year as the benefits of the procedures become more widely known. While there are limited data on the annual frequency of examinations in countries with health-care levels III and IV, the annual frequency of diagnostic medical examinations has remained fairly constant. For diagnostic dental examinations the annual frequency has remained fairly constant for health-care levels I and II, but has substantially increased for health-care levels III and IV. In addition, the trend for increasing urbanization of the world population, together with a gradual improvement in living standards, inevitably means that more individuals can access health-care systems. As a consequence, the population dose due to medical exposures has continuously increased across all health-care levels.

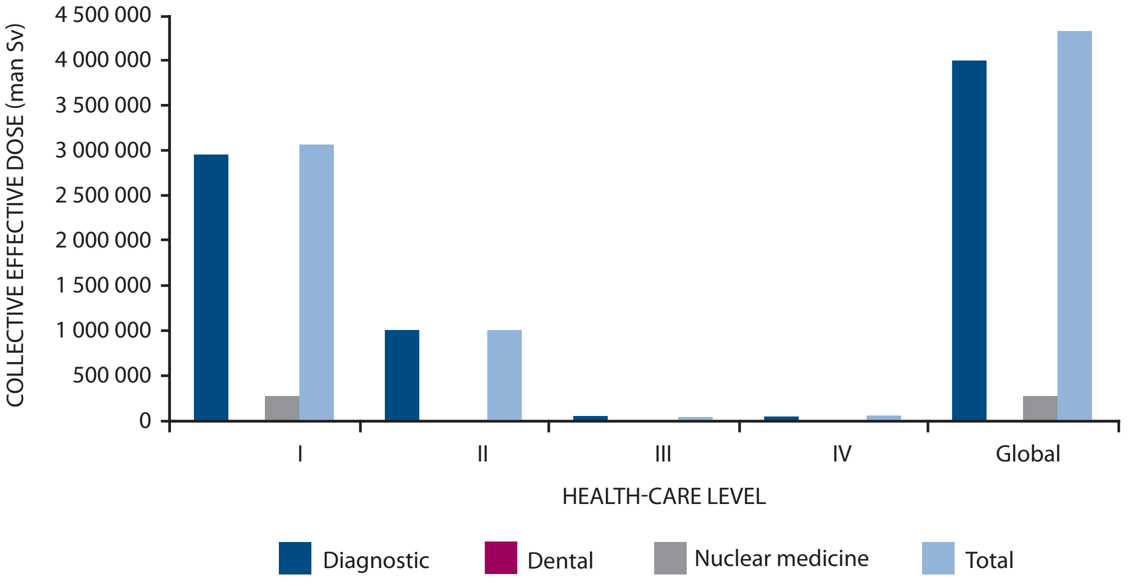
40. Table 4 and figure X summarize the annual collective effective dose from diagnostic exposures (including those due to diagnostic medical and dental radiology, and due to diagnostic nuclear medicine procedures) for the period 1997–2007. Most of the worldwide collective effective dose arises from diagnostic examinations in health-care level I countries. The total annual collective effective dose from all diagnostic exposures is approximately 4,200,000 man Sv.

Table 4. Annual collective effective dose from all diagnostic exposures (including those due to diagnostic medical and dental radiology, and due to diagnostic nuclear medicine procedures)

Health-care level	*Population (millions)*	*Annual collective effective dose (man Sv)*			
		Medical	*Dental*	*Nuclear medicine*	*Total*
I	1 540	2 900 000	9 900	186 000	3 100 000
II	3 153	1 000 000	1 300	16 000	1 000 000
III	1 009	33 000	51	82[a]	33 000
IV	744	24 000	38		24 000
World	6 446	4 000 000	11 000	202 000	4 200 000

[a] Refers to health-care levels III-IV.

Figure X. Annual collective effective dose from all diagnostic exposures for each health-care level and the global totals (1997–2007)



41. The annual per caput effective dose to the global population due to all sources of ionizing radiation is summarized in table 5 and figure XI. Natural background radiation represents just less than 80% of the total per caput effective dose of about 3 mSv. Diagnostic examinations result in a per caput effective dose of 0.66 mSv. Medical exposures now contribute around 20% of the average annual per caput dose to the global population. The total annual collective effective dose to the global population is estimated to be 19.2 million man Sv (see table 6), most of which arises from natural background radiation. Diagnostic exposures account for approximately 4.2 million man Sv. Annually there are approximately 3.1 billion diagnostic medical radiological examinations and 0.48 billion diagnostic dental radiological examinations.

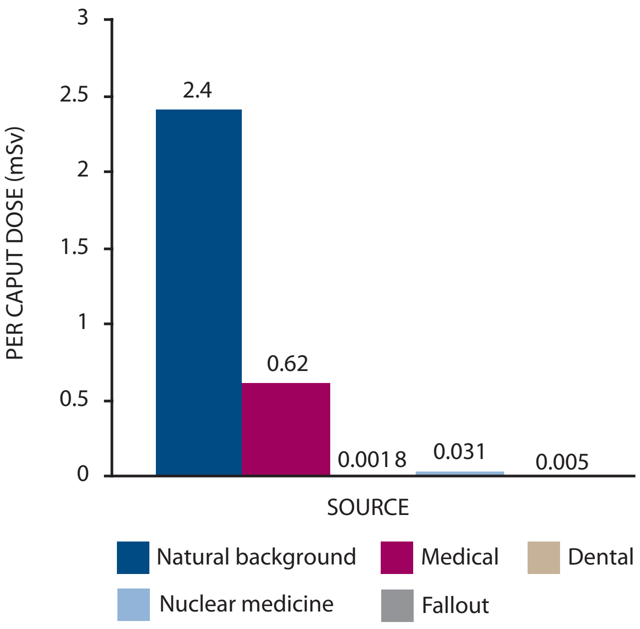
Table 5. Global annual per caput effective dose

Source	*Annual per caput effective dose (mSv)*	*Contribution (%)*
Natural background	2.4	79
Diagnostic medical radiology	0.62	20
Diagnostic dental radiology	0.001 8	<0.1
Nuclear medicine	0.031	1.1
Fallout	0.005	<0.2
Total	3.1	100

Table 6. Global annual total collective effective dose

Source	*Annual collective effective dose (man Sv)*	*Contribution (%)*
Natural background	16 000 000	79
Diagnostic medical radiology	4 000 000	20
Diagnostic dental radiology	11 000	<0.1
Nuclear medicine	202 000	1.0
Fallout	32 000	<0.1
Total	20 200 000	100

Figure XI. Annual per caput effective dose (mSv) 1997–2007



42. New medical X-ray technologies and techniques (particularly with respect to CT scanning) are proving increasingly useful clinically, resulting in rapid growth in the number of procedures in many countries and hence in a marked increase in collective dose. In at least one country, this has given rise to a situation where medical exposures have resulted in population and per caput doses equal to or greater than those from the previously largest source (i.e. natural background radiation); other countries will follow.

43. Diagnostic nuclear medicine has increased worldwide from about 23.5 million examinations annually in 1988 to an estimated 32.7 million annually during the period 1997–2007, and this has resulted in an annual per caput dose of about 0.031 mSv. The estimated annual collective dose has increased from about 74,000 man Sv in 1980 to an annual collective dose of about 202,000 man Sv by the end of the period 1997–2007. About half of the dose results from cardiovascular applications. The distribution of nuclear medicine procedures among countries is quite uneven, with 90% of examinations occurring in level I health-care countries, which represent about 24% of the world's population.

There were about 0.9 million patients treated therapeutically each year with unsealed radionuclides.

44. There were an estimated 5.1 million patients treated annually with radiation therapy during the period 1997–2007, up from an estimated 4.3 million in 1988. About 4.7 million were treated with teletherapy and 0.4 million with brachytherapy. The 24% of the population living in health-care level I countries received 71% of the total radiation therapy treatments.

45. Medical exposure has grown very rapidly over the last three decades in some industrialized countries. As an example, figures XII and XIII show that increases in medical uses in the United States in the period 1980–2006 resulted in an increase in the total annual per caput effective dose from 3.0 mSv to 6.2 mSv, making medical exposure comparable with the exposure due to natural background radiation [N26].

46. Table 7 summarizes the trends in diagnostic radiology practice since 1988. Over the period shown, the annual number of diagnostic radiological examinations has increased by a factor of 2.25 (see figure XIV). This increase has arisen in part because of the increase in the global population and because of the increase in the annual frequency of diagnostic radiological examinations by a factor of 1.7 (see figure XV). Over the same period the annual collective effective dose to the world population has increased from 1,800,000 man Sv in 1988 to 4,000,000 man Sv (see figure XVI). There has also been an upward trend in the annual per caput effective dose, as may be seen in figure XVII.

Figure XII. Annual per caput effective dose (mSv) for the United States population in 1980 [M37]

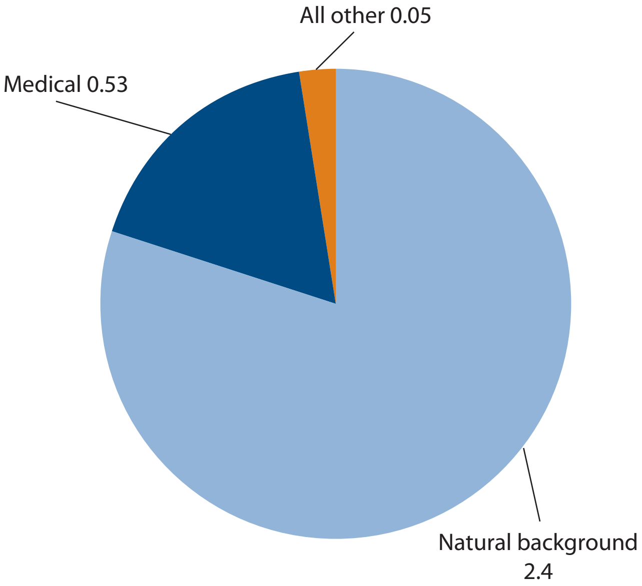


Figure XIII. Annual per caput effective dose (mSv) for the United States population in 2006 [N26]

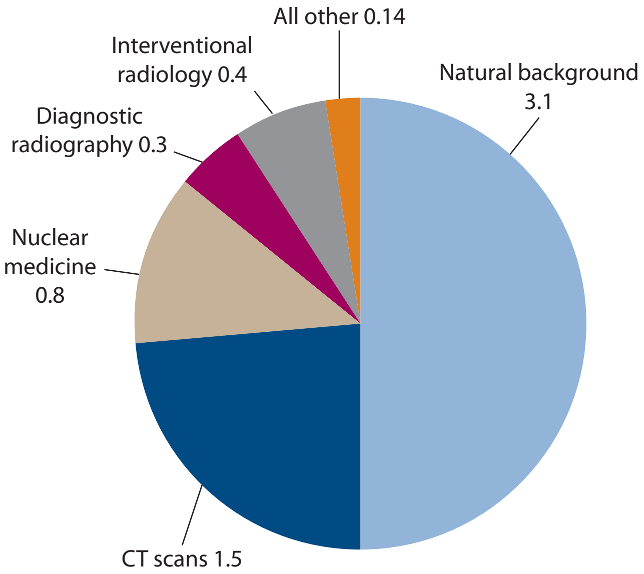


Table 7. Trends in the global use of radiation for diagnosis: diagnostic medical radiological examinations
From UNSCEAR Global Surveys of Medical Radiation Usage and Exposures

Survey	*Annual number of examinations (millions)*	*Annual frequency (per 1 000 population)*	*Annual collective effective dose (1 000 man Sv)*	*Annual per caput dose (mSv)*
1988 [U7]	1 380	280	1 800	0.35
1993 [U6]	1 600	300	1 600	0.3
2000 [U3]	1 910	330	2 300	0.4
2008	3 143	488	4 000	0.62

Figure XIV. Trend in the annual number of diagnostic medical radiological examinations

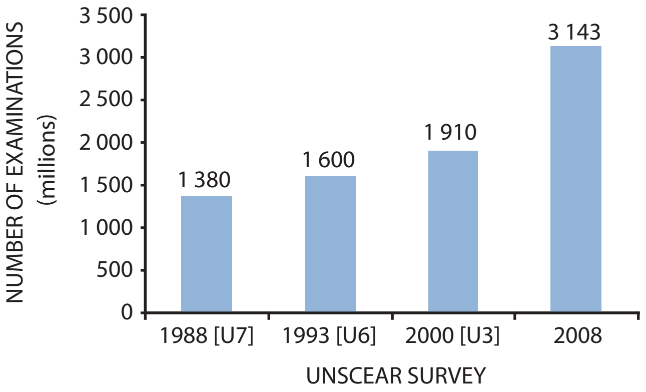


Figure XV. Trend in the annual frequency of diagnostic medical radiological examinations

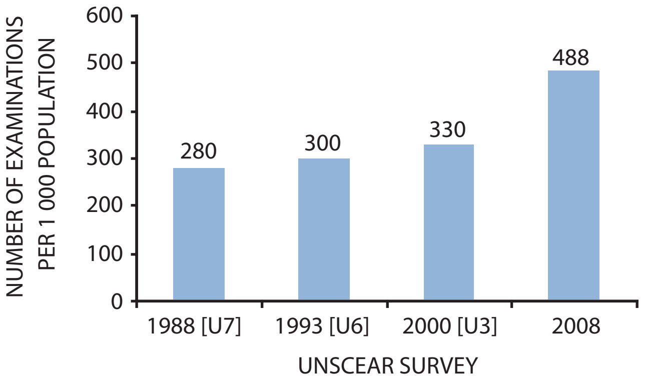


Figure XVI. Trend in the annual collective effective dose from diagnostic medical radiological examinations

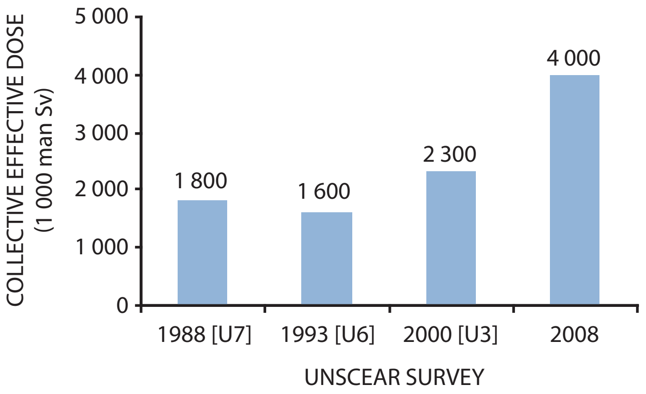
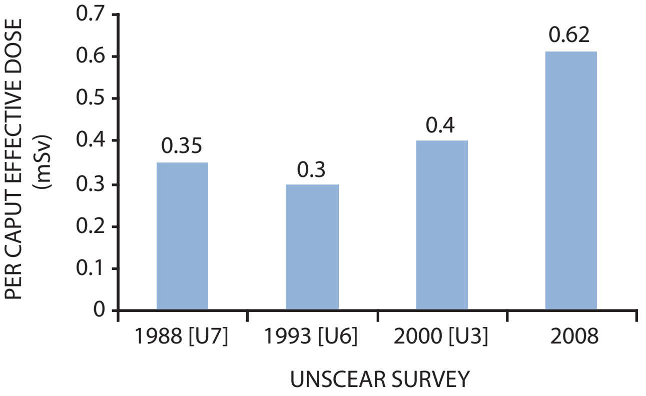


Figure XVII. Trend in the annual per caput effective dose from diagnostic medical radiological examinations



47. Trends in the global use of dental radiology are given in table 8. The number of dental radiological examinations has increased since 1988 (figure XVIII). This is mainly because of the increase in the world's population; the annual frequency of dental radiological examinations has remained fairly constant over this period (figure XIX). The annual collective effective dose has decreased since 1988 (figure XX). Given that the number of examinations has increased, this decrease results from the reduction in the dose per examination associated with the introduction of improved films and film–screen systems. Similarly, there has been a substantial decrease in the per caput dose due to dental radiology (figure XXI).

Table 8. Trends in the global use of radiation for diagnosis: dental radiology
Data from UNSCEAR Global Surveys of Medical Radiation Usage and Exposures

Survey	*Annual number of examinations (millions)*	*Annual frequency per 1 000 population*	*Annual collective effective dose (1 000 man Sv)*	*Annual per caput dose (mSv)*
1988 [U7]	340	70	17	0.003
1993 [U6]			18	0.003
2000 [U3]	520	90	14	0.002
2008	480	74	11	0.002

Figure XVIII. Trend in the annual number of dental radiological examinations
No data were obtained in the 1993 survey

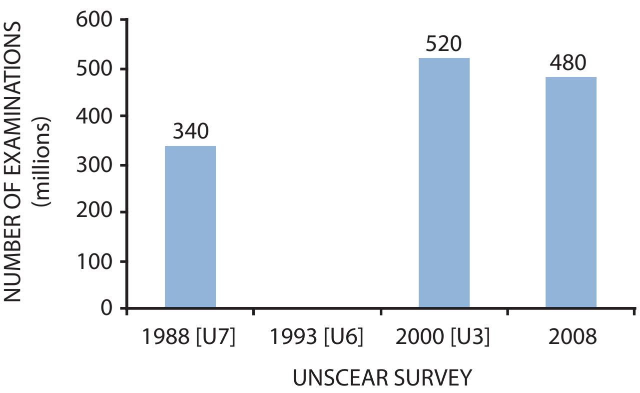


Figure XIX. Trend in the annual frequency of dental radiological examinations
No data were obtained in the 1993 survey

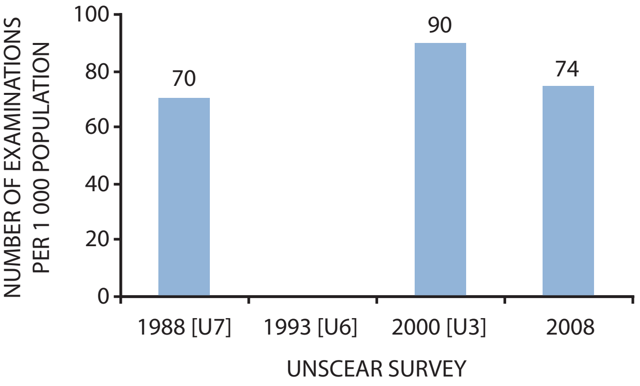


Figure XX. Trend in the annual collective effective dose from dental radiological examinations

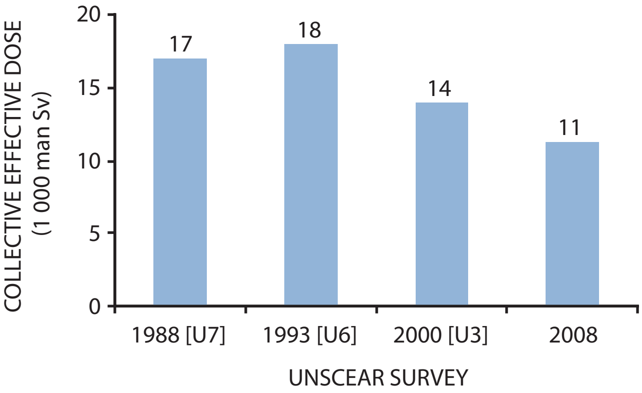
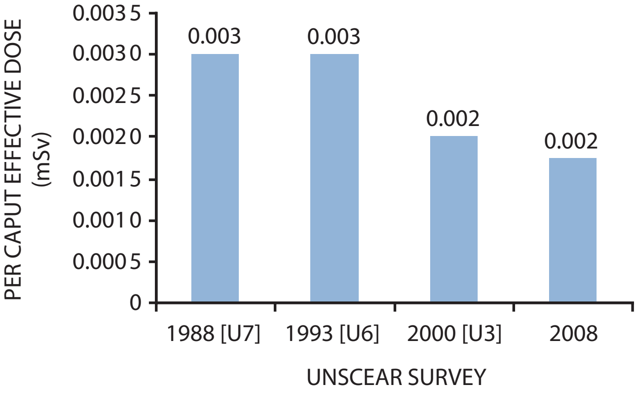


Figure XXI. Trend in the annual per caput effective dose from dental radiology



48. Trends in diagnostic nuclear medicine procedures are summarized in table 9. Since 1988 there has been a modest increase in the number of examinations, comparable with the increase in the global population (figure XXII). The annual frequency of diagnostic nuclear medicine procedures has remained fairly constant since 1988 (figure XXIII). However, the collective effective dose due to diagnostic nuclear medicine procedures has tripled (figure XXIV). This is because of the introduction of high-dose cardiac studies and a reduction in the frequency of other types of procedure. The annual per caput dose has remained constant since 1993 (after having doubled between 1988 and 1993) (figure XXV).

Table 9. Trends in the global use of radiation for diagnosis: nuclear medicine
Data from UNSCEAR Global Surveys of Medical Radiation Usage and Exposures

Survey	*Annual number of examinations (millions)*	*Annual frequency (per 1 000 population)*	*Annual collective effective dose (1 000 man Sv)*	*Annual per caput dose (mSv)*
1988 [U7]	23.5	4.7	74	0.015
1993 [U6]	24	4.5	160	0.03
2000 [U3]	32.5	5.6	150	0.03
2008	32.7	5.1	202	0.031

Figure XXII. Trend in the annual number of diagnostic nuclear medicine procedures

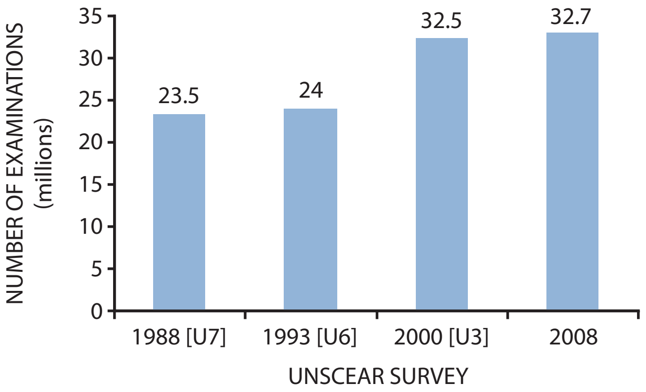


Figure XXIII. Trend in the annual frequency of diagnostic nuclear medicine procedures

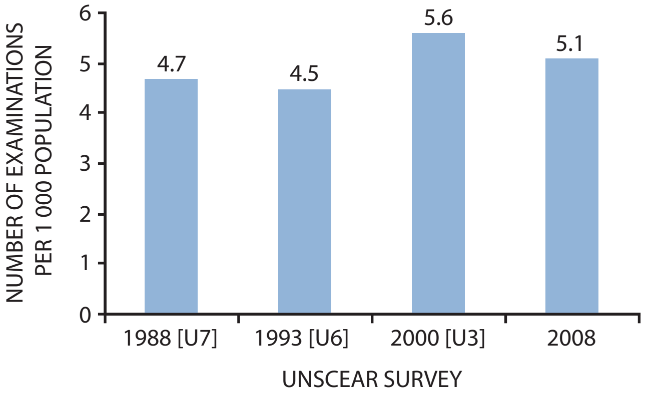


Figure XXIV. Trend in the annual collective effective dose from diagnostic nuclear medicine procedures

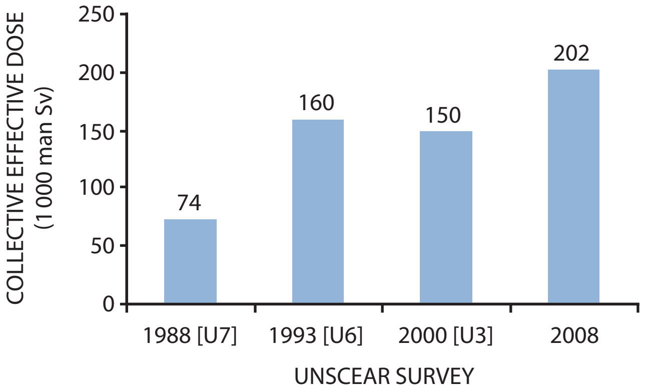
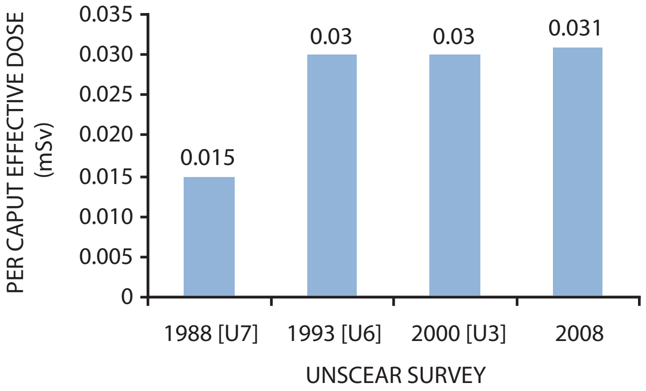


Figure XXV. Trend in the per caput effective dose from diagnostic nuclear medicine procedures



APPENDIX A.
METHODOLOGY FOR ESTIMATING WORLDWIDE MEDICAL EXPOSURES

I. INTRODUCTION

A1. As early as 1962 the Committee [U15] provided tables of information on medical exposures. Data were supplied by approximately 20 countries. The data indicated the total population and total annual frequency of examinations (expressed as annual number of examinations per 1,000 population in the general population). Emphasis was predominantly on gonadal dose and genetically significant dose, since at that time hereditary effects were felt to be very important. By 1972 the Committee [U11] had added estimation of marrow dose as well, but again only reporting the total annual frequency of examinations. In 1977 the Committee [U10] began to include data on the annual frequency of specific examination types for at least one country (Sweden). In the 1982 UNSCEAR Report [U9], data on the annual frequency of specific examinations were presented for 16 countries, and estimates of effective dose equivalent for various examinations were reported for two countries (Japan and Poland). Absorbed doses to some organs were also estimated. Genetically significant dose and marrow dose were no longer used at that time, having been replaced by effective dose equivalent as a quantity of interest.

A2. In the 1988 UNSCEAR Report [U7] the Committee greatly expanded its presentation on medical exposures and attempted to estimate global exposure rather than simply presenting country-specific data. This was possible as data from large countries, such as China and countries in Latin America, became available. In addition, the Committee decided to prepare and distribute a survey questionnaire to Member States aimed at acquiring data on medical exposures in addition to those that appeared in the published literature. This survey methodology has continued to the present day.

A3. The Committee recognized that estimation of the population dose due to medical exposures had significant weaknesses [U3, U9]. In spite of the efforts of the UNSCEAR secretariat, data were still available for only about a quarter of the world's population. Most of the data on frequency and types of radiological examination were mainly available from developed countries [M39]. A method was sought to extrapolate the existing data to other countries where no data were available. Members of the UNSCEAR secretariat examined possible correlations that might be helpful. Some correlations that were examined in relation to frequency of medical radiation exposures, but which were found not to be helpful, included the percentage of gross domestic product spent on health care, the number of hospital beds per 1,000 population, and the number of examinations or procedures per X-ray, nuclear medicine or radiation therapy machine. Mettler et al. developed an analytical model to estimate the availability and frequency of medical uses of radiation worldwide [M39]. Because frequency and equipment data are unavailable for many countries, Mettler et al. investigated data sources that were available and that correlated reasonably well with examination frequency. In their original paper they found that there was a good correlation between the number of people in the population divided by the number of physicians and the annual frequency of diagnostic radiological examinations. This subsequently led to the four-level health-care model, which has been used in recent UNSCEAR reports [M39, U3, U7, U9]. The model has also been used in performing analyses of diagnostic X-ray examinations [M40].

A4. The model used to analyse population exposure assigned countries to four health-care levels as follows:

- Level I with at least one physician for every 1,000 people;
- Level II with one physician for every 1,000–2,999 people;
- Level III with one physician for every 3,000–10,000 people;
- Level IV with less than one physician for every 10,000 people.

A5. The changes in the population distribution across the four health-care levels between 1970 and 2007 is shown in figure A-I. About half of the world's population live in countries that have 1,000–2,999 people per physician, and this percentage has stayed relatively constant for the last 25 years. There has been a gradual decline in the percentage of the world's population living in level I countries.

A6. While the distribution of population by health-care level has not changed significantly, the world's population has increased substantially, rising from just over 4 billion in 1977 to about 6.5 billion in 2006, an increase of over 60% (figure A-II).

A7. By analysing the available data using these health-care level criteria and data on the annual frequency of selected examinations from various countries, it was possible to obtain an average annual frequency for these examinations for a given health-care level and apply this value to the other countries of the same health-care level for which the Committee had no specific data. This allowed a global estimate of the number and type of examinations or procedures to be presented in the UNSCEAR 1988 Report [U7] as well as in all subsequent reports of the Committee [U3, U4, U6].

Figure A-I. Population distribution across the four health-care levels (1970–2007)

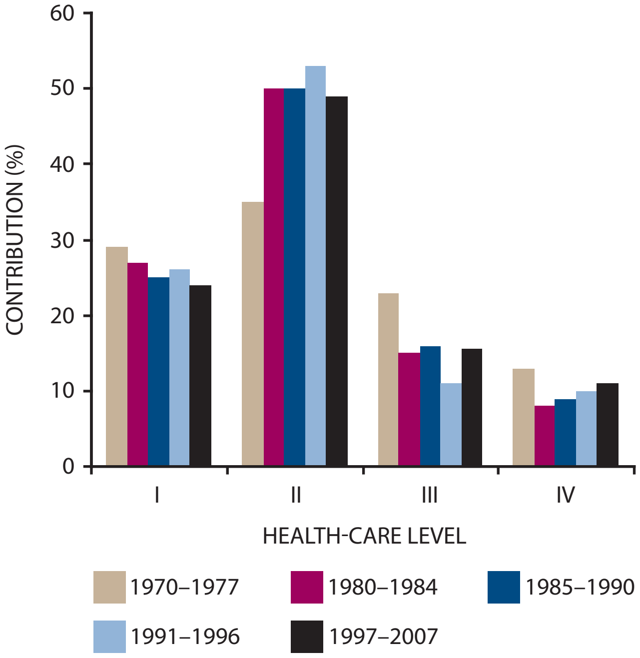
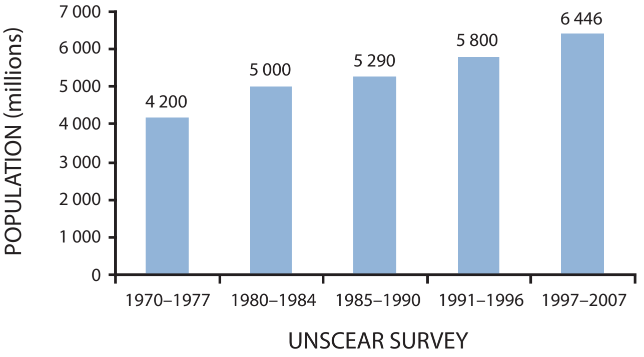


Figure A-II. Change in the global population over the period covered by the various UNSCEAR Global Surveys of Medical Radiation Usage and Exposures



A8. The UNSCEAR 1988 Report also presented the first estimate of collective effective dose equivalent to patients from diagnostic radiology and diagnostic nuclear medicine [U7]. This estimate was made by multiplying the total number of specific examinations by the effective dose equivalent per examination. The data collected on the calculated effective dose equivalent for various examinations were presented. In more recent reports of the Committee, effective dose has been used rather than effective dose equivalent [U3]. The specific dosimetric methodologies are presented below.

A9. The questionnaire used in the most recent UNSCEAR Global Survey of Medical Radiation Usage and Exposures comprises five parts. The first part requests general information and data on the number of practitioners for various groups in a country. Form 1 requests information on diagnostic and therapeutic equipment. Forms 2, 3 and 4 cover diagnostic radiological examinations, nuclear medicine procedures (both diagnostic and therapeutic) and radiation therapy treatments, respectively.

II. METHODOLOGY FOR ANALYSIS OF DOSIMETRY IN DIAGNOSTIC AND INTERVENTIONAL RADIOLOGY

A10. This section comprises a review of the various approaches to patient dosimetry and is based upon the approach described by the International Commission on Radiation Units and Measurements (ICRU) in ICRU Report 74, “Patient dosimetry for X-rays used in medical imaging” [I46]. Further details on patient dosimetry may be found elsewhere [F1, F3, H34, I17, I32, J2, M22, N1, S17, S18, S19, U3, W16].

A11. Over the years, a number of patient dosimetric quantities have been developed. These dosimetric quantities will be described in subsequent paragraphs.

A12. The ICRU [I47] has defined energy fluence, Ψ, as the quotient of dR by da, where dR is the radiant energy incident on a sphere with a cross-sectional area da. This quantity specifies the energy carried by the photons in an X-ray beam:

$$\Psi = \mathrm{d}R/\mathrm{d}a \qquad \text{Units: J m}^{-2}$$

A13. Kerma, K, is defined at a point and is given by:

$$K = \mathrm{d}E_{er}/\mathrm{d}m \qquad \text{Units: J kg}^{-1} \text{ or Gy}$$

where dE_{er} is the sum of the initial kinetic energies of all the charged particles liberated by photons in a mass dm [I30]. For medical exposures, air kerma, K_a, is commonly used. Air kerma for photons of a single energy is given by:

$$K_a = \Psi\,(\mu_{tr}/\rho)_a \qquad \text{Units: J kg}^{-1} \text{ or Gy}$$

where $(\mu_{tr}/\rho)_a$ is the mass energy transfer coefficient for air. For medical exposures, the photon beam is usually not monoenergetic; in these circumstances the mass energy transfer coefficient must be weighted according to the energy distribution of the energy fluence.

A14. Air kerma rate, $\dot{K}_a$, is given by:

$$\dot{K}_a = \mathrm{d}K_a/\mathrm{d}t \qquad \text{Units: J kg}^{-1}\text{ s}^{-1}\text{ or Gy s}^{-1}$$

where $\mathrm{d}K_a/\mathrm{d}t$ is the increment of air kerma in a time interval $\mathrm{d}t$.

A15. The deposition of energy due to ionizing radiation in a material is quantified by the absorbed dose, D [I47]. Absorbed dose is defined as:

$$D = \mathrm{d}\bar{\varepsilon}/\mathrm{d}m \qquad \text{Units: J kg}^{-1}\text{ or Gy}$$

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by the radiation to matter of mass $\mathrm{d}m$. Absorbed dose, D_t, to a material t is related to the energy fluence, Ψ, by the mass energy absorption coefficient in that material, $(\mu_{en}/\rho)_t$, under conditions of charged particle equilibrium. For photons of a single energy, D_t is given by:

$$D_t = \Psi\,(\mu_{en}/\rho)_t \qquad \text{Units: J kg}^{-1}\text{ or Gy}$$

In medical images where polychromatic X-ray photons are usual, the mean value of $(\mu_{en}/\rho)_t$, weighted according to the energy distribution of the energy fluence, is used. If bremsstrahlung is negligible,

$$(\mu_{en}/\rho)_t = (\mu_{tr}/\rho)_t \qquad \text{hence } D_t = K_t$$

A16. Absorbed dose rate, $\dot{D}$, is defined as [I30]:

$$\dot{D} = \mathrm{d}D/\mathrm{d}t \qquad \text{Units: J kg}^{-1}\text{ s}^{-1}\text{ or Gy s}^{-1}$$

Incident dose is the dose on the central axis of the X-ray beam at the point where the X-ray beam enters the patient; it does not include backscatter. Entrance surface air kerma (ESAK) is the air kerma on the central X-ray beam axis at the point where the X-ray beam enters the patient or phantom [I17, I46]; it includes the effect of backscatter (see figure A-II). ESAK is recommended by the ICRU for dosimetry in medical imaging. However, many of the publications reviewed in this report use entrance surface dose (ESD), which does not include the effect of backscatter. For consistency, ESD has been used in this report.

A17. The quantity “exposure”, X, is defined by the ICRU [I47] as:

$$X = \mathrm{d}Q/\mathrm{d}m \qquad \text{Units: C kg}^{-1}$$

where $\mathrm{d}Q$ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated or created by photons in air of mass $\mathrm{d}m$ are completely stopped in air.

A18. For measurements of dose from medical exposures it is important that both the quantity and the measurement point must be specified. This is particularly important when specifying ESD. When making measurements close to the entrance surface of the patient or phantom, it is critical whether the quantity being measured is incident air kerma that ignores backscatter or ESAK that includes backscatter. Thus the distance from the measurement point to the entrance surface of the patient or phantom should be specified. Air kerma area product is deduced from the field size in a particular plane perpendicular to the central axis of the X-ray beam and the air kerma for the central axis in this plane (see figure A-III).

A19. The International Commission on Radiological Protection (ICRP) has recommended that average absorbed dose in a tissue or organ be the basic quantity for assessing stochastic risks [I48]. The ICRU [I2] has defined the average absorbed dose, $D_{T,}$ in a specified organ or tissue T as the total energy imparted to the tissue, ε_T, divided by the mass, m_T:

$$D_t = \varepsilon_T/m_T$$

A20. The risk of a stochastic effect is dependent on the type and energy of the radiation as well as on the absorbed dose. As a consequence, the ICRP [I3] has recommended that the organ dose be weighted by a radiation weighting factor.

A21. For stochastic risk assessment, the ICRP [I3] has introduced the quantity equivalent dose, H_T. The equivalent dose in a tissue T is given by:

$$H_T = \sum_R w_R D_{T,R}$$

where $D_{T,R}$ is the average absorbed dose to tissue T from radiation R, and w_R is the radiation weighting factor ($w_R = 1$ for X-rays). For medical exposures, gauging the risks of stochastic effects is complicated because almost invariably more than one organ is irradiated. The ICRP introduced the unique quantity *effective dose equivalent* (H_e or *EDE*) in its Publication 30 [I36], and then redefined and renamed the quantity *effective dose* (E) in ICRP Publication 60 [I3], for expressing stochastic risk to radiation workers and to the whole population [I3]. To evaluate effective dose, the equivalent dose to a tissue or organ, H_T, is weighted by a dimensionless tissue weighting factor w_T. Multiplying the equivalent dose (H_T) of an organ or tissue by its assigned tissue weighting factor (w_T) gives a “weighted equivalent dose”. The sum of weighted equivalent doses for a given exposure to radiation is the effective dose. Thus:

$$\begin{aligned} E &= \sum_T w_T H_T \\ &= \sum_T w_T \sum_R w_R D_{T,R} \end{aligned}$$

A22. Table A1 summarizes the various tissue weighting factors (w_T) as prescribed by the ICRP over the years. Tissue weighting factors represent a judgement by the ICRP of the relative contribution of organs or tissues to the total detriment associated with stochastic effects [I46]. The sum of the tissue weighting factors is unity. Thus the numerical value of effective dose resulting from a non-uniform irradiation is intended to be that equivalent dose which, if received uniformly by the whole body, would result in the same total risk. (Whole-body doses are usually meaningless for assessing the risk of medical exposures, because non-uniform and localized energy deposition is averaged over the mass of the entire body.)

Figure A-III. Simple exposure arrangement for radiography illustrating some of the dosimetric and geometric quantities recommended for determination of patient dose [I17]

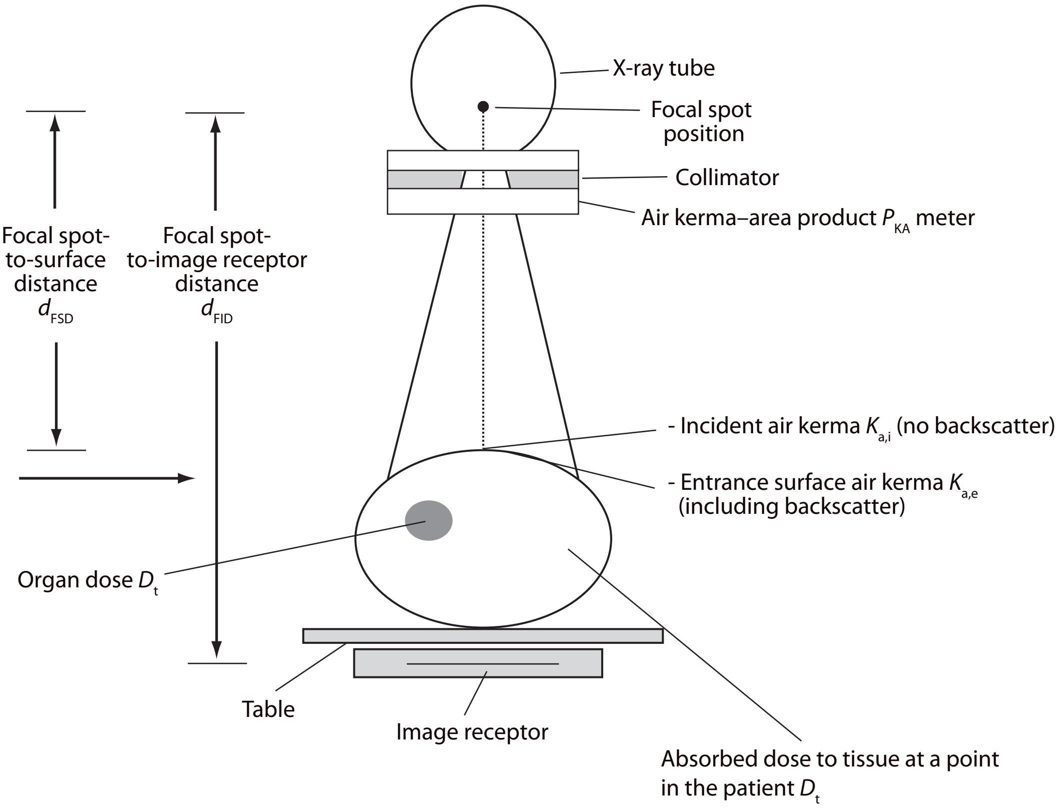


Table A1. Summary of tissue weighting factors [I3, I6, I36]

Organ	*Tissue weighting factors, w_T*		
	ICRP 30 [I36] 1979	*ICRP 60 [I3] 1991*	*ICRP 103 [I6] 2008*
Gonads	0.25	0.20	0.08
Red bone marrow	0.12	0.12	0.12
Colon		0.12	0.12
Lungs	0.12	0.12	0.12
Stomach		0.12	0.12
Bladder		0.05	0.04
Breasts	0.15	0.05	0.12
Liver		0.05	0.04
Oesophagus		0.05	0.04
Thyroid	0.03	0.05	0.04
Skin		0.01	0.01
Bone surfaces	0.03	0.01	0.01
Salivary glands			0.01
Brain			0.01
Remainder	0.30	0.05	0.12

A23. The tissue weighting factors are judged to be independent of the type and energy of radiation incident on the body. The nominal stochastic risk coefficients for effective dose to workers and members of the public are based on the notional risk of radiation-induced cancer and severe hereditary disorders averaged over these populations. Moreover, to assess the risks from exposures at low doses and dose rates, the ICRP has introduced a dose and dose-rate effectiveness factor (DDREF) of 2, which is included in the nominal stochastic risk coefficients.

A24. Both the radiation and tissue weighting factors are derived from the observed rates of expression of these effects in various populations exposed to radiation and from radiobiological studies. As more research evidence has become available, the ICRP has prescribed different values for these weighting factors [I6] (see table A1). Thus the reported effective dose equivalents are not strictly comparable with the reported values of effective dose for a particular examination, since their derivations involve different weighting factors. Another limitation of the use of effective dose in the assessment of medical exposures is that it may be difficult to perform a coherent trend analysis in the future. This may affect comparisons of the results between UNSCEAR reports.

A25. There are other issues regarding the use of effective dose to gauge the risk of potential effects from medical exposures. The most significant relates to differences in age, sex and health status of the medically exposed populations compared with the population characteristics used by the ICRP [I3, I6, I36] to derive its nominal risk coefficients [I46]. For example, the age distribution and life expectancy of patients having percutaneous transluminal coronary angioplasty (PTCA) procedures is different to that of the general population or a population of radiation workers [B25]. Consequently the ICRU suggests that effective dose should not be used for the assessment of risk from medical exposures [I46].

A26. The ICRP suggests that estimating stochastic risks for a specific population is sometimes better achieved using absorbed dose and specific data relating to the relative biological effectiveness of the radiation and risk coefficients, taking into account health status and/or life expectancy [I3, I6, I36, I46].

A27. The ICRU recommends that stochastic and deterministic risks associated with medical exposures be assessed from a detailed knowledge of organ doses, absorbed dose distribution, age and sex [I46]. Effective dose is not considered suitable for this purpose by the ICRU. However, many authors in the literature survey of reports on doses from medical examinations and in references cited in the present report have used effective dose, despite its limitations, as a surrogate quantity to assess patient exposures, in part because it is convenient to use. Effective dose has therefore been used in this report for purposes of comparison with previous publications despite its weaknesses for gauging risks as noted above.

A28. In most radiology procedures, the primary X-ray beam will directly irradiate only part of the patient. Effective dose is a risk-related quantity, which takes into account which organs are irradiated and by how much. It is a derived quantity and its evaluation provides a numerical value for the uniform whole-body exposure that would result in the same overall radiation risk as the respective partial-body exposure.

A29. In diagnostic radiology it is common practice to measure a radiation dose quantity that is then converted into organ doses and effective dose by means of conversion coefficients. These coefficients are defined as the ratio of the dose to a specified tissue or effective dose divided by the normalization quantity. Incident dose, air kerma, ESAK, ESD or kerma–area product (KAP) can be used as normalization quantities [I46].

A30. Estimating effective dose from values of organ doses is particularly difficult in radiology, because usually only part of the body is directly irradiated owing to the collimation of the X-ray beam to the area of clinical interest. In addition, often only part of an organ is included in the primary beam, the remainder being exposed to scattered radiation.

A31. Irrespective of which approach is adopted to estimate doses and risks resulting from diagnostic X-ray examinations, there are weaknesses. For example, there are considerable uncertainties on estimates or measurements of organ dose in many circumstances. There are also differences in the size and position of radiosensitive organs within the bodies of individuals and even within phantoms. Inspection of normalized organ dose data reveals some variability in this respect. There is a large difference in the organ dose depending on whether or not the organ is in the primary beam [I26, J1, K23, L21, P15, R19, R21, R22, S39, Z9, Z10, Z11, Z12, Z13]. All of these factors lead to uncertainty in organ dose estimation.

A32. These problems exist even if a well-defined part of the body is irradiated. For example, in head CT or dental radiology, the value for effective dose will be dependent upon whether the thyroid/oesophagus is assumed to be in the primary beam. Assumptions have also to be made about the amount and location of red bone marrow and about bone surfaces in the skull [L5, L6].

A33. There are three main approaches to the assessment of patient doses in diagnostic radiology: *(a)* direct dose measurements on a patient; *(b)* dose measurements in physical phantoms; and *(c)* Monte Carlo radiation transport calculations. The most common approach is the combination of an easily measurable quantity such as KAP with the respective conversion coefficients derived from Monte Carlo calculations. Direct measurement of patient dose is limited to relatively few superficial organs, such as the eye, skin, thyroid or testes.

A34. A general problem faced in clinical practice is the difficulty associated with making measurements on groups of patients whose size and build differ markedly from the norm [F9]. In these circumstances one accepted approach is to perform the measurements on all patients undergoing this procedure during a measurement period and then take the average of the dose values as the outcome for a standard sized patient, 70 kg ± 10 kg. This will give a reasonable estimate of that dose provided that the number of patients is not too small, perhaps a minimum of ten patients [E5].

A35. An alternative approach is to apply a height and weight conversion factor to allow for deviation in size and composition from that of reference man [L4]. Correcting for patient size was first proposed by Lindskoug [L4] and has been further developed by Chapple et al. [C1]. It enables reference values to be obtained from large-scale patient dose surveys by correcting each individual dose quantity to what it would have been had the individual corresponded to the size and composition of reference man.

A36. The collective effective dose to the population is the sum, over all types of examinations, of the mean effective dose, E_e, for a specific examination type multiplied by the number of these examinations, n_e. The number of examinations may be deduced from the annual frequency (expressed as number of examimations per 1,000 population) and the estimated population for that country or health-care level.

A37. The per caput effective dose is also used to quantify exposures that result from diagnostic radiology. It is the collective effective dose averaged over the population of both exposed and non-exposed individuals. The weakness of the per caput dose approach is that medical exposures tend to be performed on a subset of the population whose members are ill.

A. Projection radiography

A38. In projection radiography, the assessment of air kerma or dose (with or without backscatter) at the entrance surface of the patient is a common approach to patient dosimetry. This may be achieved by measurement of tube radiation output in mGy/mAs at a given point (without a patient) using an ionization chamber, followed by calculation of the ESD from recorded exposure and geometric data, as well as the use of an appropriate backscatter factor. ESD or ESAK may be measured using thermoluminescent dosimetry (TLD).

A39. A common method for measuring patient doses is to use TLDs. The dosimeters are packaged in plastic sleeves that are sterilizable, and are attached to the patient's skin using surgical tape. Correction factors for the energy dependence of the dosimeters and their sensitivity are applied to the raw TLD data. A background correction is also applied.

A40. In addition to TLDs, glass dosimeters are widely used in Japan to assess medical exposures owing to their superior technical characteristics. Glass dosimeters have been used to assess ESD in intraoral radiography and for endovascular treatments [K31, N14].

A41. Physical phantoms that simulate patient anatomy can be used for dosimetry [C1, M2]. Some phantoms have a fair degree of anatomical accuracy and are a reasonably accurate representation of human anatomy, both in terms of the size and position of the organs and with respect to the attenuation properties. A problem with some anthropomorphic phantoms is that they are not tissue equivalent, which leads to inaccurate dosimetry for diagnostic radiology [S38]. The ICRU has described the requirements for physical dosimetry phantoms [I30].

A42. There are limitations regarding measurements in a physical dosimetry phantom. These relate to the need to use a large number of dosimeters to estimate the dose to physically large organs, the non-uniform distribution of radiation within the phantom and the effect of small uncertainties in the position of the radiation field. As a consequence, this method of patient dosimetry as well as the other methods (measuring ESD with TLDs) are not suitable for routine patient dose assessments.

A43. Monte Carlo computational techniques are also used to estimate organ or tissue doses. These are computer-based methods that employ computational models to simulate the physical processes associated with the interaction of an X-ray beam with the human body. There are two types of computational model: mathematical and voxel phantoms. Monte Carlo calculations are used to deduce energy deposition of X-ray photons in computational models of human anatomy [I30]. Normally, patient dose is assessed by applying suitable Monte Carlo calculated conversion coefficients to a routinely measured quantity such as KAP or ESD. Mathematical phantoms are a three-dimensional representation of a patient. The organs and the whole body are defined as geometric bodies (such as cylinders and ellipsoids). The various phantoms used have been of increasing anatomical accuracy and complexity [C21, I26, J1, K23, S39].

A44. Voxel phantoms are based on either CT or MR images of actual patients. Organ sizes and positions are deduced from the volume elements determined from the imaging data. As a consequence these phantoms are physically more accurate, the only limitation being the size of the voxels used. Various voxel phantoms have been described in references [P15, V13, Z9, Z10].

A45. As mentioned above, there are uncertainties in the estimation of organ doses. For example, relatively small differences in patient build can result in large differences in organ doses depending on whether the organs lie within or outside the primary beam [G21, S40]. In chest radiology the uncertainty in dose to the lower large intestines can be as large as 48% [I46]. Other uncertainties in Monte Carlo calculations arise from uncertainties in attenuation coefficients, the patient phantom and the model of the X-ray source.

A46. If the dose or air kerma at a specified point is known, it is possible to use normalized organ dose data to deduce organ doses for a typical patient, effective dose being calculated from the organ doses. Normalized organ dose data are available for many examination types, including CT. They are generally based upon Monte Carlo simulations of examinations [D3, D4, D6, H13, J1, J3, R2].

A47. Numerous publications have tabulated backscatter factors for X-rays [B22, C22, G3, G4, G22, H28, H29, I23, K24, K25, M29, P16, S41], which may be required in estimating entrance skin dose. Various handbooks of dose conversion coefficients have been published [D6, H13, H30, H31, H32, J1, J3, K23, R19, R20, R21, R22, S42, S43, V13, Z9, Z11, Z12, Z13].

A48. A computer-based Monte Carlo program for calculating patient doses resulting from medical radiological examinations has been developed by Tapiovaara et al. [T17]. This computer program uses hermaphrodite phantoms for six ages ranging from newborn to adult. There is good agreement between this program and other software [H30, H32, J1] when used to calculate organ dose conversion coefficients.

B. Fluoroscopy

A49. Approaches to patient dosimetry are different for procedures that involve the use of fluoroscopy equipment [B1]. During these examinations an automatic exposure control is used to adjust the generator settings to compensate for changes in attenuation in the X-ray beam. Consequently the tube potential and tube current change continuously as the projection direction changes because of changes in attenuation through the patient. Furthermore, the anatomical area of the patient irradiated by the primary beam varies, and different tissues have different attenuation coefficients. This means that it is difficult to monitor maximum ESD directly, as the anatomical position where this occurs may not be known in advance [W4]. In addition, dosimeters placed on the patient's skin may not be in the primary beam for all projection directions used in some procedures (e.g. interventional cardiology). In these circumstances, dose–area product (DAP) or air KAP may be assessed, depending upon the calibration of the measurement instrument. These are quantities that have the advantages of being easy to measure and to correlate with risk. Additionally they are independent of the distance from the X-ray tube [A13, B21, C23, M31].

A50. In fluoroscopy, large-area transmission ionization chambers are commonly used to assess patient doses [C10]. These instruments measure KAP (Gy cm^2) or DAP (Gy cm^2) [I46], depending on the calibration of the instrument [I46, W26]. These quantities can be used to deduce the total energy imparted to the body or effective dose. It is also possible to derive other dose quantities from the KAP or DAP reading (e.g. ESD and mean organ doses) [I46, W26].

A51. Transmission ionization chambers must be calibrated in situ, because for geometry involving an undercouch X-ray tube and overcouch detector the attenuation of the patient couch must be taken into account [C24]. The uncertainty on DAP or KAP readings is approximately 6% for an overcouch X-ray tube geometry [L25] and up to 20% for an undercouch X-ray tube geometry, depending on how well the DAP meter has been calibrated [C24].

A52. The structure of transmission ionization chambers often includes high-atomic-number elements [I46], which means that their calibration is dependent on the radiation beam energy [B25, L25]. Instrument calibration is therefore particularly important for fluoroscopy equipment on which additional copper filtration is used.

A53. There is increasing concern about skin dose levels in cardiology and interventional radiology [I1]. This is because of the discovery of deterministic injuries in patients who have undergone long procedures using suboptimal equipment and performed by individuals inadequately trained in radiation protection. Assessment of maximum ESD is particularly difficult, as the projection direction and irradiated area change during interventional procedures. Various measurement techniques have been proposed, including slow films [G11], real time software [F12], DAP [V18] and calculation [M12].

A54. Organ doses resulting from fluoroscopy procedures may also be assessed using TLDs loaded into a physical phantom. Dosimeters may be placed in the phantom at positions corresponding to the organs of interest, and a typical fluoroscopy procedure is simulated on the phantom using the appropriate X-ray equipment [C1]. The TLDs are read out and the organ doses deduced. Surface doses during fluoroscopy have also been assessed using glass dosimeters [N14].

A55. Measurement of either air KAP or DAP is probably the method of choice for assessing the doses and effective dose, and hence the potential risks, resulting from interventional procedures. DAP correlates reasonably well with radiation risk by means of conversion factors [H13]. These conversion factors are examination-specific and may be deduced from Monte Carlo organ dose calculations made for simulated interventional procedures. This approach has been used in reporting many of the patient dose data in response to the surveys (sections III and IV of this appendix).

A56. At present there are no established technical approaches that provide a direct indication of maximum ESDs. However, there are four technical approaches that are being developed: *(a)* calculation of entrance dose from the generator settings, assuming a given focus–skin distance; *(b)* directly determining entrance dose from either the air KAP or the DAP and collimator settings, also assuming a given focus–skin distance; *(c)* use of special solid-state detectors placed on the skin surface of the patient; and *(d)* use of a large-area field-sensing ionization chamber, which measures DAP and entrance dose at a given focus distance simultaneously [T2]. Methods *(a)*, *(b)* and *(d)* require an assumption about backscatter radiation, whereas the detector in *(c)* will automatically include it. The use of detectors placed on the skin is a potential problem, in that with different angulations of the X-ray tube, the dosimeter may not be placed at the position where the maximum skin dose occurs (as this may not be known beforehand). The dosimeters may also be visible on the displayed image. The other approaches inevitably yield an overestimate of maximum ESD.

A57. One design of ionization chamber incorporates an ultrasonic distance ruler at the chamber [T2]. This instrument can therefore deduce ESD. The computer linked to the chamber applies an inverse square law correction based on the measurement of the chamber-to-patient distance made using the ultrasonic ruler. Consequently this instrument design can provide an on-line display of ESD, but if different angulations of the X-ray tube are used, this method will also overestimate the maximum ESD.

C. Mammography

A58. Dosimetry in mammography is particularly difficult, as low-energy X-rays are used to image the breast [N4]. This places particular demands on the instruments used to measure breast dose, as they need to be energy independent down to 15 keV or an appropriate calibration factor should be applied.

A59. Moreover, while simple measurement of ESD on top of an appropriate phantom has been considered as a suitable quantity, this does not take into account the attenuation properties of breast tissue, which vary according to both breast composition and X-ray radiation quality. Depth-dose data are critically dependent upon breast composition and the X-ray spectrum [D3, D4, D12].

A60. It is widely acknowledged that within the breast it is the glandular tissue that is most radiosensitive, rather than fat or connective tissue. Mean glandular dose or average absorbed dose in glandular tissue has been recommended by the ICRP as the relevant dosimetric quantity for mammography [D6, I5, I46, N4]. While the quantity mean glandular dose correlates reasonably well with the associated radiation risk, it cannot be measured directly and therefore has to be inferred from other measurements.

A61. Hammerstein et al. [H9] proposed a model for a standard breast comprising 50% adipose and 50% glandular tissue. The composition of this breast was deduced from the elemental composition of a relatively small number of autopsy sections. Hammerstein et al. also proposed using a conversion factor to be applied to the measured ESD [H9].

A62. Mean glandular dose, D_G, can also be derived from incident air kerma, $K_{a,i}$, to a standard breast phantom; this has a superficial layer of either 0.4 cm of glandular tissue or 0.5 cm of adipose tissue with a varying thickness of 50:50 adipose and glandular tissue between the two superficial layers [D4]. A conversion coefficient is used to deduce D_G [I46]:

$$D_G = c_G\, K_{a,i} \qquad \text{(Gy)}$$

A63. Many authors have published conversion coefficients for assessing doses in mammography [A14, D4, D12, J11, R23, S43, W27, W28, Z14]. Conversion coefficients are tabulated as a function of half-value layer and compressed breast thickness [D4]. There are variations of up to approximately 15% between different conversion coefficients [I46]. In addition, breast composition also varies with compressed breast thickness [G15, K26, Y11, Y12].

A64. Since this earlier work, a number of authors have used Monte Carlo techniques to model the interaction of low-energy X-ray beams within breast tissue [D3, D4, R2].

D. CT dosimetry

A65. Air kerma–length product, P_{KL}, is recommended by the ICRU for CT dosimetry [I46]. The air kerma–length product is the integral of the air kerma free in air along a line of length parallel to the axis of rotation of the CT scanner and is given by:

$$P_{KL} = \int_L K_a(L)\, \mathrm{d}L \qquad \text{(Gy cm)}$$

This quantity may also be assessed inside a phantom, $P_{KL,CT.}$

A66. The CT air kerma index free in air, $CTDI_{air}$, has also been defined by the ICRU [I46] for dosimetry of fan beam scanners. It is the integral of the CT axial air kerma profile, $K_a(z)$, along the axis of rotation of the CT scanner for a single rotation divided by the nominal beam collimation, T.

$$\begin{aligned} CTDI_{air} &= 1/T \int_{-\infty}^{+\infty} K_a(z)\, \mathrm{d}z \\ &= P_{KL}/T \qquad \text{(Gy)} \end{aligned}$$

A67. For a multislice CT scanner with N slices of collimation T

$$CTDI_{air} = P_{KL}/(NT) \qquad \text{(Gy)}$$

A68. For phantom measurements on CT scanners, a CT air kerma index, $C_{K,PMMA}$, can also be defined [I46].

$$\begin{aligned} C_{K,PMMA} &= \frac{1}{T} \int_{-\infty}^{+\infty} K_{a,PMMA}(z)\, \mathrm{d}z \\ &= P_{KL,PMMA}/T \qquad \text{(Gy)} \end{aligned}$$

A69. Other specialized dosimetric techniques have been used to assess patient radiation dose in CT, as it is difficult to directly determine organ doses [S17, S18]. These techniques have been described in a series of publications [F3, I32, J2, M22, S18, S19, U3, W16]. These dosimetric approaches are based upon the use of three quantities dedicated to CT dosimetry: weighted CT dose index ($CTDI_W$), volume-weighted CT dose index ($CTDI_{vol}$) and dose–length product (DLP).

A70. Dedicated CT dosimetry phantoms are recommended by the ICRU [I30]. The phantom is placed on the CT scanner couch so that the scanner's axis of rotation coincides with the longitudinal axis of the phantom [I46]. The centre of the CT scanner slice or multiple slices is aligned to the centre of the phantom. Measurements are made at the centre and periphery of the CT dosimetry phantom, which is manufactured from polymethylmethacrylate (PMMA).

A71. CT dosimetry is based upon the use of PMMA phantoms with diameters of 16 cm and 32 cm to represent an adult head and body, respectively. Measurements are made, usually with a pencil ionization chamber of 100 mm length, at the centre of the phantom and 1 cm below the surface at four equally spaced locations.

A72. The weighted $CTDI_w$ in either phantom is given by:

$$CTDI_w = 1/3\ CTDI_{100,c} + 2/3\ CTDI_{100,p}$$

where $CTDI_{100,p}$ is the average of the four $CTDI$ measurements (see above) made at the periphery of the phantom. $CTDI_{100,c}$ is the measurement made at the centre of the phantom. $CTDI_w$ is measured for a range of technique factors (i.e. tube current, tube voltage, slice collimation) typical of those used clinically.

A73. $CTDI_{100}$ (expressed in mGy) is defined as the integral over 100 mm along a line parallel to the axis of rotation (z) of the dose profile $D(z)$ for a single rotation, at a fixed tube potential, divided by the nominal collimation of the X-ray beam used by the CT scanner [S18]:

$$CTDI_{100} = 1/NT \int_{-50mm}^{50mm} D(z)\,\mathrm{d}z$$

where, for a single rotation, the number of CT slices is N, the nominal thickness of each slice is T, and NT (expressed in cm) is the total detector acquisition width and is equivalent to the nominal beam collimation [S18]. $CTDI_{100}$ is usually measured using a pencil ionization chamber of 100 mm length.

A74. $CTDI_{vol}$ (expressed in mGy) is given by the following equation:

$$CTDI_{vol} = CTDI_w/P$$

where P is the CT pitch factor given by:

$$P = \Delta d/NT$$

where Δd is the distance (expressed in cm) moved by the patient table in the z direction, between serial scans or per rotation in helical scanning [I32, S19].

A75. $CTDI_w$ may be normalized to the tube current–time product. Normalized $CTDI_w$ may also be given for a standardized nominal beam collimation of 10 mm [S19]. For specific models of CT scanner, relative conversion coefficients are provided for a range of collimation settings. In CT scanners that operate in automatic exposure control mode where the tube current is automatically modulated, average tube current or current–time product is used to take account of the effect of this modulation [K11, K12, L17].

A76. DLP (expressed in mGy cm) is given by the following equation:

$$DLP = CTDI_w NT_n$$

where N is the number of slices of collimation T in centimetres per rotation and n is the total number of rotations. Alternatively, DLP may be calculated using:

$$DLP = CTDI_{vol} L$$

where L is the scan length, determined by the outer margin of the volume irradiated in the CT scan [M22, S19].

A77. The International Electrotechnical Commission (IEC) has recognized the need for a dose display on CT scanners and has recommended that $CTDI_{vol}$ be used [I32]. On some machines, DLP is also displayed. These equipment displays mean that patient dosimetry in CT is made easier by using recently manufactured machines. The IEC has also considered developing a standard for the recording of dosimetry data in the DICOM header.

A78. One of the problems associated with performing patient dosimetry measurements using $CTDI$ on CT scanners with a large number of rows of detectors is the required integration length. For a nominal beam width of 128 mm, an integration length of 300 mm is required if scattered radiation is to be appropriately assessed [M36]. Conversion factors have been developed to allow a standard $CTDI$ phantom and a 100-mm-long ionization chamber to assess $CTDI$ on multislice CT scanners [M36].

A79. Effective dose E may be inferred from the DLP using appropriate conversion coefficients ($(E_{DLP})_{regime}$). Conversion coefficients have been calculated for different regions of the body at a range of standard ages [J2, J3, K13, S18, S19, S20, S21]. These conversion coefficients are derived from mathematical phantoms [K13] using Monte Carlo modelling. Measured conversion coefficients have been published by Chapple et al. [C13] for paediatric patients. These conversion coefficients were deduced from a series of measurements made using anthropomorphic phantoms that simulate a range of ages from 0 to 15 years, into which TLDs had been placed.

E. Dental panoral tomography

A80. ESD is commonly measured in intraoral dental radiology.

A81. In dental panoral tomography (and also in CT), air kerma–length product is used for dosimetry. Air kerma–length product, P_{KL}, is the integral of the air kerma over a length L [I17].

$$P_{KL} = \int_L K(z)dz$$

F. Dual-energy absorptiometry

A82. In dual-energy absorptiometry it is common to use approaches to patient dosimetry that are similar to those employed for projection radiography (i.e. measurement of ESD or effective dose using anthropomorphic phantoms).

III. METHODOLOGY FOR ANALYSIS OF DOSIMETRY IN NUCLEAR MEDICINE

A. Dosimetric approaches

A83. The MIRD (medical internal radiation dose) system was developed primarily for use in estimating radiation doses received by patients from administered radiopharmaceuticals.

A84. The simplest form of the dose equation is:

$$D = N \times DF$$

where N is the number of disintegrations that occur in a source organ and DF is given by:

$$DF = \frac{k\sum_i n_i E_i \phi_i}{m}$$

where n_i = number of particles with energy E_i emitted per nuclear transition;

E_i = energy of particle emitted (MeV);

ϕ_i = fraction of energy emitted that is absorbed in the target;

m = mass of target region (kg);

k = the proportionality constant used to resolve the units (Gy kg·(MBq s MeV)$^{-1}$).

The equation for absorbed dose in the MIRD system is [T18]:

$$D_{r_k} = \sum_h \tilde{A}_h \, S(r_k \leftarrow r_h)$$

In this equation, r_k represents a target region and r_h represents a source region. The term $\tilde{A}_h$ is the number of disintegrations in a source region h and all other terms must be amalgamated into the factor S, which becomes:

$$S(r_k \leftarrow r_h) = \frac{k\sum_i n_i \, E_i \, \phi_i (r_k \leftarrow r_h)}{m_{r_k}}$$

A85. The ICRP has developed a system for calculating internal doses to radiation workers who inhale or ingest radionuclides. The technical basis is identical to that shown above, but different symbols are used for many of the quantities. Moreover, values of permissible intakes and air concentrations for many radionuclides are derived from dose limits established for workers. The details are not given here, because this report focuses on dosimetry for the purposes of nuclear medicine.

A86. However, the ICRP has also published extensive compendia of dose estimates for radiopharmaceuticals in its Publications 53 [I34] and 80 [I25]. In these documents, the available literature supporting the design of a kinetic model for each of the (over 100) radiopharmaceuticals is reviewed and a kinetic model is given, as well as dose estimates for adult and 15-, 10-, 5- and 1-year-old subjects.

A87. As discussed above, the ICRP has defined the quantity effective dose [I3] for the purpose of gauging stochastic risks from radiation exposure. The discussion above concerning the limitations of the use of effective dose for assessing the exposures due to medical radiology also apply to its use for assessing exposures due to nuclear medicine. Thus, although the quantity has limitations, it is used here as a surrogate to assess patient exposures because of its convenience.

IV. METHODOLOGY FOR ANALYSIS OF DOSIMETRY IN RADIATION THERAPY

A88. Data for analysis of trends and annual frequency of procedures in radiation therapy are derived from published literature, supplied by professional organizations and governments, and/or from the survey forms. The data are typically more difficult to obtain than those for diagnostic radiology or nuclear medicine. There are some inherent difficulties with the definition and comparison of the reported values. Some surveys report the number of patients treated, others report the number of treatment regimens (each of which may have up to 30 treatments) and still others report treatments. For this analysis it has proven valuable to supplement these estimates by considering data on the number and type of installed machines.

A89. The UNSCEAR reports have often presented the intended absorbed or equivalent organ doses for various treatments. However, these are typically of the order of tens of grays. The concept of effective dose strictly applies only to lower dose levels (in the region where only stochastic effects occur), and therefore neither effective dose nor collective effective dose may legitimately be used for the high dose levels of radiation therapy. As a result, no contribution has been calculated for radiation oncology or included in the estimates of worldwide annual per caput effective dose or collective effective dose from medical exposures.

A90. There are risks of stochastic and deterministic effects for patients who undergo radiation therapy resulting from radiation exposure of tissues outside the target radiation field. The risk of a second cancer is particularly important for those radiation oncology patients who survive treatment for malignant disease or receive radiation therapy for benign disease. However, the Committee has been unable to obtain sufficient data to adequately quantify these risks.

APPENDIX B.
LEVELS AND TRENDS OF EXPOSURE IN DIAGNOSTIC RADIOLOGY

I. SUMMARY FROM UNSCEAR 2000 REPORT [U3]

B1. The utilization of X-rays for diagnosis in medicine varied significantly between countries. Information on national practices that had been provided to the Committee by a sample of countries was extrapolated to allow a broad assessment of global practice, although inevitably there were significant uncertainties in many of the calculated results. On the basis of a global model in which countries were stratified into four levels of health care depending on the number of physicians relative to the size of population, the world annual total number of medical radiological examinations for 1991–1996 was estimated to be about 1,900 million, corresponding to an annual frequency of 330 per 1,000 world population (table B1). Estimates of these quantities for 1985–1990 were 1,600 million and 300 per 1,000 population, respectively. The global total of examinations was distributed according to the model among countries with different health-care levels 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 and IV (20 per 1,000 population). In addition to such medical radiological examinations, there was also an estimated global total of about 520 million dental radiological examinations annually, corresponding to an annual frequency of 90 per 1,000 world population. The assumed distribution between health-care levels is: more than 90% occur in level I and less than 0.1% in levels III and IV. Notwithstanding the estimated mean frequencies of examination for each health-care level quoted above, there were also significant variations in the national frequencies between countries in the same health-care level.

B2. Estimated doses to the world population resulting from diagnostic medical and dental radiological examinations are summarized in table B2. For 1991–1996, the global annual collective effective dose due to medical radiological examinations was estimated to be about 2,330,000 man Sv, corresponding to an average annual per caput dose of 0.4 mSv; estimates of these quantities for 1985–1990 were 1,600,000 man Sv and 0.3 mSv, respectively. The distribution of the collective dose among the different health-care levels of the global model was as follows: 80% in countries of level I (giving a mean annual per caput dose of 1.2 mSv); 18% in countries of level II (corresponding to 0.14 mSv per caput); and 2% in countries of health-care levels III and IV (corresponding to 0.02 mSv per caput). Diagnostic dental radiological examinations were 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 were less than the corresponding estimates for 1985–1990 of 18,000 man Sv and 0.003 mSv per caput. However, the uncertainties in all these estimates were considerable and this apparent trend may not be real. Approximately 68% of the global collective dose due to dental radiology arises from countries in health-care level I, with contributions of about 31% and less than 1% from countries in health-care level II and level III/IV, respectively.

B3. The numbers of X-ray generators (excluding dental units) available for diagnostic radiology varied considerably between countries and between the health-care levels of the global model, with estimated averages of 0.5, 0.2 and 0.02 per million population for levels I, II and III/IV, respectively (table B1). The estimated average annual number of medical radiological examinations per medical X-ray generator was lower for countries of health-care levels III and IV (1,100) than for those of level II (2,300) and level I (2,700). The estimated average values of annual collective dose per medical X-ray generator followed a similar global pattern: 1.2 man Sv per unit in health-care levels III and IV; 2.0 man Sv per unit in level II; and 3.6 man Sv per unit in level I. However, there may be an under-reporting of medical and dental equipment in some countries.

B4. The estimated global annual per caput effective dose per medical radiological examination for 1991–1996 was 1.2 mSv, which is comparable to the value of 1.0 mSv estimated for 1985–1990. However, the levels of dose to individual patients varied significantly among the different types of examination and also among countries. The contributions to collective dose provided by the different categories of examination are summarized in table B3 according to health-care level. On a global scale, population exposure due to medical radiology was dominated by the use of CT (which accounted for 34% of the annual collective dose) rather than examinations of the upper gastrointestinal (GI) tract (12%), which had been estimated to be the most important procedure for the period 1985–1990. This new pattern applied principally for countries of health-care level I, where the mean contribution from the use of CT was 41%. However, the dominant practice in health-care level II countries was chest fluoroscopy (50% of collective dose), and in countries of levels III and IV it was examination of the lower GI tract (34%), with CT use providing contributions of only 5% and 2%, respectively.

II. DOSES FOR SPECIFIC X-RAY PROCEDURES

A. Diagnostic radiography

B5. In the United Kingdom of Great Britain and Northern Ireland, the former National Radiological Protection Board (NRPB) (now the Radiation Protection Division of the Health Protection Agency) performed surveys of patient doses for common radiological examinations [S7]. A national database is used to collect data on patient doses from routine examinations according to a national protocol [N1].

B6. The NRPB has published data for common radiological examinations in terms of ESD and DAP [H34].

B7. Table B4 is a summary of patient dose data for conventional diagnostic radiological examinations (adapted from reference [H33]). It has been revised with additional patient dosimetry data. Effective dose estimates are given in the table. These have been calculated by the authors of the NRPB report, by the authors of the cited document or by applying a conversion factor used by the NRPB to the additional dosimetry data assessed in the cited patient dose survey.

B8. Various authors have compared flat panel direct digital detectors with computed radiography (CR) systems [B12, Z4]. For the same image quality, radiation doses were halved using direct digital radiography (DDR) during excretory urography [Z4]. Doses for chest imaging were 2.7 times lower for a direct digital detector compared with film–screen radiography and 1.7 times lower compared with a computed radiography system.

B9. In another study, Ludwig et al. used monkeys as surrogates for paediatric patients in order to deduce the dose saving from the introduction of flat panel detectors for lumbar spine radiography [L11]. Dose savings of 75% without loss in image quality were predicted.

B10. Vañó et al. [V8] have developed a computerized system for dose monitoring in radiology. Technical details for a series of examinations performed on a CT system were deduced from the DICOM header. A computer workstation, linked to the hospital PACS network, calculates ESD and DAP from the technical parameters. The dose monitoring system calculates a running average for ESD and DAP for the most recent ten patients. It then compares this running average with reference levels. A warning signal is given if the running average is higher than the preset reference value.

B11. There is some evidence that the use of “technique factors” suggested by manufacturers can lead to higher doses in projection radiography [P17]. Peters and Brennan [P17] were able to reduce patient doses by optimizing technique factors. Weatherburn et al. [W20] investigated patient dose levels associated with bedside chest radiography following the replacement of a film–screen system with a computed radiography system. They discovered in a randomized controlled trial that ESDs were higher in the computed radiography group.

B12. Vañó et al. [V14] performed a retrospective analysis of patient dose levels in projection radiography using a computed radiography system. They found that immediately following the introduction of computed radiography, doses increased by between 44% and 103% for lumbar spine and chest examinations when compared with the film–screen combination. Since this initial period, patient doses have been reduced. This analysis is based upon relatively large sample sizes of between 1,800 and 23,000.

B13. Radiation doses for standard radiographic examinations in an accident and emergency department were studied by an Italian group [C28]. They concluded that effective doses for direct digital radiography were typically 29% and 43% lower than for film–screen or computed radiography.

B14. Since the previous report, digital imaging has been introduced into many centres worldwide. In summary, the impact of the introduction of digital imaging on patient dose levels in diagnostic radiography is unclear.

B. Mammography

B15. Mammography has also undergone many technological changes. Originally it was performed with conventional X-ray tubes using industrial direct exposure X-ray film to have good image quality. The introduction of dedicated mammography equipment, having a specialized tube with a molybdenum target/molybdenum filtration, combined with the introduction of film–screen cassettes with a rear phosphor screen, substantially reduced radiation doses.

B16. This reduction in dose facilitated consideration of the introduction of mass screening programmes. Given the public health benefits of breast cancer screening, many countries in health-care level I have introduced mass screening programmes. As a consequence, there has been a large increase in the frequency of use of mammography.

B17. The introduction of film–screen mammography coupled with molybdenum target tubes with molybdenum filters has reduced ESD to about 0.01 Gy [G8]. However, a number of individuals have advocated increasing film optical density so that the target optical density coincides with the point on the film–screen characteristic curve with maximum slope and hence contrast amplification [F2]. This has been shown to improve cancer detection rates [Y3].

B18. Compressed breast thickness was analysed by Ogasawara and Date for Japanese women [O5]. The typical compressed breast thickness for Japanese women was under 3.8 cm, comparable to that in the Republic of Korea [O3].

Mean glandular doses are likely to be similar. Typical glandular doses were reported as 1.5 mGy in studies in Japan and in Taiwan Province of China [D8, T6]. While the compressed breast thickness reported in a German study [H22] was 5.57 cm, the mean glandular dose was comparable to that in surveys of Asian women (1.51 mGy). A similar value (1.5 mGy) was reported in a Canadian study [F10].

B19. Young [Y2] surveyed radiation doses in the United Kingdom trial of breast screening in women aged 40–48 years. Doses for 2,296 women were estimated. The average dose was 2.0 mGy for a craniocaudal film and 2.5 mGy for an oblique view. Doses in younger women were approximately 7% higher than in older women (those aged over 50 years).

B20. The Food and Drug Administration in the United States approved the first full-field digital mammography unit in 2000 [C25]. The introduction of digital mammography in the United States has been relatively slow, with digital units comprising 6.4% of the accredited mammography units [L26, M32]. Digital mammography offers potential benefits in the imaging of young women and women with dense breasts [P22, P24]. However, the high cost of digital mammography represents a limitation on its acquisition by screening programmes [T5].

B21. Doses to over 5,000 women were examined on a General Electric 2000D full-field digital mammography system in a two-year period [M6]. Dose information was obtained from the DICOM header. Mean glandular doses for both craniocaudal and mediolateral oblique projections were 1.8 mGy and 1.95 mGy, respectively. Fischmann et al. also found that doses for full-field digital mammography were comparable to those for film–screen systems [F4].

B22. Gennaro et al. [G15] calculated the ESAK for a sample of 800 craniocaudal full-field digital mammograms. Mean glandular doses were in the range 1.27–1.37 mGy and 1.37–1.49 mGy for 50% and 30% glandularity, respectively. These dose levels are lower than for film–screen mammography.

B23. The Digital Mammographic Imaging Screening Trial (DMIST) included 49,528 women from 33 participating academic and community practices in the United States and Canada (25.5 months of enrolment from 2001 to 2003). All women in the trial underwent both film–screen and digital mammography. Mean glandular doses were between 1.7 and 2.5 mGy for the digital systems and between 1.5 and 2 mGy for the film–screen mammography units [P25].

B24. As may be deduced from table B4, the variation in dose is relatively small for mammography. The small range in doses is consistent with the practice of optimized mammography subject to quality control.

C. Fluoroscopy and angiography

B25. *Direct fluoroscopy*. Most regulatory systems internationally have prohibited the use of direct or non-intensified fluoroscopy [I11]. However, direct or non-intensified fluoroscopy is still performed in some countries. The number of dose surveys on non-intensified fluoroscopy systems is somewhat limited. Dosimetry on these systems is important, not least from a historical perspective.

B26. In a study in Brazil, doses for barium enema were reported as 63 Gy cm^2, with a range of 85–316 Gy cm^2. A mean dose of 107 Gy cm^2, with a range of 25–118 Gy cm^2, was reported for hysterosalpingograms [C2]. Most of the DAP arose from direct fluoroscopy and not from radiographic images. Mean DAP for seriography was 167 Gy cm^2 (range 25–118 Gy cm^2) [C2].

B27. Marshall et al. performed a study of chest examinations using non-intensified fluoroscopy in Albania [M3]. They investigated seven direct chest fluoroscopy systems. DAP ranged from 0.34 to 3.64 Gy cm^2, with effective doses in the range 0.06–0.42 mSv. The ESD was typically 17 mGy for a PA chest fluoroscopy, which is nearly 100 times higher than the reference dose for the equivalent examination performed using a film–screen system in the United Kingdom [H34].

B28. *Image intensified fluoroscopy*. In the United Kingdom, the NRPB published data on DAP received by patients for common examinations involving fluoroscopy [H33]. This survey was undertaken in a limited number of centres and may not be representative of national practice.

B29. Average DAP for endoscopic retrograde cholangiopancreatography (ERCP) in Greece was studied by Tsalafoutas et al. [T8]. The average DAP was 13.7 Gy cm^2 for a diagnostic procedure and 41.8 Gy cm^2 for a therapeutic one.

B30. Patient doses for barium meal examinations were measured in three hospitals in Serbia and Montenegro by Ciraj et al. [C14]. A total of 74 patients were monitored in three hospitals with a minimum of 19 in each. All patients weighed within 10 kg of 70 kg. Median values of KAP varied by a factor of 3, from 7.2 to 22.1 Gy cm^2. The authors also calculated effective doses. These ranged from 1.7 to 4.8 mSv [C14], which illustrates the variation between hospitals.

B31. In summary, there are wide variations in dose levels for fluoroscopy procedures, reflecting differences in local practice, equipment and staff. The impact of digital imaging on dose levels is also unclear.

D. Interventional radiology

B32. Interventional radiology procedures have experienced a dramatic increase in frequency in recent years, principally because of the numerous significant benefits. Specifically, it is now possible to perform in a radiology department on an outpatient basis procedures that previously would have necessitated surgical treatment in hospital. This results in considerably reduced trauma for the patient, and the hospital gains because more patients can be treated as outpatients at a lower cost. Consequently, both hospitals and the public demand access to more interventional radiology. This inevitably leads to an increase in the frequency of interventional radiology procedures.

B33. This growth in demand has implications for population doses [C11, N10, W10]. Specifically, some interventional procedures are very complicated, and often involve extended fluoroscopy times and the operation of fluoroscopy equipment in high-dose-rate mode. This leads to high patient doses. In some patients the procedures are repeated owing to restenosis.

B34. Table B5 is a summary of various sources of patient dose data for interventional radiology procedures; it has been adapted from a table produced by Hart and Wall [H33]. The original table has been revised with the inclusion of additional patient dose survey results in interventional radiology. Effective dose has been included for comparative purposes. Effective dose was calculated by either the NRPB or the original authors of the cited reports. In those instances where the authors of the survey did not deduce the effective dose, the NRPB conversion factor has been applied to the DAP to derive the value quoted.

B35. Data on various fluoroscopy and interventional procedures have been analysed by the NRPB in the United Kingdom [H33, H34]. However, as the NRPB indicates, many of the data were obtained from too small a number of hospitals or X-ray rooms to be indicative of national practice in the United Kingdom.

B36. Results from a large-scale survey of patient doses in interventional radiology have been published by Marshall et al. [M1]. Forty fluoroscopy rooms were monitored using calibrated DAP meters linked to laptop computers. Size-corrected DAP values for seven groups of interventional procedures were published. Size correction was performed using previously published approaches [C1, L4].

B37. It is clear from the data presented in these tables that considerable variations in patient dose exist between centres. Doses are dependent upon factors related to both equipment and procedure, as well as on the skill of the interventionalist and the clinical protocol adopted in a specific centre. In addition, some centres perform more complex procedures, and hence dose levels tend to be higher [P6]. The data presented in these tables should therefore be regarded as indicative of radiation dose levels received by patients.

B38. Lavoie and Rasuli have assessed ESDs for angiographic procedures in Canada [L2]. The mean ESD was 0.16 Gy for a transluminal aortogram, rising to 2.1 Gy for a liver tumour embolization. Uterine embolization had a mean ESD of 1.3 Gy [L2].

B39. The effect of the choice of puncture site on radiation doses in intrainguinal angioplasty has been studied [N9]. The mean DAP was 7.95 Gy cm^2 for a retrograde puncture site and 1.07 mGy cm^2 for antegrade punctures, which illustrates the effect of examination protocol on patient doses.

B40. Doses from cerebral embolization studies were reported by Theodorakou and Horrocks [T9]. The average DAP was 48 Gy cm^2 for a posterior–anterior plane and 58 Gy cm^2 for a lateral plane. Typical doses were 60 mGy to the patient’s right eye and 24 mGy to the thyroid gland.

B41. Ropolo et al. have deduced a factor to convert DAP to effective dose (0.15 mSv/(Gy cm^2)) [R7] for abdominal and vascular interventional radiology procedures. They concluded that there was a good correlation between DAP and fluoroscopy time, as well as DAP and number of images.

B42. A large United States study has been reported by Miller et al. [M13]. The Society of Interventional Radiology was asked by the Food and Drug Administration to undertake a survey of dose levels in interventional radiology. Twenty-one interventional procedures were studied over a three-year period. Dose data from 2,142 cases were reported. Dosimetry data were obtained in terms of DAP and cumulative dose (i.e. total air kerma at the interventional reference point). Table B6 (adapted from reference [M13]) summarizes the mean, 95% confidence intervals, minimum and maximum DAP (cGy cm^2), and cumulative dose (mGy).

B43. Vetter et al. [V5] estimated the effective dose resulting from uterine artery embolization of leiomyomata. They observed that the estimated effective dose of 34 mSv for uterine artery embolization (deduced from the DAP) was twice that for an abdominal CT scan.

B44. Bor et al. [B20] performed a series of measurements in Turkey for a range of interventional radiology procedures. DAP and entrance doses were assessed for a series of 162 adult patients. Conversion factors were used to deduce effective dose. Table B7 is a summary of effective doses measured in this study compared with previously published data [C12, H1, M2, M4, M14, S26, T12, Z5]. The effective dose levels assessed in Turkey are comparable to those reported in previous surveys.

B45. Struelens studied patient doses for interventional procedures in seven different hospitals in Belgium [S25]. Average DAPs for angiography of the lower limbs, carotid arteries and cerebral embolizations were 68, 36 and 230 Gy cm^2, respectively. Average skin doses were 77, mGy and 262 mGy, respectively, for the same three procedures [S25].

B46. Bridcut et al. investigated patient doses resulting from 3-D rotational neurovascular studies [B7]. Three-dimensional rotational angiography is a recently introduced technique in which the X-ray tube and detector rotate around the patient during an interventional X-ray procedure. Reconstruction techniques are used to present the radiologist with

3-D volume data. This technique is particularly useful in the treatment of cerebral aneurysms. The average DAP was 48 Gy cm^2 for conventional digital subtraction angiography and 2 Gy cm^2 for 3-D rotational angiograph.

E. Interventional cardiology

B47. Coronary angiography is used in the diagnosis of coronary artery disease [P19]. In these examinations, contrast medium is introduced into the bloodstream using a catheter to provide images of the heart. Coronary angiography is used in the diagnosis of obstructive coronary artery disease to determine whether an angioplasty or coronary artery bypass surgery is appropriate [F6]. Coronary angiography is the most common angiographic procedure and tends to be undertaken in those aged 45 years or over. Angiography may also be performed in other areas of the body, for example to diagnose obstructive disease in the extremities or the head.

B48. A literature search has been performed to deduce typical dose levels for cardiac interventional procedures. Dose data for coronary angiograms are presented in table B8. The reviews of PTCA patient dosimetry studies are summarized in table B9 and data for stent procedures are presented in table B10. Table B11 is a review of the patient dosimetry studies for pacemaker insertions. It may be deduced from this literature review that the typical DAP was 32 Gy cm^2 for a coronary angiogram, 44 Gy cm^2 for a PTCA, 46 Gy cm^2 for a stent procedure and 18 Gy cm^2 for a pacemaker insertion.

B49. Conversion factors may be used to deduce the effective dose from DAP or KAP readings and have been published by various authors for cardiac interventional procedures [B14, M14, M35, R19]. The average conversion factor is 0.17 mSv/(Gy cm^2).

B50. Larrazet et al. studied the effect of various factors on DAP during percutaneous coronary angioplasty [L14]. DAP was 175 Gy cm^2 for a radial technique compared with 138 Gy cm^2 for a femoral technique. Predilation, direct stenting significantly reduced the DAP.

B51. In common with other interventional procedures, dose levels in interventional cardiology are influenced by staff and the clinical protocol used, as well as the type of equipment.

F. Computed tomography

B52. A review of the published literature has been undertaken. Data on DLP and effective dose for head, body, spine, angiography and other types of CT scans on adults are given in tables B12, B13, B14, B15 and B16, respectively. Table B17 summarizes patient doses for CT scanning in paediatric patients.

B53. The annual frequency of CT examinations has exhibited a dramatic increase since CT's introduction [H3]. In the United Kingdom in 1990, 20% of the annual collective dose due to all radiological examinations resulted from CT examinations, even though there were a relatively small number of scanners [S1, S2]. Recent publications have confirmed the upward trend in the contribution of CT to the total collective dose from medical examinations [N16, N17]. In 1998 Shrimpton and Edyvean estimated the contribution to have risen to 40% [S17]. This had increased to 50% in 2003 [H24]. The number of CT scanners had almost doubled in the six years since the original survey, [S3]. However, the number of CT scanners per caput is over 50% higher in the European Union as a whole and over 400% higher in the United States than in the United Kingdom [B3]. The collective effective dose to the citizens of countries that have a higher number of CT scanners per caput is likely to be even higher than that in the United Kingdom.

B54. The NRPB performed a survey of CT practice in the United Kingdom between 2002 and 2003, surveying 126 of the estimated 471 CT scanners in the country. In the period since the previous survey in 1991, all the CT scanners had been replaced and were capable of scanning in the helical mode. Over a third of the CT scanners surveyed were capable of multislice scanning (2–16 slices). A questionnaire was sent to each centre to obtain information on scanning protocols and sequences. Typical doses from CT scanning in the United Kingdom are summarized in tables B12 and B13 [S19].

B55. Huda and Mergo [H5] have investigated the impact of the introduction of multislice or helical CT. Table B14 provides a comparison of effective doses for three regions of the body. It is interesting to compare doses with time from these various surveys of CT practice [H4, J2, S1]. The European data for head CT scanning are comparable to the reported mean effective doses, being in the range 1.6–1.8 mSv. This is particularly remarkable, given that the first paper [S1] preceded the last by nearly a decade [H4]. The introduction of spiral/axial multislice CT has resulted in an increase in effective dose by a factor of over 2.5 for chest CT and of over 2 for abdomen CT (table B14).

B56. A survey of patient doses from CT examinations has been undertaken in Hungary [P1]. The authors estimated an annual total of 623,000 CT examinations in 1999 on 54 operational machines. This equates to 62.3 examinations per 1,000 individuals.

B57. A comparison of the performance of CT scanners in Nordic countries has been undertaken by Torp et al. [T1]. Results for brain, chest and lumbar spine scans are given in tables B15, B16 and B17, respectively. Effective dose was calculated using the method developed by the NRPB [J3].

B58. In two editorials in the American Journal of Roentgenology, Rogers [R13, R14] raised awareness of the need for dose reduction in CT, especially the need to adjust CT exposure factors for paediatric patients [D7, P11]. As a consequence, optimization of CT examinations has become an important topic with a high level of public interest [M26, P12, R15].

B59. In the United States, a nationwide survey of patient doses from CT was undertaken during 2000–2001 as part of the series of NEXT surveys of X-ray trends [S24]. Information on patient workload and CT scanning technique factors was obtained from 263 facilities in 39 states. X-ray output measurements were performed both free in air and in a standard head phantom manufactured from PMMA. From these measurements, CTDI and mean effective dose were deduced.

B60. The NEXT survey estimated that there were 7,800 CT facilities in the United States. The estimated number of CT examinations and procedures (both adult and paediatric) was 58,000,000. The survey revealed that 30% of CT scanners performed axial scanning only. Helical scanners comprised 69% of CT scanners. Of the machines surveyed, 29% were capable of multiple slices. Just 1% of the machines were electron beam CT scanners [S24].

B61. The estimated effective doses for CT scanning in the United States are summarized in table B18.

B62. A nationwide survey of CT examinations was undertaken in 2000 in Japan [N13]. This survey indicated that there were 87.8 CT scanners per million population. The distribution of examinations according to age was 100,000 in children aged up to 14 years, and 3.54 million for persons aged 15 years and older (i.e. 290 examinations per 1,000 population). The most common examination was head scanning, which comprised 80% of the examinations in children and 40% of those in adults. A breakdown of the annual number of CT examinations in Japan is given in table B19.

B63. The effective dose per examination assessed in this Japanese survey was 2.4, 9.1, 12.9 and 10.5 mSv for head, chest, abdomen and pelvis scans, respectively. The trend in the number of CT scanners, examination frequencies, number of CT scans, collective effective dose and effective dose per person in Japan is summarized in table B20 [N13].

B64. A survey of radiation exposure for multislice CT was conducted by Brix et al. [B18] in Germany in 2001. The facilities for each of the 207 multislice CT scanners in Germany were contacted, of which 113 replied. The response rate was slightly higher for public hospitals (60%) than for private practice (43%). All facilities were asked to provide data on scan parameters and annual frequency for 14 standard examinations. Standard CT dosimetry quantities were deduced using formulae that had been experimentally verified. The results of the survey for multislice CT scanners are summarized in table B21. The results of the previous survey are summarized in table B22 [G13] for comparison. (An examination may comprise more than one series.)

B65. Comparison of the results of the two surveys indicated that the scanner annual workload is considerably higher for multislice CT (5,500) than for single-slice CT (3,500), a difference of 63%. Average effective dose for CT examinations was 7.4 mSv for single-slice, 5.5 mSv for dual-slice and 8.1 mSv for quad-slice CT scanners. The increase in dose for quad-slice CT scanners was not as great as reported by Giacomuzzi et al. [G14], probably owing to the optimization of procedures. The authors predicted that improved clinical efficacy and new applications will lead to rising examination frequencies [G14].

B66. Zammit-Maempel et al. studied the radiation dose to the lens of the eye during scanning of the paranasal sinuses [Z1]. TLDs were attached to the patient to measure eye and thyroid doses in the axial and coronal planes on a Siemens CT scanner using 140 kV, 100 mAs and 1 mm collimation. Eye doses of 35.1 mGy for the coronal plane and 24.5 mGy for the axial plane were measured. Thyroid doses were 2.9 mGy and 1.4 mGy, respectively. The use of a low-dose scanning technique resulted in an eye dose of 9.2 mGy and a thyroid dose of 0.4 mGy.

B67. The use of CT in the diagnosis of renal colic has been investigated [K4]. The effective mean dose from low-dose helical scanning was 1.35 mSv for female patients. Low-dose helical CT was considered to be the method of choice.

B68. Multidetector CT (MDCT) has enabled angiographic examinations to be performed on CT scanners. As a consequence, MDCT is being explored as an alternative to conventional angiographic examinations. In another study [K5], doses from conventional and CT angiography of the renal arteries were compared. For conventional renal angiography, effective dose was deduced from the DAP. Two dose reduction strategies in conventional renal angiography were compared with the default factory settings. Effective dose was reduced from 22 mSv to 11 mSv if half the number of digital subtraction angiography images were taken and to 9.1 mSv if the beam filtration was increased. The effective dose from CT angiography was 5.2 mSv, lower than any of the low-dose conventional angiography procedures.

B69. Nickoloff and Alderson measured radiation doses from a 64-slice cardiac CT scanner [N25]. Effective doses for 64-slice CT angiography were in the range 8–25 mSv, compared with 3–6 mSv for a routine chest CT and 14–26 mSv for diagnostic coronary angiography with fluoroscopy [N25]. The main cause for concern was the high equivalent dose to the breast of 30–100 mSv.

B70. Radiation doses from CT and cone beam CT in dentistry were studied by Ludlow et al. [L12]. As might be expected, the effective dose varied depending upon whether the salivary gland was included in the calculation. The effective dose for a cone beam CT mandibular/maxilliary scan was 36 µSv, or 78 µSv if the salivary glands were included in the calculation. For a maxillary scan only, the effective doses were 19 and 42 µSv, respectively. For a mandibular scan, the respective effective doses were 35 and 75 µSv. These doses are less than the effective dose for conventional CT.

B71. Mori et al. compared patient doses for 256-slice CT with those for 16-slice CT [M24]. A prototype 256-slice CT scanner was developed to take dynamic 3-D images of moving organs such as the heart. The estimated effective doses for chest, abdomen and pelvis examinations were 2.2, 2.6 and 3.3 mSv, respectively. Dose profile integrals were between 11% and 47% lower for 256-slice CT than for 16-slice CT [M24].

B72. Van der Molen et al. [V9] have investigated the reductions in effective dose achievable on 16-slice CT scanners compared with 4-slice CT, once the scanning protocol was optimized. Dose reduction was greatest for abdomen and pulmonary CT angiography, the magnitude of the dose reduction depending on the examination. Effective doses for optimized 16-slice CT ranged from 1.9 mSv for head scans to 7.2 mSv for abdomen scans.

B73. Mettler et al. [M41] have reviewed the published literature on radiation doses from CT scanning. These data are presented in table B23.

B74. Effective doses for CT colonography are in the range 1–18 mSv, with a typical effective dose of 8 mSv [I19].

B75. In summary, patient dose levels for CT examinations are higher than for many other types of diagnostic medical exposure. The introduction of multislice CT scanning has shortened examination times and has enabled more examinations to be performed on a single scanner. The increase in workload associated with multislice CT scanning will impact on population doses.

G. Dental radiology

B76. Dental radiological examinations are among the most common medical exposures [H12]. There are two basic techniques: intraoral and dental panoral tomography [G10, H2]. The former involves placing a film inside the mouth and the use of a dedicated dental X-ray tube. In dental panoral tomography both the tube and the film move around the head.

B77. Geist and Katz [G9] surveyed 65 dental schools in the United States and Canada. They found that 86% use E-speed film. Direct digital imaging is used by just over half (58%) for intraoral radiography and by 11% for extraoral. The use of dose reduction techniques was quite high, with 88% using long focus–skin distances, 47% rectangular collimation and 100% rare-earth film–screen systems for intraoral radiography.

B78. The use of digital imaging for intraoral radiography by general dental practitioners in the Netherlands was investigated [B10]. The study indicated that centres using digital imaging devices took more radiographs. Centres using photostimulable storage phosphor plates took an average of 42.8 radiographs weekly, compared with 32.5 for film–screen users and 48.4 for centres with solid-state detectors. The study concluded that, despite the increase in the frequency of use, the introduction of digital imaging would reduce effective doses by about 25%, as digital intraoral radiography requires 50–80% lower doses.

B79. A Chinese study looked at eye doses in full-mouth dental radiography [Z2]. The dose to the lens of the eye was 250 μGy. The dose to the thyroid was 125 μGy, to the pituitary 110 μGy, to the parotid 150 μGy and to the breast 12 μGy.

B80. In panoral tomography, the X-ray tube and film rotate around the patient's head to obtain an image of the entire dentition and jawbones. X-ray manufacturers have introduced panoramic equipment that allows the operator to select the part of the jaw or dentition to be imaged. Effective doses for one machine have been reported as being in the range 6–19 μSv, depending upon which anatomical programme has been selected [L6].

B81. Doses for dental implant imaging were assessed by Lecomber et al. [L10]. Conventional radiography, cephalometry, linear cross-sectional tomography and CT were compared. Doses were measured using thermoluminescent dosimeters in an anthropomorphic phantom. Salivary gland doses were 0.004 mSv for dental panoral tomography and 0.002 mSv for both cephalometric imaging and cross-sectional tomography. CT doses were substantially higher, at 0.31 mSv.

B82. Doses in dental radiology have recently been assessed by Helmrot and Alm Carlsson [H2]. ESAK and DAP for four common intraoral dental examinations in Sweden varied from 1 mGy ESAK for an incisor to 2.5 mGy ESAK for a molar/upper jaw examination. DAP values for panoral tomography were in the range 0.06–0.1 Gy cm^2 for adult examinations and 0.03–0.04 Gy cm^2 for paediatric examinations.

B83. Manufacturers have developed dedicated CT scanners for dental radiology. These devices use cone beams and software specific to maxillodental CT scanning [S12]. They are used for the diagnosis of a wide variety of maxillofacial diseases in addition to dental implant imaging [H38].

B84. Digital volume tomography (DVT) is a recently introduced technique in dental radiology [C5]. It is intended to be a low-dose alternative to CT and panoramic tomography. A study has been performed by Cohnen et al. [C5] to assess DVT. Two types of DVT were compared with CT scanning. Radiation doses were measured using TLDs placed in an Alderson–Rando phantom. The results are given in table B24. DVT acquires an image optimized for the display of bony structures and other high-contrast objects, at the expense of soft-tissue imaging. It operates at a lower dose than either dental CT or sinus CT.

B85. Doyle et al. [D13] assessed dose–width product (DWP) and DAP for 20 panoral tomography dental units and compared their findings with a series of earlier studies [I33, N15, O6, P13, T13, W17] (table B25).

B86. Iwai et al. [I24] have estimated the effective dose for dental cone beam X-ray CT examinations. Effective doses were 7.4 µSv for the maxillary incisor, 6.3 µSv for the maxillary first molar, 12 µSv for the mandibular first molar, 9 µSv for the temporomandibular joint (TMJ) and 14 µSv for the middle ear when assessed using 3-dimensional X-ray multi-image micro-CT. For an ortho-CT machine the effective doses for the mandible, maxilla and TMJ were 13, 22 and 23 µSv, respectively.

B87. Dose levels from dental radiology are, in the main, low compared with other types of diagnostic medical exposure. The impact of dental CT will have to be closely monitored.

H. Bone mineral densitometry and dual-energy X-ray absorptiometry

B88. Bone mineral densitometry is a rapidly growing specialized radiological technique. It is used to deduce bone mass and bone density from X-ray or gamma ray transmission measurements.

B89. Low bone density is associated with a higher fracture risk. Though it affects a small but significant fraction of the male population, low bone mass is a particular problem in post-menopausal women. As a consequence, most bone mineral densitometry scans are performed on post-menopausal women.

B90. Effective doses for pencil beam and for array modes of operation (dual-energy X-ray absorptiometry (DEXA) examinations) are given in table B26 [N5]. There is a clear trend towards more frequent and shorter examinations [L3].

B91. The effective dose for an anterior–posterior (AP) lumbar spine scan was 59 µSv on a Lunar Expert-XL fan beam DEXA scanner [S13]. The effective dose was 56 µSv for an AP femoral neck scan, 71 µSv for lateral spine morphometry and 75 µSv for a whole-body scan.

B92. Effective doses to children from DEXA have been assessed by Njeh et al. [N8]. Patient doses were assessed using lithium borate TLDs in anthropomorphic child phantoms. Effective doses for posterior–anterior (PA) spine procedures were 0.28 µSv for a 5-year-old and 0.20 µSv for a 10-year-old. The effective dose for a whole-body scan was 0.03 µSv to a 5-year-old and 0.02 µSv for a 10-year-old.

B93. In summary, dose levels to patients having DEXA examinations are small compared with those for most other diagnostic medical examinations.

III. DOSES FOR SPECIFIC POPULATIONS

A. Paediatric patients

B94. Data on paediatric doses are very difficult to analyse, because the height and weight of children is very dependent on age [H11]. In addition, it is inappropriate to use effective dose to quantify patient dose levels for paediatric and neonatal radiology. In order to compare centres, an agreement was reached within the European Union to collect data for five standard ages, i.e. for newborn, 1-year-old, 5-year-old, 10-year-old and 15-year-old children.

B95. Some data are available in the United Kingdom for paediatric patients [H34]. These data are summarized in table B27 for five common radiographic examinations in terms of ESD, and in table B28 for three fluoroscopic examinations (DAP). As these data were obtained from a small sample of centres, these values may not be representative of practice nationally.

B96. Compagnone et al. [C15] assessed ESDs and deduced effective doses for various paediatric examinations. Effective doses were 0.005 mSv for chest PA and 0.10 mSv for abdomen AP examinations.

B97. Patient doses from paediatric radiology have been assessed in a large Spanish hospital [V10]. Dose values were obtained for four common projection radiography examinations performed using a photostimulable storage phosphor computed radiography system. The DICOM header was interrogated to provide information on the examination, patient and technique factors. ESD was deduced using knowledge of the measured tube output. Over 3,500 patient dose values were obtained. A summary of the results of this survey is given in table B29.

B98. A multicentre study of patient doses from CT scanning in children has been undertaken in Belgium [P7]. Values of effective dose were in the ranges 0.4–2.3 mSv, 1.1–6.6 mSv and 2.3–19.9 mSv for head, thorax and abdomen scans, respectively.

B99. ESDs in micturating cystourethrography (MCU) examinations in children have been monitored by Fotakis et al. [F11]. Despite its limitations noted earlier, effective dose was evaluated for comparative purposes using the factors published by the ICRP [I3]. The mean effective dose was 0.86 mSv for male patients and 0.76 mSv for female patients.

B100. Skin doses during paediatric cardiac catheterization examinations have been assessed [L13]. The average ESD to infants and children was 870 mGy.

B101. The effective dose during the percutaneous treatment of varicocele in adolescents was 18 mSv [P9]. This compared with the doses from abdominal X-rays (1.31 mSv) and for urography (4.6 mSv).

B102. In another study, Ono et al. [O9] investigated the annual frequency and type of X-ray examinations performed on neonates as a function of birthweight in a neonatal intensive care unit. The radiology records of over 2,400 neonates were investigated. On average, neonates weighing less than 720 g birth weight had 26 films. While the number of ESDs per neonate was dependent on birth weight, the maximum dose was not. For chest examinations the dose varied between 0.02 and 0.17 mGy, depending on birth weight.

B103. Kiljunen et al. have collected a series of patient doses for thorax examinations on paediatric patients in six hospitals in Finland in the years 1994–2001 and in two hospitals in 2004 [K31]. Patient doses correlated exponentially with projection thickness. As a consequence, diagnostic reference levels were specified in terms of both ESD and DAP as a function of patient projection thickness rather than by age band.

B104. Onnasch et al. [O10] evaluated DAP for three different types of angiocardiography system over a period of eight years. Data on 2,859 patients were acquired. Mean effective doses for seven paediatric cardiac interventions are given in table B30 [O10]. Onnasch et al. also investigated the total effective dose for patients with different types of congenital heart disease who underwent multiple examinations over 12 years [O10]. On average a paediatric patient would have four examinations. The mean total effective dose for a child with congenital heart disease who had multiple examinations was 19 mSv (range 0.64–184 mSv).

B. Foetal dosimetry

B105. The risks to the foetus of radiation exposure are well established. Consequently, most X-ray and nuclear medicine departments have mechanisms for avoiding unintended irradiation of the foetus. There are relatively few studies of radiation doses to the foetus, reflecting the effectiveness of these mechanisms.

B106. A retrospective study performed in the Islamic Republic of Iran [A1] involved over 1,300 patients referred to a medical physicist for dose estimation. The average age of the foetus was 31 days and the mean foetal absorbed dose was 6–8 mGy. Most examinations were performed for non-malignant gastrointestinal or urological problems.

B107. Osei and Faulkner studied the foetal dose received by a series of 50 pregnant women in the north of England [O1]. These women had asked their physicians about the risks of ionizing radiation to the foetus. Virtually all the dose estimations were performed retrospectively, as most of the women were unaware that they were pregnant at the time of the examination. Table B31 is a summary of the estimated mean of foetal absorbed dose per examination for this group of women. Also given in table B31 are reported typical means from the published literature. Most of the foetal doses in this table are based upon a United Kingdom survey made in the mid 1980s and may not be representative of current practice.

B108. Most of the foetuses (68%) had a gestational age of less than 8 weeks; a further 26% had a gestational age between 8 and 25 weeks. Five of the foetuses (10%) received a total dose of over 10 mGy. The majority (58%) received doses of below 5 mGy. Estimated doses to the women tended to be higher than would be deduced from average doses for the examination. In addition, the women tended to be older than the norm.

B109. Wagner et al. [W6] have produced a guide to the medical management of pregnant patients and diagnostic irradiation. In their book, a series of case studies are presented. While the majority were diagnostic radiological examinations, some nuclear medicine procedures were performed. Most doses were in the range 20–40 mGy. These doses are higher than those reported by Osei and Faulkner [O1], mainly because many patients in the series reported by Wagner et al. had CT scans [W6].

B110. The estimated foetal dose while patients underwent ERCP procedures was 3.1 mSv in a study in the United States [T7]. Foetal doses were reviewed in a study of the use of double pigtail stents in the treatment of hydronephrosis [H20]. The mean uterus/foetal dose was 0.40 mGy (range 0.03–0.79 mGy).

B111. CT can be used for the detection of pulmonary embolism in pregnant patients [R8]. Doses from helical CT were calculated [W12]. Foetal doses varied with gestational age, being in the range 3.3–20.2 mGy in the first trimester and rising to 51.3–130.8 mGy in the third. Mean foetal doses with helical CT were reported as being lower than with the scintigraphy technique.

B112. TLDs were used to estimate foetal dose from CT in late pregnancy using anthropomorphic phantoms [D10]. The measured foetal dose for abdomen examinations was in the range 30.0–43.6 mGy in the second trimester and 29.1–42 mGy in the third trimester.

B113. Transjugular intrahepatic portosystemic shunts (TIPS) are used in the treatment of recurrent bleeding in liver cirrhosis [W13]. The foetal dose was estimated as below 10 mSv in a German study [W13].

IV. TRENDS

A. Trends in practice

B114. Most radiological examinations are performed on a subgroup of the population who are ill. Patients who are ill tend to be either young or older than the average age of the general population. It is for this reason that the data collection forms ask for the age distribution for the examinations performed. For example, the average age of cancer patients is generally higher than the average age of the general population. Some of these patients are likely to have multiple CT examinations to diagnose and stage their disease. They are also likely to be subject to multiple follow-up CT examinations to check that there is no recurrence of the disease. Consequently their total dose will likely be somewhat higher than the average. In addition to this effect, there is a trend for the increasing use of CT examinations for the early diagnosis of diseases and the screening of asymptomatic individuals (for lung cancer, colorectal cancer, whole-body screening, and calcium scoring).

B115. The introduction of MRI has had an impact on the frequency of diagnostic radiological examinations. For example, in the period 1992–2001 in Canada, the number of MRI spine scans increased by 450%, whereas in the same period the number of CT spine scans increased by 51% and the number of radiographic examinations of the lumbar spine decreased by 11% [C25].

B116. In the main, radiology is performed more frequently on elderly individuals than on the general population. An exception is dental radiology, which tends to be performed more on younger individuals, whose teeth and dentition are still developing. With improvements in dental hygiene, however, individuals are likely to retain their teeth for longer; thus the age distribution of individuals having dental radiology will change with time.

B117. The past four decades have witnessed immense technological advances in radiology. The introduction of image intensification has led to the development of diagnostic procedures such as angiography and interventional radiology. The improvement in image quality associated with the introduction of image intensification and subsequent technical developments such as image digitization have made possible the expanded use of fluoroscopic examinations. Angiographic examinations have become more common and in some instances more complicated.

B118. Digital imaging has had the greatest impact on the conduct of barium studies. Almost overnight, conventional fluoroscopy equipment ceased to represent the state of the art. Digital imaging meant that barium studies could be performed in a shorter period of time, and spot (still) digital images were instantaneously available. This meant that fewer technologists were required to assist the radiologist performing the examination. Also, more examinations could be performed in a given period, inevitably leading to more efficient use of equipment and more examinations being performed. In addition, the introduction of colonoscopy will have an impact on the number of barium studies conducted.

B119. Digital imaging has also proved useful to interventional radiologists and cardiologists. The availability of last image hold or road mapping facilities has made it much easier for the interventionalist to orientate the displayed image with patient anatomy. The planning of procedures has become easier.

B120. The acquisition of images in a digital format permits the use of computer techniques to enhance the images. Thus it is easier to see guidewires, catheters, stents, etc. This facilitates the introduction of more complex interventional procedures. Almost all interventional radiology is performed with digital imaging equipment where it is available, even in countries with health-care levels II to IV.

B121. While digital radiography was originally introduced two decades ago, it is only recently that these systems have started to become widely available in health-care level I countries. With these systems, dose becomes a user-selectable variable. It is therefore important to select a dose sufficient to obtain the image quality required for the clinical objective of the examinations.

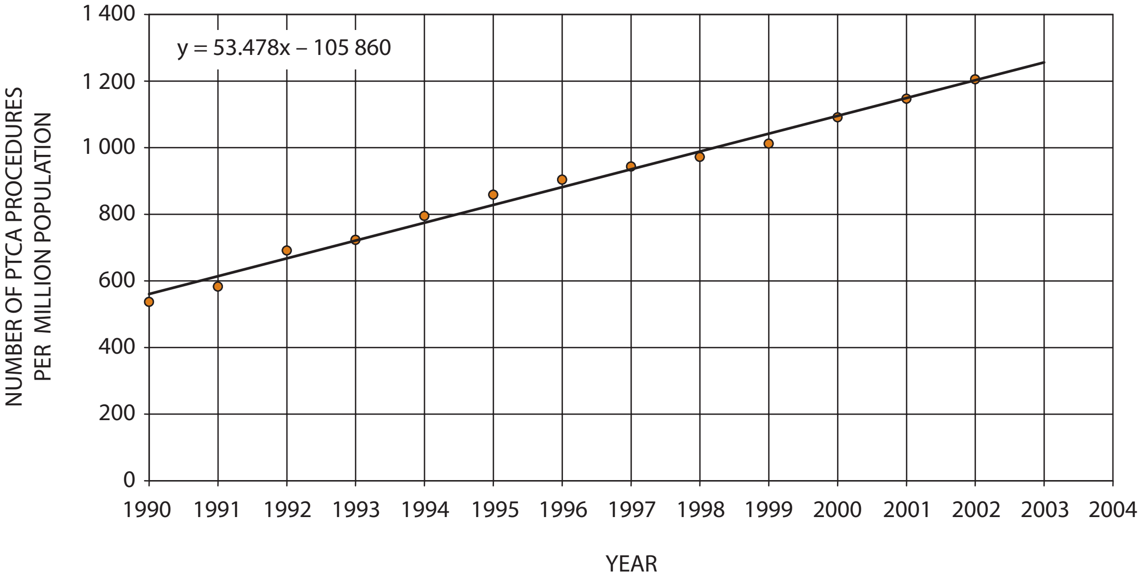
B122. Dotter and Judkins described the first percutaneous treatment of arteriosclerotic vascular obliterations in 1964 [D1]. Since then the range of interventional procedures has dramatically increased. This has been accompanied by significant developments in equipment, such as the introduction of digital imaging and more recently direct digital imaging.

B123. In recent years there has been a dramatic increase in the frequency of both diagnostic cardiological examinations (coronary angiograms) and X-ray-guided coronary treatment procedures, such as PTCA and the insertion of coronary stents and pacemakers. This increase has been motivated by the many benefits of X-ray-guided cardiological procedures. These cardiological procedures, which would previously have required open-heart surgery, can be undertaken on an outpatient basis. The patient benefits from a reduction of the trauma associated with the procedure.

B124. The aspirations of interventionalists to perform more complex procedures have been matched by the desire of manufacturers to design and market systems that meet these perceived requirements [W1]. Initially, interventionalists used equipment intended for diagnostic studies such as barium studies or to use a mobile image intensifier system in a sterile theatre. However, manufacturers nowadays sell equipment with highly differentiated designs. Thus interventional equipment designed specifically for neuroradiology or cardiology has been developed. The design and operation are thus optimized for a narrow group of procedures. For example, the imaging requirements for embolization in interventional neuroradiology is different from the requirements for barium studies.

B125. The frequency of interventional cardiological procedures has been investigated by Faulkner and Werduch [F19]. On its website [H27] the British Heart Foundation publishes statistical information on the rates of coronary angiograms, PTCA and stents per million population for various European countries for the period 1990–2003. The data are incomplete, the most complete data being for PTCA procedures. It is possible to deduce the frequency of PTCA procedures in 2006 by separately performing a regression analysis on each country's data and then extrapolating to 2006 using the average annual rate of increase. For illustration purposes, the data for the Netherlands are shown in figure B-I. Also shown is the linear regression line fitted to these data. For each country the fitting of a regression line to the PTCA annual frequency data was reasonably good, the worst fit being for Greece with a *p*-value of 0.047 and an *R*-value of 0.76. The Finnish data fitted best to a regression analysis for data after 1999, when there appears to be a change in the rate of increase in the annual number of procedures. This general approach was used to analyse the coronary angiography and stent data for those countries where the data were available.

Figure B-I. Frequency of PTCA procedures in the Netherlands for the period 1990–2003
A regression line has been fitted to the data ($p < 0.001$; $R = 0.995$)



B126. For some countries, frequency data on the number of coronary angiograms and stents per million population were not available on the website. In order to estimate the number of coronary angiograms and stents, the ratio of the annual frequency of coronary angiograms to PTCAs and the ratio of the annual frequency of stents to PTCAs were calculated for each country using the data available. The average ratio of coronary angiograms to PTCAs was 3.6, and the average ratio of stents to PTCAs was 0.72. These ratios were used to estimate the number of coronary angiogram and stent procedures for cases where data were not available.

B127. There were limited data available for the number of pacemaker insertions performed for each country where data were available. The ratio of pacemaker insertions to PTCAs for the country in 2000 was used to deduce the number of pacemaker insertions in 2006 from the estimated number of PTCA procedures. If this ratio was not available for a given country, the average ratio across those countries where data were available was used.

B128. Table B32 gives the estimated number of procedures per million population and the total number of procedures in 2006 for various European countries. In the table, data estimated from the annual frequency of PTCAs using the ratio method are given in italics. Data on the population for European countries were obtained from the Central Intelligence Agency website [C26]. The total number of procedures for each country was deduced by multiplying the annual frequency (expressed as number per million population) by the size of the country's population (in millions). For Bulgaria and Ireland, limited data were available on the British Heart Foundation website, which gave only the number of PTCA procedures for years around 2000 and no data for other years. The average annual rate of increase across Europe was used to deduce the number of PTCA procedures in 2006. The ratio method was then used to deduce the estimated number of coronary angiograms per million population and of stents per million population for Bulgaria and Ireland.

B129. It may be deduced from table B32 that in the 29 European countries studied, the estimated average number of coronary angiogram is 5,045 (range 670–11,646) per million population (population-weighted average). The average number of PTCA procedures in Europe is 1,510 (range 186 to 3,704) per million population. The corresponding figures for stent procedures are 836 (range 134 to 2,667) per million and 926 (range 53–2,481) per million for pacemaker insertions. On average there are 3.6 coronary angiogram examinations for every stent procedure. This ratio varies between countries and will reflect the local practice regarding the classification of combined coronary angiogram and PTCA procedures and stent procedures. Data for recent years will be affected by the rate of introduction of drug-eluting stents, as these have an impact on the restenosis rate.

B130. López-Palop et al. [L18] have surveyed interventional cardiology practice in Spain in 2003. Data were acquired from 112 centres (104 adult, 8 paediatric), representing nearly all centres in Spain. Over 40,000 percutaneous coronary interventions were performed; an increase of 14.4% in a year; 92.5% of interventions involved the use of stents. The number of mitral valvuloplasty procedures increased by 23% in 2003 to 433.

B131. The annual frequency of screening mammography varies between countries. For example, the Canadian Cancer Society recommends that women aged 50 years to 69 years have a screening mammogram on a biennial basis [C25], whereas in the United Kingdom's National Health Service Breast Screening Programme, women aged 50 to 69 are offered mammography on a triennial basis [L27]. The number of screening mammography examinations performed in a specific country depends on the health-care level, the eligible population, and the screening interval and uptake.

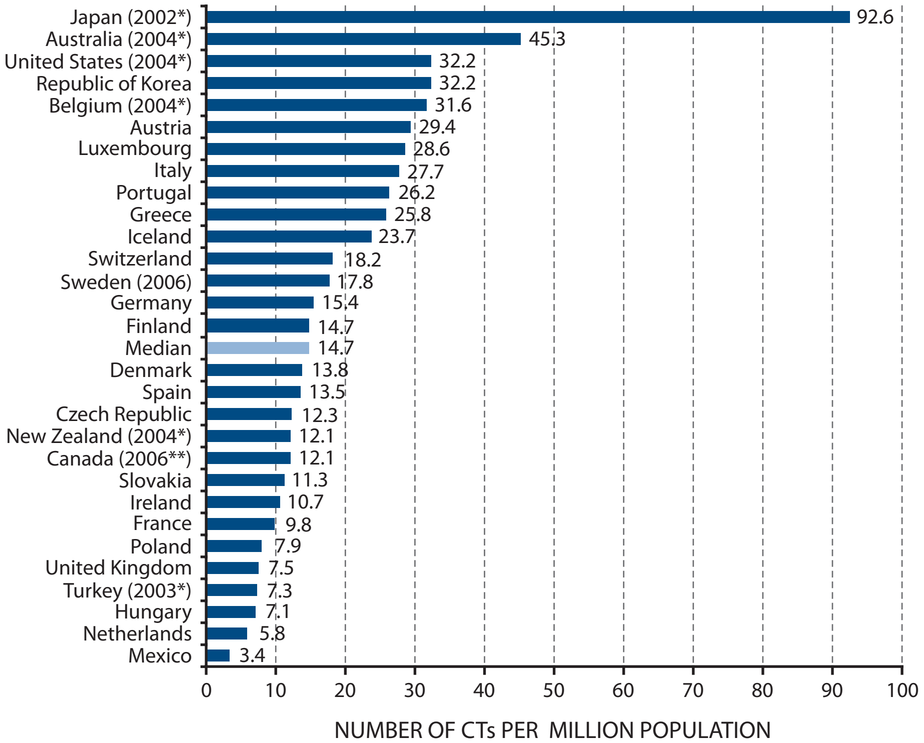
B132. CT scanners were introduced into clinical use in 1972 by EMI in the United Kingdom [H3]. The clinical benefits of these procedures were realized immediately. The use of computers in medical imaging has subsequently revolutionized radiology, with the introduction of digital radiography and the digitization of images produced by image intensifier television systems.

B133. In Canada, the number of CT scanners increased by 82% in the period 1990–2005 [C25]. There was a variation of almost a factor of 4 in the number of CT scanners per million population in different states, yet the variation in the number of angiography suites per million population was less than a factor of 3, and the variation in the number of catheterization laboratories per caput was only a factor of 2. Typically there were 2.1 CT scanners for every MRI machine.

B134. The Organisation for Economic Co-operation and Development (OECD) has reported wider variations in the number of items of medical imaging equipment. Figure B-II summarizes the number of CT scanners per million population. Japan has the largest number of CT scanners per population, approximately 60 times more than Mexico. The median number of CT scanners in the countries studied in the OECD survey [C25] was 14 per million population. However, the data may not be representative of the number of CT scanners in Germany.

Figure B-II. Number of CT scanners per million population in OECD countries [C25]

Sources: OECD Health Data 2007, OECD, for all countries except Sweden and Canada; Belgian Health Care Knowledge Centre, *HTA of Diagnostic Resonance Imaging*, KCE report vol. 37C, 2006, for Sweden; National Survey of Selected Medical Imaging Equipment, Canadian Institute for Health Information, for Canada. Reproduced with permission from the Canadian Institute for Health Information



*Latest year for which data are available.

**As of January 1, 2006.

B135. Temporal changes in the number of CT scanners for three European countries and Canada over the period 1990–2005 are summarized in figure B-III. The largest increase occurred in Italy, where the number of CT scanners increased by a factor of over 3. There was a 68% increase in the number of CT scanners between 1998 and 2002 [C25]. In the period 1991–2005 the number of CT scanners in Canada increased from 200 to 361 [C25].

B136. Mettler et al. [M37] investigated CT practice in the United States. The authors concluded that in the period 1993–2006 the annual growth in the number of CT procedures was over 10% (figure B-IV). The rate of increase has been steeper since 1998 (just under 17%), which is probably associated with the introduction of helical and multislice CT scanning.

Figure B-III. Number of CT scanners per million population in selected G8 countries for which time series were available, 1990–2005 [C25]

Sources: OECD Health Data 2007; National Survey of Selected Medical Imaging Equipment (2003, 2004 and 2005). Reproduced with permission from the Canadian Institute for Health Information

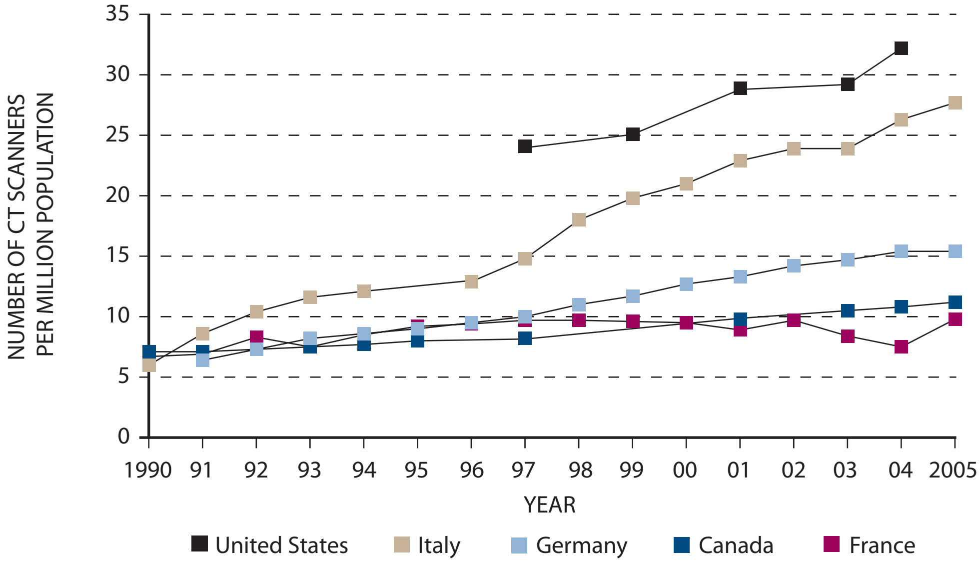
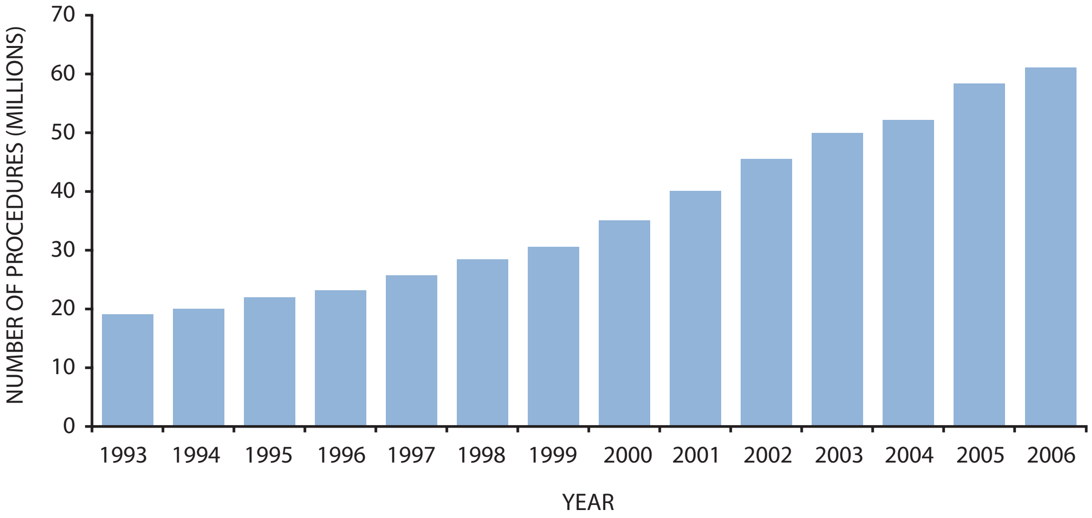


Figure B-IV. Number of CT procedures annually in the United States [M37]



B137. With the advent of helical and multislice scanning together with the associated use of slip ring technology, CT has undergone a renaissance. The shortening of scan times, coupled with the rapid reconstruction of CT images made possible by modern computer processing power, has resulted in an increased demand for CT scanners. Given the relatively high doses associated with these machines, it is likely that CT examinations will make the largest contribution to population dose from man-made exposures in many countries.

B138. The development of multimodality CT scanners will inevitably lead to an increase in the number and annual frequency of CT scans. These machines allow the acquisition of nuclear medicine scans and CT scans using the same machine. They are described in greater detail in appendix C on nuclear medicine.

B. Trends in patient doses

B139. International organizations, regulatory bodies and standards organizations have promoted dose reduction for medical exposures [L8]. Equipment manufacturers have responded to this with a series of technological developments and advances to reduce patient doses. Thus doses for a single examination have tended to decrease because of continuing improvements in equipment design and performance. Doses for diagnostic examinations can be reduced by giving careful consideration to the use of X-ray equipment, its design and how the procedure is performed. Methods of dose reduction in diagnostic radiology have been reviewed elsewhere [F2].

B140. Film–screen systems are used in conjunction with manual film processing in many centres worldwide, whereas in centres of health-care level I countries, automatic processing is almost invariably used. The number of repeat films made necessary because of problems with manual processing may be as high as 50%, whereas for automatic processors this can drop to 6% [R3].

B141. Image intensifiers have replaced direct fluoroscopy systems, because the former have enabled the examinations to be performed in low ambient light rather than under conditions of dark adaptation. In addition, patient and staff doses with the non-intensified equipment were unacceptably high.

B142. Increasing the gain of an image intensifier insert means that less radiation is required to be incident upon the input surface of the insert to produce the same light output. High-gain systems can reduce patient doses [B2]. Inappropriately adjusted control systems may result in unnecessarily high patient doses. Checking image intensifier input dose rates under automatic control usually forms part of a quality assurance programme. Automatic systems can compensate for a loss in image intensifier gain without the operator being aware of the problem. This has led to one overexposure incident in the United Kingdom [G1]. A significant proportion of the population dose from the overexposure arose from the use of automatic control systems with image intensifiers that suffered a rapid loss in gain.

B143. Manufacturers are developing new detectors with higher detective quantum efficiency (DQE) [D2]. The introduction of detectors based on amorphous selenium could reduce patient doses. These detectors have higher DQEs than conventional film–screen combinations or computed radiography systems and require a lower dose to form an image containing an equivalent level of noise.

B144. The detection efficiency of amorphous selenium depends on the thickness of the material and the X-ray energy. The DQE of amorphous selenium is approximately twice that of the thallium-doped caesium iodide typically used in image intensifiers [Y1]. Terbium-activated gadolinium oxysulphate, used as a fluorescent screen for radiographic imaging, has a DQE comparable to that of amorphous selenium [Y1].

B145. In the United Kingdom, the Royal College of Radiologists published a handbook on referral criteria designed to fit in the coat pocket of junior doctors and consultants [R1]. The European Commission has adopted an amended version of this document [E3]. The original handbook has also been subsequently revised and replaced [R26]. These publications are based upon research evidence and a consensus approach. They provide advice to the referring physician when a particular radiological examination is recommended for the assessment of a specific clinical condition; their use is intended to avoid inappropriate or unnecessary radiation exposure.

C. Survey results

B146. Table B33 is a summary of the world population distribution according to the four health-care levels as used in previous UNSCEAR assessments of medical exposures. Countries were allocated to a health-care level according to the number of physicians per caput. Data on the population of each country and the number of physicians per caput were obtained from the WHO website [W2].

B147. Table B34 is a summary of the number of physicians and health-care professionals recorded in the UNSCEAR survey. The data have been stratified according to the four health-care levels described above. Data on the number of radiology technicians, medical physicists and other physicians performing radiology have been solicited in this survey.

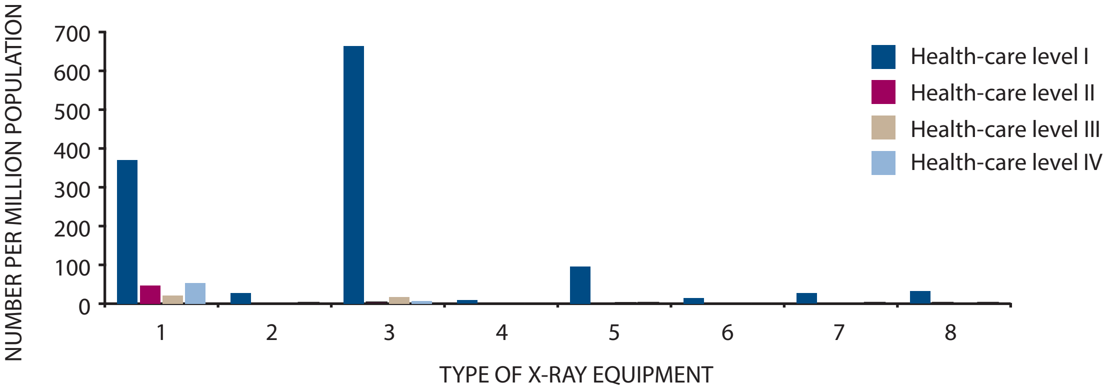
B148. The numbers of physicians and other health-care professionals per million population are summarized in table B35. The weighted average is obtained from the number of physicians in a country weighted according to its population. For health-care level I countries the weighted average number of physicians per million population was 3,530, which represents an increase of just over 600 per million population, or of just under 20%, since the previous survey [U3]. For health-care level II countries the number of physicians per caput has nearly doubled since the previous survey.

There is some uncertainty in the data presented in this table as there are no internationally agreed definitions for some of the professions. The number of physicians per caput in Zimbabwe has decreased over the period of this report; Zimbabwe's inclusion in the health-care level III category may need to be reviewed in the future.

B149. Information on the number of items of diagnostic radiology equipment in each country has been obtained as part of the UNSCEAR survey of practice. Data on digital imaging systems were also requested in this survey. Table B36 summarizes the data returns for various types of conventional diagnostic X-ray generators, bone mineral densitometers and CT scanners, with table B37 summarizing the data received on digital diagnostic equipment.

B150. The data given in tables B36 and B37 have been analysed according to the number of items of equipment, normalized to the size of the population of each country supplying data. This analysis is presented in tables B38 for conventional generators, bone mineral densitometers and CT scanners, and in table B39 for digital equipment. Figure B-V summarizes the number of items of radiological equipment per million population across the four health-care levels.

Figure B-V. Numbers of items of radiological equipment per million population across the four health-care levels
1: general; 2: mammography; 3: dental; 4: interventional; 5: general fluoroscopy; 6: angiography, 7: bone densitometry, 8: CT



B151. For health-care level I countries the number of conventional medical X-ray generators has increased to 370 per million population from 293 per million population in the previous survey [U3]. The number of digital mammography units constitutes just over 25% of the total, whereas for conventional X-ray generators the proportion of digital units is considerably lower for health-care level I countries. The number of CT scanners has nearly doubled to 32 scanners per million population in health-care level I countries.

B152. Trend analysis for health-care level II countries is less robust, owing to the limited number of survey returns. However, it is apparent from the survey that there has been an increase of nearly a factor of 2 in the number of mammography units per caput. Similarly, the number of CT scanners per caput has increased by a third since the previous UNSCEAR survey of practice [U3].

B153. Table B40 contains an analysis of the temporal trends in the average provision for medical radiology.

B154. Temporal trends in the number of conventional X-ray generators, dental X-ray units and CT scanners over the period covered by the various UNSCEAR surveys are summarized in figures B-VI, B-VII and B-VIII, respectively. The estimated number of conventional X-ray generators in health-care level I countries decreased until 1991–1996 and then increased again with this survey.

Figure B-VI. Temporal trends in the provision of conventional X-ray generators

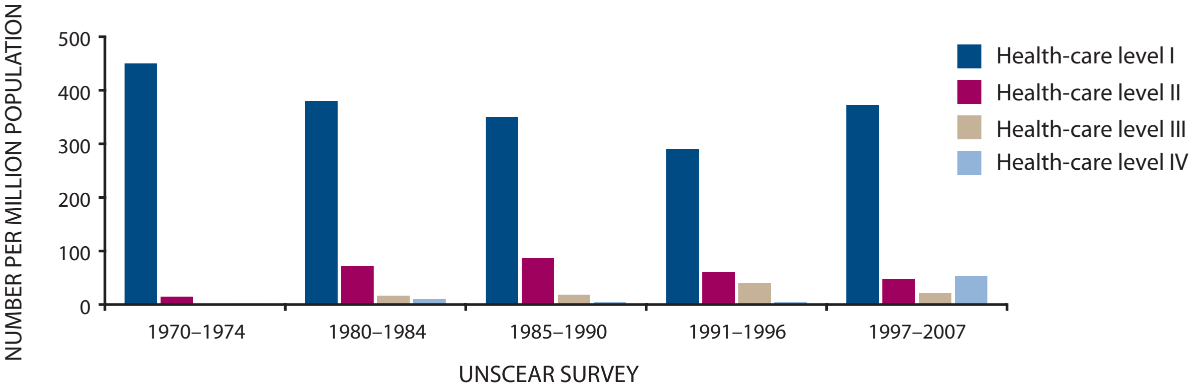


Figure B-VII. Temporal trends in the provision of dental X-ray generators

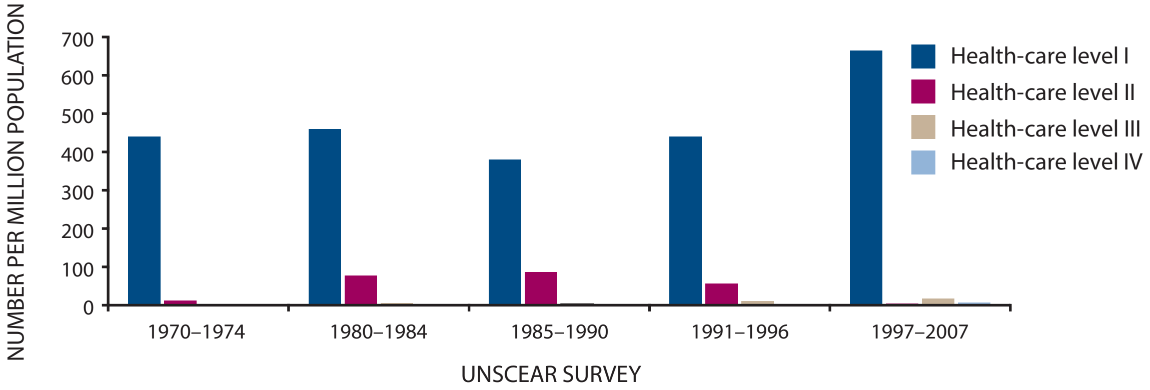
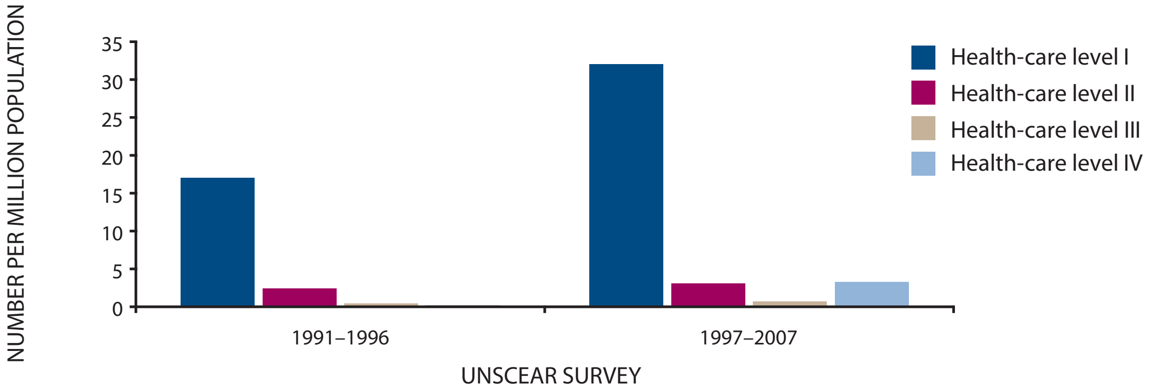


Figure B-VIII. Temporal trends in the provision of CT scanners



B155. The UNSCEAR survey also requested information on the annual number of medical radiological examinations. These data are summarized in tables B41(a–d).

B156. The total number of diagnostic medical and dental examinations performed in various countries obtained from the UNSCEAR survey is summarized in table B42. The survey data in tables B41(a–d) have been analysed according to the number of medical and dental radiological examinations per thousand population performed annually, and this information is presented in tables B43(a–d). The weighted average has been obtained from the number of examinations per caput, weighted according to the size of the country's population. In general, for health-care level II countries the number of examinations has increased for virtually all examination types. There is a large imbalance in the number of procedures per caput across the four health-care levels.

B157. Table B44 is a summary of the total annual number of diagnostic medical and dental examinations performed per thousand population obtained from the UNSCEAR survey. The weighted average total number of diagnostic examinations is approximately 1,180 per thousand population and approximately 350 dental radiological examinations per thousand population, equating to about 1,530 medical and dental examinations per 1,000 population in total in health-care level I countries. For health-care level II countries there were on average just over 410 medical and 15 dental examinations per 1,000 population. The total number of medical and dental examinations was just under 430 per thousand population for health-care level II countries.

B158. Tables B45(a–d) summarize the mean patient dose and variation on the mean for all diagnostic medical and dental radiological examinations included in the UNSCEAR survey. Data in italics are for ESAK. Data in bold are for DAP, whereas CTDI values are underlined. In mammography, mean glandular dose has been used as the dosimetric quantity.

B159. Mean effective doses and variation on the mean value are summarized in tables B46(a–d). Weighted average effective dose has been estimated using the effective dose values given in the UNSCEAR survey of practice for each country, weighted according to population size of that country. Data were available only for level I and level IV countries. The values of effective doses per examination were comparable in these two health-care levels. Mean effective doses for various examinations are given in figures B-IX, B-X and B-XI.

Figure B-IX. Mean effective doses for various interventional procedures in health-care level I countries

1: PTCA cardiac; 2: cerebral; 3: vascular; 4: other; 5: non-cardiac angiography; 6: cardiac angiography

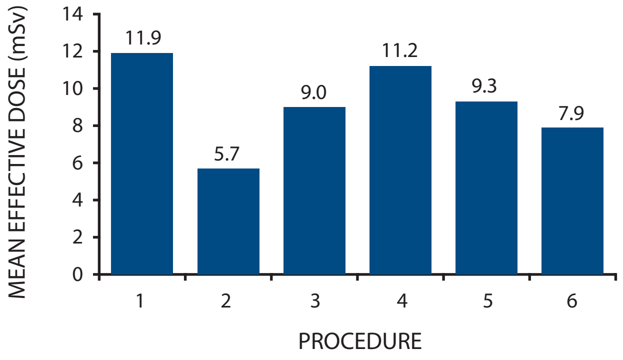


Figure B-X. Mean effective doses for various CT examinations in health-care level I countries

1: head; 2: thorax; 3: abdomen; 4: spine; 5: pelvis; 6: other

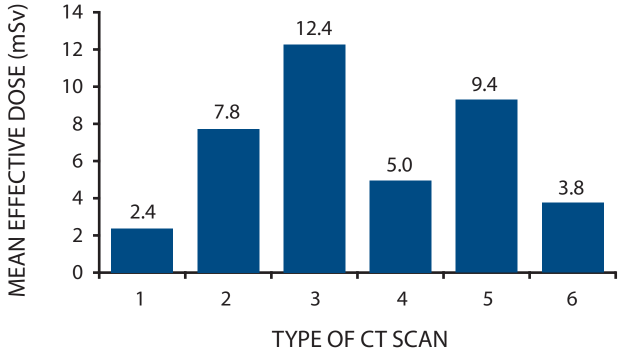
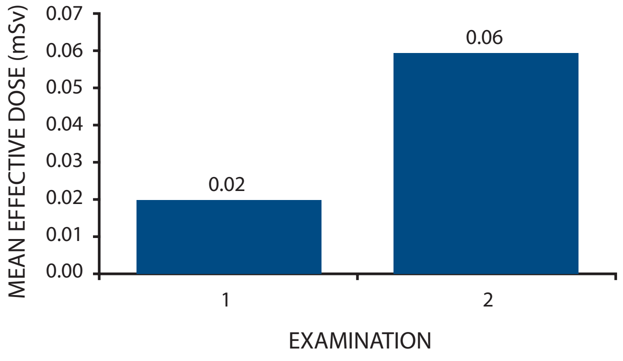


Figure B-XI. Mean effective doses for various dental examinations in health-care level I countries

1: intraoral; 2: panoral tomography



B160. Table B47 is a summary of the distribution by age and sex of patients undergoing medical and dental radiological examinations. The weighted average has been calculated. Most medical examinations are performed on individuals aged over 40 years. There is a fairly even split between medical examinations performed on men and on women; the exceptions are mammography, which is mainly performed on women, and pelvimetry, which is performed only on women, usually aged between 15 and 40 years.

B161. In dental radiology, most examinations are performed on individuals aged between 16 and 40 years. There is an almost equal split of examinations between the two sexes. In general the age and sex distribution of individuals undergoing medical and dental exposures is comparable to that of the previous survey [U3].

B162. The annual collective dose due to diagnostic radiology was estimated by multiplying the number of examinations per thousand population for a health-care level country by the effective dose for that examination and the total population of that country obtained using the health-care model summarized in table B33. Using the data in table B48, the average effective per caput dose from medical exposures was 1.91, 0.32 and 0.03 mSv for health-care levels I, II and III–IV, respectively.

B163. For dental examinations, the total collective dose to the population was estimated as 9,900 man Sv for health-care level I countries, 1,300 man Sv for health-care level II countries and 89 man Sv for health-care level III–IV countries. The total collective dose to the world population from dental exposures estimated on the basis of the survey returns and using the UNSCEAR health-care model is 11,000 man Sv.

B164. The total collective dose from all medical and dental exposures is estimated as 2,900,000 man Sv for health-care level I countries, 1,000,000 man Sv for health-care level II countries and 57,000 man Sv for health-care level III–IV countries. The contribution made by dental exposures to the total is approximately 0.25% for health-care level I countries, 0.03% for level II countries and 0.002% for countries of level III–IV.

B165. The total collective dose to the global population from medical exposures is estimated to be 4,000,000 man Sv and from dental exposures 11,000 man Sv. About 73% of the collective dose to the global population due to medical and dental radiological examinations is received by individuals living in health-care level I countries. The populations of level II receive about 25%, while the populations of level III–IV countries receive only about 1%. This essentially reflects the variation in the frequency of medical and dental radiological examinations between health-care levels.

B166. Vanmarcke et al. [V1] have estimated the collective dose to the population of Belgium in 2001. In this study they used the same approach as was used in the previous UNSCEAR report [U3] and which has been employed here. The estimated annual per caput dose from diagnostic radiological examinations was 1.8 mSv, with 0.2 mSv from nuclear medicine. Approximately half of the dose (0.9 mSv) arose from CT examinations.

B167. The estimated annual per caput dose to the Belgian population was higher than the average effective per caput dose estimated here for medical and dental procedures in level I countries [V1]. This is consistent with Belgium having a higher annual frequency of medical examinations per caput than the average for level I countries (i.e. 1,255 per 1,000 population annually).

B168. Scanff et al. [S44] have investigated the dose to the French population from diagnostic medical procedures. Data on the frequency of examinations in 2002 were obtained. The estimated annual number of medical examinations was in the range 672–1,001 per 1,000 population, slightly lower than the average for level I countries estimated here. The estimated annual per caput effective dose was in the range 0.66–0.83 mSv, with CT examinations contributing 39% of the collective dose. The per caput effective dose is less than that estimated here. This is consistent with CT examinations making a smaller contribution to the population dose than in other level I countries in this study.

B169. In the United Kingdom, the Health Protection Agency has estimated the dose to the United Kingdom population from medical exposures [H33]. Hart and Wall estimated that there were 700 medical examinations per 1,000 population annually, giving rise to an annual per caput dose of 0.33 mSv, considerably lower than those for France, Belgium and other level I countries estimated in this annex [H33, S44, V1]. The lower per caput dose was attributed to the lower doses per examination and fewer examinations per person in the United Kingdom [H33].

B170. The National Council on Radiation Protection and Measurements (NCRP) [N26] has estimated the dose to the population of the United States due to diagnostic radiology and nuclear medicine (table B49). The annual collective effective dose to the population of the United States was estimated to be 900,000 man Sv, with an annual per caput effective dose of 3 mSv, somewhat higher than that estimated for health-care level I countries here.

B171. Table B50 summarizes the contribution made by the various types of radiological examination to the total number of procedures, stratified according to the UNSCEAR health-care level model. Just over 87% of radiological examinations worldwide are diagnostic, with 13% being dental. Worldwide, CT scanning accounts for just under 6% of all examinations.The percentage contribution to the collective dose for various types of medical and dental examination is summarized in table B51. It may be deduced from table B51 that just under 43% of the total dose to the world population arises from CT scanning.

B172. Temporal trends in the annual frequency of diagnostic medical radiological examinations are summarized in table B52. For health-care level I countries the number of diagnostic medical radiological examinations has increased from 820 to 1,332 per 1,000 population over the period covered by the UNSCEAR surveys, mainly because of the steep increase noted in the current survey. Over the same period, the increase in the annual frequency of diagnostic radiological examinations in health-care level II countries has increased by a factor of over 12. For health-care level III and IV countries the number of diagnostic radiological examinations per caput has remained approximately constant.

B173. Table B53 summarizes the temporal trends in the annual frequency of diagnostic dental radiological examinations since the first UNSCEAR survey in 1970–1979, though the approach to estimating the annual frequency has changed over this period. The annual frequency of diagnostic dental examinations has remained fairly constant in health-care level I countries, while in level II countries it has increased by a factor of 20. The annual frequency of diagnostic dental procedures in health-care level III and IV countries has also dramatically increased.

B174. Table B54 illustrates the temporal trends in the average effective dose for some diagnostic medical radiological examinations in health-care level I countries over the period covered by the various UNSCEAR surveys of medical practice. In general, average effective doses for radiography examinations have decreased in this period (e.g. chest and head).

B175. Effective doses for upper and lower GI examinations that involve the use of fluoroscopy were constant for the first two surveys. Then there was a major decrease to less than half for the third survey period, and those lower doses have been maintained for the present survey. This could reflect the introduction of digital fluoroscopy systems for barium studies and/or the impact of optimization studies in the period 1991–1996.

B176. In the first survey period, the only CT scans were examinations of the head. In the next survey, body scanning was introduced. The change in practice impacts on the average effective doses because the dose for a head CT examination is less than that for a typical body scan.

B177. The estimated dose to the world's population from diagnostic medical and dental radiological examinations in the period 1997–2007, stratified according to the UNSCEAR health-care level model, is given in table B55. The total annual collective dose due to all diagnostic medical radiological examinations estimated using the approach of previous UNSCEAR reports was 4,000,000 man Sv, and 11,000 man Sv due to diagnostic dental examinations. The total annual collective effective dose due to all diagnostic radiology was 4,011,000 man Sv.

B178. Figure B-XII illustrates the variation in per caput effective dose for diagnostic medical exposures with health-care level. The per caput effective dose to individuals living in health-care level I countries is approximately six times that received by individuals in health-care level II countries. By comparison, the per caput effective dose for individuals living in health-care level III and IV countries is less than one-tenth of that in health-care level II countries.

Figure B-XII. Variation in per caput effective dose for diagnostic medical radiological exposures with health-care level

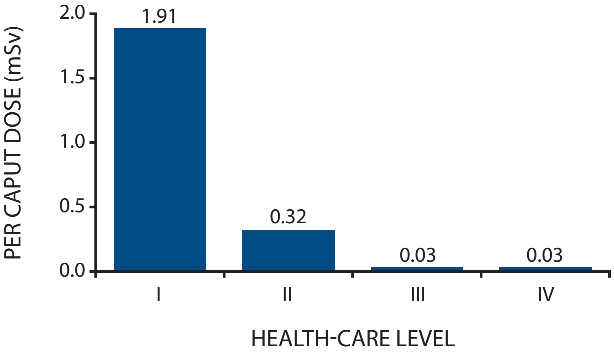
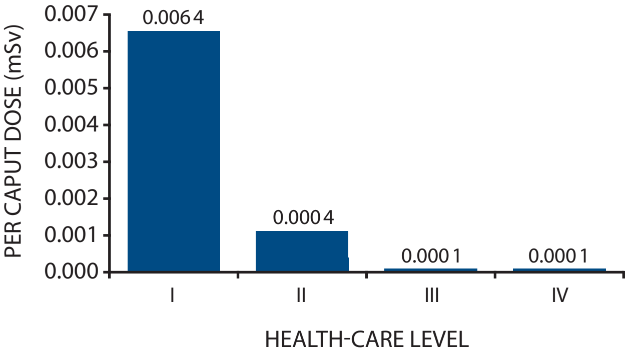


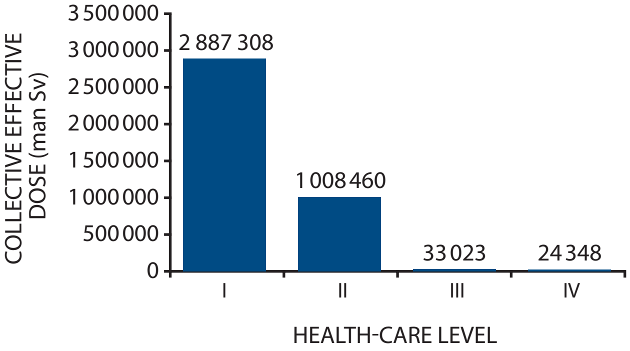
Figure B-XIII illustrates the variation in per caput effective dose with health-care level for diagnostic dental radiological examinations.

Figure B-XIII. Variation in per caput effective dose for diagnostic dental radiological exposures with health-care level



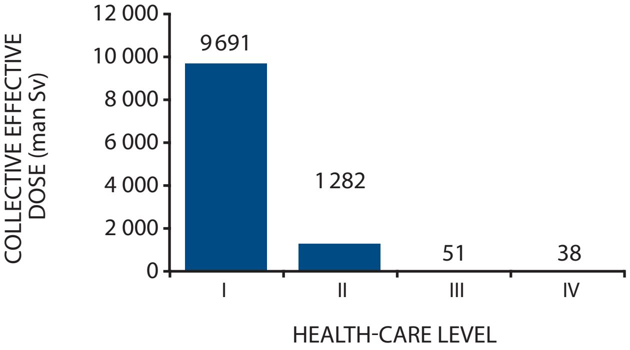
B179. The variation in collective effective dose due to diagnostic medical radiological examinations is given in figure B-XIV. Most of the collective effective dose is received by individuals living in health-care level I countries, where this value is more than twice that for health-care level II countries.

Figure B-XIV. Variation in collective effective dose from diagnostic medical radiological examinations



B180. Figure B-XV illustrates the variation in collective effective dose due to diagnostic dental radiological examinations. Once again the majority of the collective effective dose is received by individuals living in health-care level I countries.

Figure B-XV. Variation in collective effective dose from diagnostic dental radiological examinations



B181. As with previous estimates of the annual collective effective dose to the world's population from diagnostic medical examinations, there are considerable uncertainties in this estimate. This uncertainty arises in part from data limitations in the survey returns at all health-care levels, but particularly for health-care levels II, III and IV. Survey returns submitted by countries in health-care level I represented just under half of the total population in this category. This represents a reasonable level of response. For health-care levels II, III and IV, the survey returns submitted represented only about 1% of the total population in each category. As a consequence there are major uncertainties in the estimates for the annual frequency of each radiological examination, particularly for health-care levels II, III and IV. This is compounded by uncertainties in population estimates and in the effective dose received for specific radiological examinations. Thus the value for the annual collective effective dose given here should be regarded as a reasonable estimate, but one on which there is some considerable uncertainty.

V. SUMMARY

B182. A survey of practice in medical and dental radiology has been undertaken. Responses from various countries have been received. These data have been supplemented by information on medical and dental radiological examinations obtained from a review of the published literature.

B183. A global model, as used in earlier UNSCEAR reports, has been used. In this model, countries are stratified into four health-care levels, depending on the number of physicians per 1,000 members of the population. As with previous UNSCEAR surveys of global exposure, there are considerable uncertainties on the results estimated using this global model.

B184. The uncertainty arises from a number of sources, but primarily in extrapolating from the limited survey data obtained. In addition, patient dose surveys sample the patient dose distribution, which can have a wide range (i.e. the doses received by some individuals may be 100 to 1,000 times those received by others). In addition, the small sample size in the UNSCEAR survey could mean that the annual frequency data are distorted. There is also an uncertainty on the population estimates for the global population, although this uncertainty is much smaller than the others.

B185. According to this global model, the annual frequency of diagnostic medical examinations in health-care level I countries has increased from 820 per 1,000 population in 1970–1979 to 1,332 per 1,000 in this survey. Comparative values for health-care level II countries exhibit an even greater increase, from 26 per 1,000 population in 1970–1979 to 332 per 1,000 in 1997–2007. Between the periods 1970–1979 and 1997–2007, level III and IV countries have shown a slight decrease in the annual frequency of diagnostic medical examinations: from 23 per 1,000 population to 20 per 1,000 population for level III countries and from 27 per 1,000 population to 20 per 1,000 population for level IV countries.

B186. Temporal trends in the annual frequency of diagnostic dental examinations have been obtained. For health-care level I countries, the annual frequency has slightly decreased, from 320 per 1,000 population to 275 per 1,000 between the periods 1970–1979 and 1997–2007, whereas for the countries of other health-care levels, the number of diagnostic dental radiological examinations has increased.

B187. In the period covered by this UNSCEAR report, the estimated annual collective effective dose to the world population due to diagnostic medical and dental radiological examinations is estimated to be 4,000,000 man Sv. This represents an increase in collective dose of approximately 1,700,000 man Sv, or of just over 70% from the previous evaluation. This increase in collective dose has occurred because of two main factors. Firstly, the per caput effective dose has increased from 0.4 mSv to 0.62 mSv, mainly as a result of the increased annual frequency of CT scanning. Secondly, the world population itself has increased.

Table B1. Global use of medical radiology (1991–1996) [U3]

Estimates derived from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

PART A: NORMALIZED VALUES

Quantity		*Number per million population[a] 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

Quantity		Number per million population[a] at health-care level				
		I	II	III	IV	Globally
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

[a] Extrapolated, with rounding, from limited samples of data.
[b] Based on following population sample sizes for global model: 67% for level I, 50% for level II, 9% for levels III and IV, and 46% overall.
[c] Based on following population sample sizes for global model: 39% for level I, 49% for level II, 4% for levels III and IV, and 37% overall.
[d] 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] 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] 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] 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.

PART B: ABSOLUTE NUMBERS

Quantity		Total number (millions) at health-care level[a]				
		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	0.000 1	0.4
X-ray imaging						
Equipment	Medical	0.45	0.2	0.02	0.002	0.7
	Dental	0.67	0.2	0.01	<0.000 1	0.9
	Mammography	0.04	0.001	0.000 1	0.000 1	0.04
	CT	0.027	0.007	0.000 3	0.000 1	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	0.000 1	0.000 02	0.012
	Rectilinear scanners	0.001	0.001	0.000 1	0.000 01	0.002
	PET scanners	0.000 3	0.000 01	0	0	0.000 31
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	0.000 2	0.4
Teletherapy						
Equipment	X-ray	0.004	0.001	0.000 02	0.000 01	0.005
	Radionuclide	0.002	0.002	0.000 1	0.000 04	0.004
	Linac	0.005	0.001	0.000 04	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	0.000 1	0.000 04	0.004
Annual number of patients[g]		0.3	0.05	0.01	(0.01)[h]	0.4

Quantity	*Total number (millions) at health-care level*[a]				
	I	*II*	*III*	*IV*	*Globally*
Population					
Total population	1 530	3 070	640	565	5 800

[a] Extrapolated, with rounding, from limited samples of data.
[b] Based on following population sample sizes for global model: 67% for level I, 50% for level II, 9% for levels III and IV, and 46% overall.
[c] Based on following population sample sizes for global model: 39% for level I, 49% for level II, 4% for levels III and IV, and 37% overall.
[d] 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] 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] 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] 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 B2. Estimated doses to the world population from diagnostic medical and dental radiological examinations[a] (1991–1996) [U3]

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	<0.000 1	14 000	13
IV	565	0.02	<0.000 1	13 000	11
World	5 800	0.4	0.002	2 330 000	14 000

[a] As was discussed in appendix A, because many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly among the population, these dose estimates should not be used for the assessment of detriment.

Table B3. Contributions to frequency and to collective dose from the various types of diagnostic medical (excluding dental) radiological examination assumed for global model (1991–1996) [U3]

Examination	*Contribution (%)*			
	Level I	*Level II*	*Levels III and 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

Examination	*Contribution (%)*			
	Level I	*Level II*	*Levels III and IV*	*World*
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 B4. Summary of patient dose data for diagnostic medical radiological examinations

Examination	*ESD (mGy)*	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Skull and facial bones					
Nasal bones			0.01		[H33]
Facial bones	1		0.01	3	[H33]
Mastoids			0.06		[H33]
Skull (PA + LAT + 0.75AP)	1.4–2.5		0.06	2 580	[G2, H33]
Skull PA	2.7		0.027		[Z6]
Skull LAT	2.1		0.021		[Z6]
Skull			0.027		[C28]
Skull			0.1		[M41]
Skull (CR)			0.029		[C28]
Skull (DDR)			0.022		[C28]
Cephalometry			0.01	40 000	[N23, S43]
Mandible	1.35		0.014	2	[H33]
TMJ			0.012		[H33]
Sinuses and antra	2.2		0.022	50	[H33]

Examination	*ESD (mGy)*	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Head, soft tissue					
Dacryocystography		1.8	0.05	1	[H33]
Pharyngography			0.06		[H33]
Post-nasal space	0.2		0.002	20	[H33]
Salivary glands			0.056		[H33]
Sialography		2	0.056	24	[H33]
Eyes	2.5		0.025		[H33]
Head	1.94		0.019		[V8]
Teeth					
Intraoral			0.005		[L5, N23]
Intraoral			0.005		[M41]
Panoramic			0.01		[N23]
Panoramic			0.01		[M41]
Cerebral angiography					
Carotid/cerebral		48.5	4	90	[M2]
Carotid/cerebral		28	0.78	55	[H33]
Carotid/cerebral		42		57	[K30]
Myelography					
Myelography		12.3	2.46	68	[H33]
Discography			1.3	75	[M34]
Lumbar radiculography			3.5	106	[M34]
Neck, soft tissue					
Soft tissues of neck		0.1	0.003	1	[H33]
Larynx			0.07		[H33]
Laryngography			0.07		[H33]
Cervical spine					
Cervical spine	0.3, 1.7		0.07	83	[H33]
Cervical spine		0.49	0.064	104	[H33]
Cervical spine			0.2		[M41]
Thoracic spine					
Thoracic spine			0.7		[W7]
Thoracic spine	3.9, 10.8		0.64	1 277	[H33]
Thoracic spine		4.2	0.8	38	[H33]
Thoracic spine			1.0		[M41]
Thoracic spine AP	6.5		0.6		[Z6]
Thoracic spine LAT	15		0.39		[Z6]
Lumbar spine					
Lumbar spine AP, LAT	6, 14.5		1	9 892	[H33]
Lumbar spine		5.7	1.2	592	[H33]
Lumbar spine			1.5		[M41]
Lumbar spine AP	10		1.1		[Z6]
Lumbar spine LAT	26		0.65		[Z6]
Lumbar spine AP/PA	4.08		0.44		[V8]
Lumbar spine LAT	17.5		0.44		[V8]
Lumbar spine AP + LAT			0.309		[C28]
Lumbar spine AP + LAT (CR)			0.476		[C28]
Lumbar spine AP + LAT (DDR)			0.179		[C28]

Examination	*ESD (mGy)*	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Lumbosacral joint					
Lumbosacral joint			0.3		[W7]
Lumbosacral joint	28.1		0.34	2 210	[H33]
Lumbosacral joint		2.2			[N2]
Sacroilliac			0.17		[H33]
Sacroilliac	5.4		0.06	1	[H33]
Sacrum and coccyx	13.9		0.17	6	[H33]
Whole spine/scoliosis					
Whole spine/scoliosis			0.1		[H33]
Whole spine/scoliosis	0.53, 0.63		0.07	78	[H33]
Whole spine/scoliosis			0.12	7	[H12]
Whole spine/scoliosis			0.14	61	[C29]
Whole spine/scoliosis	0.08			283	[P21]
Shoulder girdle					
Shoulder		0.3	0.011	21	[H33]
Shoulder			0.01		[M41]
Shoulder AP	0.19		0.001	3	[H33]
Shoulder AP/LAT	0.31, 0.98		0.009	4	[H37]
Acrominoclavicular joints			0.01		[H33]
Clavicle/collar bone			0.01		[H33]
Scapula			0.01		[H33]
Sternoclavicular joint			0.01		[H33]
Sternum			0.01		[H33]
Upper arm					
Upper arm	0.15		0.000 8	4	[H37]
Elbow					
Elbow		0.1	0.001	53	[H33]
Forearm, wrist and hand					
Fingers			0.000 5		[H33]
Hand	0.1		0.000 5	6	[H33]
Hand		0.4	0.000 4	1	[H33]
Radius and ulna/forearm			0.001		[H33]
Extremities			0.001		[M41]
Thumb			0.000 5		[H33]
Wrist/scaphoid	0.1		0.000 5	197	[H33]
Pelvis					
Pelvis			0.7		[W7]
Pelvis	4.2		0.67	4 281	[H37]
Pelvis		2.6	0.75	285	[H33]
Pelvis			0.6		[M41]
Pelvis AP		2.2	0.64		[N2]
Pelvis/hip	2.18		0.35		[V8]
Pelvis AP	1.81		0.295		[C28]
Pelvis AP (CR)	1.83		0.326		[C28]
Pelvis AP (DDR)	1.02		0.168		[C28]

Examination	*ESD (mGy)*	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Hip					
Hip			0.35		[H33]
Hip	2.7, 3.7		0.18	189	[H33]
Hip		3.1	0.54	10	[H33]
Hip	3.8		0.27	14	[H37]
Hip	7.2		0.43		[Z6]
Hip			0.7		[M41]
Orthopaedic pinning		2.6	0.7	55	[C30]
Femur					
Femur	0.5		0.002 5	18	[H37]
Femur	0.13, 0.14		0.001 4	5	[H33]
Leg length					
Leg length			0.184	13	[R24]
Knee, lower leg, ankle, foot					
Ankle	0.42		0.002	103	[H33]
Ankle		0.1	0.001	12	[H33]
Foot		0.06	0.000 6	116	[H33]
Foot	0.1		0.000 5	1	[H33]
Knee	0.49		0.002 5	404	[H33]
Knee		0.15	0.001 5	52	[H33]
Knee			0.005		[M41]
Calcanaeum/heel		0.09	0.000 9	5	[H33]
Patella			0.002 5		[H33]
Tibia and fibula			0.002		[H33]
Tibia and fibula	0.1		0.000 5	33	[H33]
Toes			0.000 6		[H33]
Skeletal survey					
Skeletal survey		18	1.8	2	[H33]
Chest					
Chest/ribs			0.02		[W7]
Chest/ribs	0.16		0.016	10 361	[H33]
Chest PA	0.5		0.05		[Z6]
Chest PA			0.02		[M41]
Chest PA	0.17		0.017	61 988	[V8]
Chest LAT	0.94		0.094	61 988	[V8]
Chest PA + LAT			0.29		[C28]
Chest PA + LAT			0.1		[M41]
Chest PA + LAT (CR)			0.041		[C28]
Chest PA + LAT (DDR)			0.23		[C28]
Thoracic inlet			0.02		[H33]
Bronchography		1.74	0.21	1	[H33]
Mammography					
Craniocaudal	1.77				[O3]
Lateral	1.88				[O3]
Craniocaudal	1.54				[J5]
Lateral	1.82				[J5]
	1.5				[T6]
	1.5				[D6]

Examination	*ESD (mGy)*	*DAP (Gy cm²)*	*Effective dose (mSv)*	*Patients*	*Reference*
	1.51				[H22]
Craniocaudal	2				[Y2]
Lateral	2.5				[Y2]
	1.5				[F10]
Craniocaudal	1.27–1.37				[G15]
Lateral	1.37–1.49				[G15]
Craniocaudal	1.8				[M11]
Lateral	1.95				[M11]
Symptomatic			0.37		[Y12]
Symptomatic			0.33		[B15, P21]
Symptomatic			0.4		[M41]
Screening (two views)	3.7		0.37	3 035	[Y12]
Screening (two views)	3.3		0.33	4 633	[B15]
Assessment			0.23	50 000	[N23]
Abdomen					
Abdomen			0.7		[W7]
Abdomen	5.4		0.76	5 500	[H33]
Abdomen		3.1	0.81	224	
Abdomen AP	7.5		1.05		[Z6]
Abdomen	2.65		0.37	22 374	[V8]
Abdomen			0.7		[M41]
Abdomen AP	1.88		0.28		[C28]
Abdomen AP (CR)	2.4		0.358		[C28]
Abdomen AP (DDR)	1.64		0.223		[C28]
Kidney and ureter					
Kidneys exposed			2.5		[H33]
Antegrade pyelography		3.5	0.6	8	[H33]
Nephrostogram, post-operative		9	1.6	57	[H33]
Retrograde pyelogram		13	2.3	27	[H33]
Urinary tract AP	2.18		0.168		[C28]
Urinary tract AP (CR)	2.51		0.193		[C28]
Urinary tract AP (DDR)			0.223		[C28]
Intravenous urography					
IVU			2.4	1 141	[H33]
IVU			3.0		[M41]
Bladder and urethra					
Cystourethrography			1.5		[H33]
Cystometrography		7	1.3	70	[H33]
Cystography		10	1.8	197	[H33]
Excretion urography/MCU		6.4	1.2	995	[H33]
Urethrography		6	1.1	19	[H33]
Gynaecology					
Pelvimetry	5.1		0.8	28	[H33]
Pelvimetry		1.4	0.41	1	[H33]
Hysterosalpingogram		4	1.2	201	[H33]
Lymphangiogram					
Lymphangiogram		0.3	0.06	1	[H33]

Examination	*ESD (mGy)*	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Tomography					
Tomography	3		0.15		[R15]
Bone mineral densitometry					
Bone mineral densitometry			0.000 5–0.035		[A7]
Bone mineral densitometry			0.000 2–0.01		[N5]
Bone mineral densitometry			0.001		[M41]
Arthrography					
Arthrography		1.7	0.17	82	[H33]
Pulmonary angiography					
Pulmonary arteriography		47	5.6	5	[H33]
Pulmonary angiogram			5		[M41]
Arterial pressures			7		[H33]
Superior venacavography			2.5		[H33]
Venacavogram		21	2.5	22	[H33]
Abdominal angiography					
Inferior venacavography			2.5		
Mesenteric angiography		85	22.1	338	[H33]
Mesenteric angiography		112		108	[K30]
Renal and visceral		92	23.9	56	[K30]
Renal and visceral		91	12.7	29	[R10]
Aortography					
Thoracic		34.5	4.1	287	[H33]
Abdominal		98	25.5	41	[W14]
Abdominal			14	19	[L16]
Abdominal			12		[M41]
Peripheral angiography					
Arteriography		27.2	7.1	759	[H33]
Arteriography		64		571	[K30]
Arteriography		26.3	4	25	[T12]
Phlebography		3.7	0.37	158	[H33]
Phlebography		23		26	[W14]
Barium swallow					
Barium swallow			1.5	4 258	[W7]
Barium meal					
Barium meal			2.6	9 718	[H33]
Barium follow-through					
Barium follow-through			3	886	[W7]
Small bowel enema					
Small bowel enema		30	7.8	176	[H33]
Barium enema					
Barium enema			8		[M41]
Barium enema			7.2	22 586	[H33]
Abdominal investigations					
Endoscopy			0.3		
Fistulogram		6.4	1.7	18	[H33]
Herniography		14	3.6	8	[H33]
Loopogram		5	1.3	4	[H33]
Peritoneogram		12	3.1	26	[H33]

Examination	*ESD (mGy)*	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Ileoanal pouchogram		15	3.9	7	[H33]
Sinography		16	4.2	71	[H33]
Biliary system					
Preliminary cholecystogram			2		[H33]
Operative cholangiography			3		[H33]
Infusion cholangiography			9		[H33]
Intravenous cholangiography		34	8.8	25	[H33]
Oral cholecystography		12	3.1	10	[H33]
ERCP		15	3.9	525	[H33]
ERCP		14.5	3.8	1 736	[M1]
ERCP			4.0		[M41]
Percutaneous transhepatic cholangiography		31	8.1	48	[H33]
T-tube choleangiogram		10	2.6	149	[H33]

Table B5. Summary of patient dose data for interventional radiology procedures

Procedure	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Biopsy				
Pathological specimen		1.6		[H33]
Biopsy	6	1.6	32	[H33]
Small bowel biopsy	1	0.26	15	[H33]
Venous sampling		0.4		[H33]
Biliary and urinary systems				
Bile duct drainage	38	9.9	8	[H33]
Bile duct drainage	43	11.2	86	[R10]
Bile duct drainage	69	17.9	10	[V2]
Bile duct drainage	150	38	18	[R9]
Bile duct drainage	70.6	18.4	123	[M13]
Bile duct drainage	86.7	22.5	9	[R10]
Bile duct drainage	43	11.2	14	[R10]
Bile duct dilatation/stenting	54	14	15	[H33]
Bile duct dilatation/stenting	51	13.3	74	[W14]
Bile duct dilatation/stenting	43	11.2	30	[M14]
Biliary intervention	54	14	153	[M1]
Bile duct stone extraction	27	7	29	[H33]
Lithotripsy	5	1.3	40	[H33]
Nephrostomy	13	3.4	68	[H33]
Nephrostomy	34.3	8.9	143	[M13]
Nephrostomy	22.7	5.9	14	[R10]
Nephrostomy	43	11.2	35	[M14]
Nephrostomy	8	2.1	21	[V6]
Nephrostomy	56	14.6	54	[R9]
Ureteric stenting	18	4.7	15	[H33]
Kidney stent insertion	49	12.7	5	[H33]

Procedure	*DAP (Gy cm^2)*	*Effective dose (mSv)*	*Patients*	*Reference*
Cardiovascular				
Embolization	75	19.5	12	[H33]
Embolization	105	27.3	27	[W14]
Embolization	114	29.6	128	[M1]
Management of varicocele	51	6.4	41	[C31]
Management of varicocele	106	25.7	10	[R10]
Management of varicocele	131	38	1	[H33]
Management of varicocele	75	17	20	[R9]
Management of varicocele	50.8	13.2	14	[M13]
Neuroembolization	202	5.7	1	[H33]
Neuroembolization	122.2	10.6	8	[M2]
Neuroembolization	116	1.7	8	[B13]
Neuroembolization	105	10.5	5	[M14]
Neuroembolization	320.1	9	382	[M13]
Neuroembolization	129	3.6	21	[J4]
Neuroembolization	81	2.3	35	[J4]
Thrombolysis	13.5	3.5	5	[H33]
TIPS	206	53.6	10	[H33]
TIPS	182	47.3	56	[W14]
TIPS	161	18.7	23	[Z3]
TIPS	524	84	4	[M14]
TIPS	335.4	87.2`	135	[M13]
TIPS	226	58.8	13	[Z3]
TIPS	77	20	10	[Z3]
TIPS		70		[M41]
Valvuloplasty	162	29.3	40	[B14]
Vascular stenting	40	10.4	14	[H33]
Vascular stenting	42	5.8	44	[O8]
Pelvic vein embolization		60		[M41]
Insertion of caval filters	48	12.5	4	[H33]
Removal of foreign bodies		7		[H33]
Uterine fibroid embolization				
Uterine fibroid embolization	298.2	77.5	90	[M13]
Uterine fibroid embolization	30.6	8	18	[A4]
Uterine fibroid embolization	211.4	55	16	[A4]
Gastrointestinal				
Feeding tube	13	3.4	16	[H33]
Gastrostomy	13	3.4	15	[H33]
Dilation/stenting oesophagus	15	1.5	96	[H33]
Dilation pyloric stenosis	27	7	4	[H33]
Colonic stent		7		[H33]
Nerve injection	1.7	0.2	22	[C30]

Table B6. Statistics on a variety of interventional radiology and interventional neuroradiology procedures [M13]

Procedure description	*Total cases*	*DAP (cGy cm^2)*				*Cumulative dose (mGy)*			
		Mean	*95% CI*	*Min*	*Max*	*Mean*	*95% CI*	*Min*	*Max*
TIPS	135	33 535	29 071, 37 999	1 427	136 443	2 039	1 760, 2 317	104	7 160
Biliary drainage	123	7 064	5 848, 8 281	302	38 631	907	730, 1 083	21	4 831
Nephrostomy, obstruction	79	2 555	1 805, 3 305	41	21 225	257	185, 328	3	2 169
Nephrostomy, stone access	64	4 514	2 859, 6 170	47	41 850	611	364, 857	10	6 178
Pulmonary angiogram, no IVC filter	106	7 731	6 520, 8 942	957	41 416	342	300, 384	34	1 479
Pulmonary angiogram, with IVC filter	17	10 826	8 072, 13 580	2 596	26 514	465	356, 575	76	987
IVC filter placement only	279	4 451	4 079, 4 822	170	20 327	166	152, 181	9	680
Renal/visceral angioplasty, no stent	53	15 749	11 633, 19 866	2 619	104 075	1 183	892, 1 474	157	5 482
Renal/visceral angioplasty, with stent	103	19 004	16 654, 21 355	983	72 420	1 605	1 375, 1 834	104	7 160
Iliac angioplasty, no stent	24	16 356	13 119, 19 592	2 060	30 099	885	729, 1 041	189	1 562
Iliac angioplasty, with stent	93	21 282	18 215, 24 350	1 148	88 650	1 335	1 141, 1 530	211	4 567
Central venous reconstruction, SVC	12	10 089	4 880, 15 298	585	27 695	573	331, 815	34	1 209
Central venous reconstruction, IVC	3	19 549		11 243	35 375	1 247		610	2 316
Aortic fenestration	2	23 358		21 403	25 312	1 178		937	1 419
Bronchial artery embolization	27	13 943	10 119, 17 767	2 821	39 289	1 123	840, 1 406	248	2 764
Hepatic chemoembolization	126	28 232	25 241, 31 224	1 712	90 415	1 406	1 216, 1 596	61	6 198
Pelvic arterial embolization, trauma	18	31 629	23 046, 40 213	9 291	62 358	1 705	1 237, 2 173	455	4 797
Pelvic arterial embolization, tumour	19	30 284	21 128, 39 441	11 002	83 811	1 846	1 338, 2 355	493	4 133
Pelvic arterial embolization, fibroids	90	29 822	25 830, 33 815	416	81 575	2 460	2 141, 2 779	15	6 990
Pelvic arterial embolization, AVM	12	48 425	34 103, 62 748	21 842	98 028	2 818	1 766, 3 871	1 071	6 149
Pelvic arterial embolization, aneurysm	4	22 385		16 497	27 900	2 599		808	3 885
Pelvic vein embolization, ovarian vein	6	41 355		12 217	102 605	2 838		1 628	5 406
Pelvic vein embolization, varicocele	14	5 082	1 753, 8 410	742	19 058	344	168, 520	41	1 007
Other tumour embolization	91	27 487	23 004, 31 970	1 668	152 005	1 579	1 298, 1 860	24	7 986
Peripheral AVM embolization	17	11 911	2 493, 21 329	330	54 129	990	245, 1 735	16	4 606
GI haemorrhage, diagnosis/therapy	94	34 757	30 599, 38 915	2 713	129 465	2 367	2 037, 2 697	105	7 160
Neuroembolization, head, AVM	177	33 976	30 313, 37 640	398	135 111	3 791	3 407, 4 175	43	13 410
Neuroembolization, head, tumour	56	35 776	30 498, 41 054	4 587	95 590	3 865	3 317, 4 414	598	10 907
Neuroembolization, head, aneurysm	149	28 269	26 113, 30 426	6 788	82 515	3 767	3 517, 4 018	1 284	9 809
Neuroembolization, spine, AVM	10	56 039	28 089, 83 989	8 079	103 399	6 288	4 219, 8 356	2 080	10 526
Neuroembolization, spine, aneurysm	1	54 014				4 214			
Neuroembolization, spine, tumour	13	47 062	29 222, 64 902	17 559	126 411	4 935	3 877, 5 993	2 380	7 504
Stroke therapy	9	19 824	11 333, 28 315	7 924	46 171	2 369	1 430, 3 309	992	4 991
Carotid stent	18	16 785	10 762, 22 807	3 193	51 544	1 382	846, 1 917	326	4 405
Vertebroplasty	98	7 813	6 578, 9 048	642	33 533	1 253	1 075, 1 431	146	3 993

Note: IVC = inferior vena cava; SVC = superior vena cava; AVM = arteriovenous malformation.

Table B7. Comparison of effective dose (mSv) for various interventional procedures [B20]

Procedure	*Reference*									
	[B20][a]	*[M14]*	*[S26][b]*	*[T12]*	*[C12]*	*[H1]*	*[M4]*	*[K14]*	*[Z5]*	*[M2]*
Hepatic	8.6/10.5	21.7	23							
Renal	11.7/13.7	6.4–13.6	16			13.6	25	6		
Thoracic	6	11.9				16.3			3.2	
Upper extremity	0.54/0.9	0.3							3.5	
Lower extremity	3.5/4.5	7.4[c]	4	4	3.1	9[d]/2.8[e]				
Carotid	2.5/4.9	4.9								
Cerebral	3.0/3.0	7.4[f]	4						4.4	3.6

[a] Diagnostic/therapeutic.
[b] Effective dose equivalent.
[c] Femoral angiography.
[d] Digital.
[e] Analogue.
[f] Therapeutic.

Table B8. Summary of patient dose data for coronary angiography examinations

DAP (Gy cm^2)	*Effective dose (mSv)*	*Patients*	*Reference*
57.8	9.4	2 174	[B19]
23.4	4.6	126	[B19]
66.5		288	[V2]
111.03		6	[V16]
147.43		3	[V16]
40.72		4	[V16]
60.21		13	[V16]
84.9		27	[D9]
76.6		45	[D9]
46		14	[V17]
60.64		62	[V18]
110.1		15	[V18]
23–79	4.6–15.8	198	[N11]
55.9		76	[P18]
27	9.2	19 215	[A15]
55	6.6	4	[H33]
26	3.1	187	[H33]
26.4		231	[H34]
30.4		8 000	[H34]
13.97	3.1	90	[L16]
63		65	[F18]
30.4	5.6	29	[B11]
18		167	[P20]
42			[H7]
29	5	20	[E6]
23.6		509	[K27]
12.7		473	[K27]
12.8		278	[K28]

DAP (Gy cm^2)	*Effective dose (mSv)*	*Patients*	*Reference*
13.2		47	[K28]
47.3		195	[T18]
57		600	[N11]
49		20	[H35]
	2.5		[K29]
	2.1		[K29]
44.25		3 079	[B15]
55.9		39	[Z15]
72.63		30	[W15]

Table B9. Summary of patient dose data for PTCA examinations

DAP (Gy cm^2)	*Effective dose (mSv)*	*Patients*	*Reference*
77.9	14.2	214	[B19]
51.6	10.2	11	[B19]
87.5		45	[V2]
113.21		7	[V16]
125.5		33	[D9]
59.8		37	[D9]
82.5		14	[V17]
115.23		13	[V18]
27–205	5.4–41	122	[N22]
101.9		54	[P18]
145		223	[B9]
46		17	[W11]
93		90	[M33]
51		89	[P20]
37.6	6.9	12	[F18]
50.6	9.3	6	[F18]
42			[H7]
75	14	20	[E6]
22.2		233	[K27]
14.4		269	[K27]
68		97	[T18]
63.4		334	[H34]
94		600	[N11]
40		10	[H35]
62.6		401	[B16]
50.8		180	[B16]
69.5		183	[B16]
130.5		58	[B16]
50.8	14.2	98	[B16]
128.3	10.2	121	[B16]
151.05		30	[W15]
33	11	9 692	[A15]
11.8		115	[K28]
15		30	[K28]

Table B10. Summary of patient dose data for stent procedures

DAP (Gy cm^2)	*Effective dose (mSv)*	*Patients*	*Reference*
165.95	7	10	[V18]
49.2	9	14	[B11]
70.7	13	7	[B11]
41		479	[P20]
58		58	[P20]

Table B11. Summary of patient dose data for pacemaker insertions

DAP (Gy cm^2)	*Effective dose (mSv)*	*Patients*	*Reference*
8.46		101	[B19]
17		627	[H34]
19		3 197	[A15]

Table B12. Summary of patient dose data for head CT examinations

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
	2.1	[P4]
739–2 130	2.8	[A8]
544	1.2	[T23]
	2.2	[N2]
610–1 684		[N3]
238–1 332	1.7	[O4]
250–1 400	1.8	[O4]
125–1 262	6.1–7.9	[M25]
183–2 173	1.6	[T20]
	1.6–2.8	[M43]
660	1.5	[H10]
36–1 180	1.7	[Y4]
	2.2	[B18]
430–758	1.4	[T19]
	1.9	[V9]
	1.5	[H14]
	1.3	[H15]
	0.9	[H36]
930	1.5	[S19]
	2.8 (neck)	[C16]
	1.4	[T22]
694	1.5	[S6]
	1.7	[C17]
	2.4	[E1]
740	0.9 (spiral)	[H5]
	1.2 (multislice)	[H5]
	1.7	[T1]

Table B13. Summary of patient dose data for body CT examinations

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
	Abdomen	
	7.4	[P4]
	7.7–13.3	[M43]
	12.4–16.1	[C16]
717–1 428		[N3]
	3.1	[H14]
105–2 537	4.9–13.2	[M25]
	15.3	[N2]
470	5.3	[S19]
352	5.3	[S6]
920	10.1	[A8]
	7.2	[V9]
	9.9 (abscess)	[T22]
	14.5 (liver metastases)	[T22]
58–1 898	7.4	[T20]
	7.8	[O4]
	7.9	[O4]
	2.4	[H10]
	3.6 (contrast)	[H10]
549	8.2	[T23]
250–440	7.0	[Y4]
278–582	7.1	[T19]
880	14.9	[I4]
	3.9	[W3]
	9.7	[B18]
	11.7	[E1]
	3.5 (axial)	[H5]
	7.7 (multislice)	[H5]
	Chest	
	3.9 (spiral)	[H5]
	10.5 (multislice)	[H5]
420	7.1	[T1]
	7.3	[P4]
348–807	10.9	[T19]
224–1 530	9.3	[A8]
580	5.8	[S19]
402	5.8	[S6]
	5.5	[B18]
50–2 157	8.9	[T20]
	3.8	[V9]
	7.5–12.9	[C16]
	2.3	[T22]
	4.9–7.8	[M43]
195	4.0	[H10]
70–270	3.5	[Y4]
35–240	2.2 (high resolution)	[Y4]
496–992		[N3]

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
	8.0	[O4]
	7.9	[O4]
215–766	5.5–9.7	[M25]
348	5.9	[T23]
	12.2	[N2]
399	6.8	[I4]
650	11.1	[E1]
Pelvis		
	10.3	[P4]
526–1 302		[N3]
205–910	9	[A8]
286–895	6–15.7	[M25]
67–1 984	7.7	[T20]
	8.9	[O4]
	8.8	[O4]
306–592	9.3	[T19]
	13.4	[N2]
478	8.1	[I4]
570	10.8	[E1]
Chest–abdomen–pelvis		
320–750	10.9	[Y4]
668	9.9	[S6]

Table B14. Summary of patient dose data for spine CT examinations

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
Lumbar spine		
	7.1	[P4]
455	7.2	[H10]
220–570	6.4	[Y4]
200–382		[N2]
	5.4	[N3]
166–870	4.9–8.1	[M25]
	4.5	[T22]
47–495	4.5	[O4]
49–500	4.6	[O4]
411	6.2	[I4]
800		[E1]
420	7.9	[T1]
Thoracic spine		
	13.1	[P4]
Cervical spine		
	3.4	[P4]
66–708	1.5	[O4]

Table B15. Summary of patient dose data for CT angiography examinations

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
	Coronary angiography	
	7.8–8.8	[S22]
	9–29	[E4]
305	5–7 (aortic)	[H10]
	9.5	[E8]
	11.7 (calcium scoring)	[E8]
	22.8 (16 slices)	[M44]
	27.8 (64 slices)	[M44]
	14.1 (256 slices)	[M44]
	14.7	[C20]
	3.0	[H39]
	6.7–10.9 (male)	[H35]
	8.1–13 (female)	[H35]
	20.6	[N24]
	8.1 (female)	[T21]
	10.9 (male)	[T21]
	6.4 (16 slices)	[H40]
	11.0 (64 slices)	[H40]
	9.8	[D5]
	Pulmonary angiography	
165	3.4	[H10]
737	19.9	[H41]
	14.4	[H21]
	4.1	[T22]
	3.0	[V9]
	4.2	[K6]
	21.5 (4 slices)	[C27]
	18.2–19.5 (16 slices)	[C27]
	5.2	[B18]

Table B16. Summary of patient dose data for various other CT examinations

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
	Appendix	
	13.3	[H21]
	Renal	
	4.5	[H21]
	4.6	[H10]
	Liver–spleen–pancreas	
97–2 876	13	[T20]
	10.2	[V9]
900		[E1]
	Kidneys	
47–2 157	11	[T20]
800		[E1]

Table B17. Summary of patient dose data for paediatric CT examinations

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
Head		
300 (<1 year)		[S21]
600 (5 years)		[S21]
750 (10 years)		[S21]
	1.3–2.3 (8 weeks)	[M43]
	1.5–2.0 (5–7 years)	[M43]
	7.6	[H15]
	6.0 (newborn)	[H14]
	4.9 (1 year)	[H14]
	4.0 (5 years)	[H14]
	2.8 (10 years)	[H14]
	1.7 (15 years)	[H14]
230 (1 year)	2.5 (1 year)	[S6]
383 (5 years)	1.5 (5 years)	[S6]
508 (10 years)	1.6 (10 years)	[S6]
	3.6 (<1 year)	[H36]
	4	[B5]
Chest		
200 (<1 year)		[S21]
400 (5 years)		[S21]
600 (10 years)		[S21]
	1.9–5.1 (8 weeks)	[M43]
	3.1–7.9 (5–7 years)	[M43]
50 (newborn)	1.7 (newborn)	[H19]
100 (1 year)	1.8 (1 year)	[H19]
140 (5 years)	2.1 (5 years)	[H19]
270 (10 years)	3.0 (10 years)	[H19]
430 (15 years)	4.1 (15 years)	[H19]
780 (18 years)	5.4 (18 years)	[H19]
	6.4 (8 weeks)	[M45]
	6.8 (7 years)	[M45]
159 (<1 year)	6.3 (<1 year)	[S6]
198 (5 years)	3.6 (5 years)	[S6]
303 (10 years)	3.9 (10 years)	[S6]
	3	[B5]
Abdomen		
330 (<1 year)		[S21]
360 (5 years)		[S21]
800 (10 years)		[S21]
	6.1 (<10 years)	[W3]
	4.4 (11–18 years)	[W3]
	4.4–9.3 (8 weeks)	[M43]
	9.2–14.1 (5–7 years)	[M43]
	5.3 (newborn)	[H14]
	4.2 (1 year)	[H14]
	3.7 (5 year)	[H14]
	3.7 (10 year)	[H14]

DLP (mGy cm)	*Effective dose (mSv)*	*Reference*
	3.6 (15 year)	[H14]
	5	[B5]
560	11	[H10]

Table B18. Effective dose from routine CT examinations in the United States according to the 2000–2001 NEXT Survey [S24]

Examination	*Percentage*[a]	*Percentage axial*	*Percentage helical*	*Axial scanning*			*Helical scanning*		
				Mean (mSv)	*SD*	*Number*	*Mean (mSv)*	*SD*	*Number*
Head (brain)	27	88	12	2	1	45	1	1	4
Abdomen–pelvis	21	35	65	17	6	16	12	7	21
Chest	11	34	66	9	4	14	6	4	22
Abdomen	10	30	70	8	4	11	6	4	19
Simple sinus	5	79	21						
Chest–abdomen–pelvis	5	34	66	28	11	10	15	10	18
Pelvis	5	31	69	7	4	11	6	4	15
Skull	5	83	17						
Spine	4	66	34						
Kidneys	2	24	76						
Liver	1	27	73						
Pancreas	1	30	70						
Other	1	40	60						

[a] The distribution of adult examinations is based on 56 facilities reporting an average of 3,165 axial and 2,680 helical examinations.

Table B19. Annual number of CT examinations in Japan [N13]

Scan region	*Male*	*Female*	*Total*
Head	8 247 000	7 763 000	16 010 000
Head–chest	203 000	162 000	365 000
Head–abdomen	98 000	69 000	167 000
Head–pelvis	40 000	31 000	71 000
Chest	2 889 000	2 115 000	5 004 000
Chest–abdomen	2 415 000	2 072 000	4 487 000
Chest–pelvis	741 000	569 000	1 310 000
Abdomen	2 963 000	2 184 000	5 147 000
Abdomen–pelvis	17 511 000	1 493 000	3 244 000
Pelvis	262 000	290 000	552 000
Other	99 000	96 000	195 000
Total	19 708 000	16 844 000	36 552 000

Table B20. CT practice in Japan: comparison of surveys [N13]

Survey year	*Number of CT scanners*	*Annual number of examinations*	*Annual number of scans*	*Collective effective dose (man Sv)*	*Per caput effective dose (mSv)*
1979 [N16]	712	1 454 000	14 850 000		
1989 [N17]	5 382	11 904 000	243 700 000	99 000	0.8
2000 [N13]	11 050	36 550 000	906 000 000	295 000	2.3

Table B21. Summary of measurements undertaken on multislice CT scanners in Germany in 2002
Data provided from 113 CT scanners [B18]

Examination	*Relative frequency (%)*	*Number of centres providing data*	*Effective dose/series (mSv)*	*Effective dose/examination (mSv)*
Brain	27.1	104	2.2	2.8
Face and sinuses	4.4	102	0.8	0.8
Face and neck	3.6	99	1.9	2
Chest	15.7	108	5.5	5.7
Abdomen–pelvis	17.6	106	9.7	14.4
Pelvis	2.6	94	6.3	7.2
Liver–kidney	5.9	103	5.5	11.5
Whole trunk	4.1	76	14.5	17.8
Aorta thoracic	1.4	90	6.1	6.7
Aorta abdomen	1.8	91	9	10.3
Pulmonary vessels	1.8	91	5.2	5.4
Pelvis skeleton	1.5	88	8.2	8.2
Cervical spine	3.2	103	2.9	2.9
Lumbar spine	5.9	107	8.1	8.1

Table B22. Summary of measurements undertaken on single-slice spiral CT scanners in Germany
Data provided from 398 CT scanners installed between January 1996 and June 1999 [B18]

Examination	*Number of centres providing data*	*Effective dose/series (mSv)*	*Effective dose/examination (mSv)*
Brain	387	1.9	2.8
Face and sinuses	379	1	1.1
Face and neck	365	1.7	2
Chest	385	5.2	6.2
Abdomen–pelvis	377	10.3	17.2
Pelvis	367	6.9	8.8
Liver–kidney	375	4.6	8.7
Whole trunk	139	14.9	20.5
Aorta thoracic	193	5	5.8
Aorta abdomen	203	6.3	7.6
Pulmonary vessels	180	3.3	3.6
Pelvis skeleton	328	8.6	8.8
Cervical spine	331	2.1	2.1
Lumbar spine	384	2.7	2.7

Table B23. Representative adult effective dose for various CT procedures [M41]

Examination	*Effective dose (mSv)*	*Reported range (mSv)*
Head	2	0.9–4.0
Neck	3	
Chest	7	4.0–18.0
Pulmonary embolism	15	13–40
Abdomen	8	3.5–25
Pelvis	6	3.3–10
Liver (3-phase)	15	5.0–25
Spine	6	1.5–10
Coronary angiogram	16	5.0–32
Calcium scoring	3	1.0–12
Virtual colonoscopy	10	4.0–13.2
Dental	0.2	

Table B24. Comparison of effective dose from various types of dental X-ray equipment [C5]

Equipment	*DVT old, soft tissue*	*DVT new, soft tissue*	*Orthophos CT*	*Dental CT 94 mA*	*Dental CT 60 mA*	*Dental CT 43 mA*	*Dental multislice CT*	*Sinus CT 94 mA*
Effective dose (mSv)	0.1	0.11	0.01	0.61	0.36	0.15	0.74	1.27

Table B25. Comparison of mean DWPs for panoramic dental radiography examinations [D13]

Study	*Sample size*	*Mean DWP (mGy mm)*	*Mean DAP (mGy cm^2)*
[D13]	20	65	89
[N15]	387	57	
[I33]	5	74	
[P13]	6		113
[W17]	16	65	113
[O6]	26	69	
[T13] (male)	62		101
[T13] (female)	62		85

Table B26. Effective dose for pencil and fan beam DEXA (premenopausal women) [N5]

Type of machine	*Scan type*	*Effective dose (mSv)*
Pencil beam	Total body	4.6
	AP spine (L1–L4)	0.5
	Lateral spine (L2–L4)	0.6
	Proximal femur	1.4
Fan beam	PA spine (L1–L4)	0.4–2.9
	Lateral spine (L2–L4)	1.2–2.5
	Proximal femur	3.0–5.9
	Total body	3.6

Table B27. Mean ESD per radiograph for paediatric patients [N2]

Examination	*Age (years)*	*Mean ESD (mGy)*
Abdomen AP	0	110
	1	340
	5	590
	10	860
	15	2 010
Chest AP/PA	0	60
	1	80
	5	110
	10	70
	15	110
Pelvis AP	0	170
	1	350
	5	510
	10	650
	15	1 300
Skull AP	1	600
	5	1 250
Skull LAT	1	340
	5	580

Table B28. DAP for common paediatric fluoroscopic examinations [N2]

Examination	*Age (years)*	*Normalized DAP per examination (mGy cm^2)*
MCU	0	430
	1	810
	5	940
	10	1 640
	15	3 410
Barium meal	0	760
	1	1 610
	5	1 620
	10	3 190
	15	5 670
Barium swallow	0	560
	1	1 150
	5	1 010
	10	2 400
	15	3 170

Table B29. Patient dose survey of paediatric radiology in a Madrid hospital [V10]

Examination	*Age (years)*	*Sample size*	*Median ESD (mGy)*
Chest (no bucky)	0–1	1 180	41
	1–5	309	34
	6–10	143	54
	10–15	92	10

Examination	*Age (years)*	*Sample size*	*Median ESD (mGy)*
Chest (with bucky)	1–5	181	87
	6–10	255	105
	11–15	363	170
Abdomen	0–1	93	91
	1–5	30	225
	6–10	69	600
	11–15	150	1 508
Pelvis	0–1	254	48
	1–5	128	314
	6–10	122	702
	11–15	137	1 595

Table B30. Effective dose for seven selected paediatric cardiac interventions [O10]

Procedure	*Number*	*Effective dose (mSv)*
ASD occlusion	259	3.88
PDA occlusion	165	3.21
Balloon dilation	122	4.4
Coil embolization	33	4.58
VSD occlusion	32	12.1
Atrial septostomy	25	3.62
PFO occlusion	21	2.16

ASD = atrial septal defect; PDA = patent ductus; VSD = ventricular septal defect; PFO = patent foramen ovale.

Table B31. Comparison of mean and reported typical mean foetal doses per examination [O1]

Examination	*Mean (from [O1]) (mGy)*	*Reported typical mean from literature (mGy)*
Abdomen AP	2.9	1.9 [S7]
Abdomen PA	1.3	0.53 [S7]
Abdomen	2.6	2.5 [W6]
Chest AP	<0.01	<0.01 [S7]
Chest PA	<0.01	<0.01 [S7]
Chest	<0.01	0.01 [W6]
Lumbar spine AP	7.5	1.9 [S7]
Lumbar spine LAT	0.91	0.41 [S7]
Lumbar spine	4.2	4.0 [W6]
Lumbosacral joint LAT	1.1	0.56 [S7]
Pelvis AP	3.4	2.0 [W6]
Thoracic spine AP	<0.01	<0.01 [S7]
Thoracic spine PA	<0.01	<0.01 [S7]
Thoracic spine	<0.01	<0.1 [W6]

Table B32. Estimated number of procedures per million population and total number of procedures in 2006 for various European countries [F19]

Country	*Number of procedures/million population*				*Population*	*Total number of procedures*			
	CA	*PTCA*	*Stent*	*Pacemaker*		*CA*	*PTCA*	*Stent*	*Pacemaker*
Austria	7 476	2 110	1 561	*1 413*	8 192 880	61 246	17 287	12 792	*11 577*
Belgium	6 842	2 190	1 328	1 222	10 379 067	71 017	22 729	13 779	12 683
Bulgaria	*670*	186[a]	*134*	*124*	7 385 367	*4 948*	1 373	*990*	*916*
Croatia	*3 816*	1 060	*763*	*710*	4 494 749	*17 150*	4 764	*3 430*	*3 191*
Czech Republic	4 642	1 483	1 033	1 041	10 235 455	47 512	15 175	10 568	10 655
Denmark	*6 448*	1 791	*1 290*	*1 199*	5 450 661	*35 143*	9 762	*7 029*	*6 535*
Estonia	2 906	738	449	692	1 324 333	3 849	978	595	916
Finland	7 997	1 926	1 158	1 143	5 231 372	41 834	10 074	6 059	5 979
France	5 955	2 318	2 230	1 185	60 876 136	362 540	141 084	135 772	72 138
Germany	*11 646*	3 235	*2 329*	2 167	82 422 299	*959 987*	266 663	*191 962*	178 609
Greece	2 931	674	569	781	10 688 058	31 325	7 205	6 077	8 347
Hungary	2 535	378	290	559	9 981 334	25 305	3 772	2 893	5 580
Iceland	6 522	2 658	1 975	827	299 388	1 952	796	591	248
Ireland	*2 851*	792[a]	*570*	*530*	4 062 235	*11 581*	3 217	*2 315*	*2 153*
Israel	7 353	3 704	*2 667*	*2 481*	6 352 117	46 704	23 528	*16 940*	*15 760*
Italy	4 556	1 540	*1 109*	*1 032*	58 133 509	264 854	89 548	*64 475*	*59 994*
Latvia	2 550	830	591	576	2 274 735	5 802	1 888	1 345	1 310
Lithuania	3 182	1 027	249	488	3 585 906	11 410	3 684	893	1 750
Netherlands	*5 098*	1 416	*1 020*	*948*	16 491 461	*84 092*	23 359	*16 818*	*15 634*
Poland	2 919	1 012	572	688	38 536 869	112 499	38 992	22 027	26 513
Portugal	3 157	825	703	599	10 605 870	33 487	8 749	7 459	6 353
Romania	1 421	207	200	142	22 303 552	31 698	4 617	4 455	3 167
San Marino	3 243	1 135	1 135	*760*	29 251	95	33	33	*22*
Spain	2 662	939	726	601	40 397 842	107 543	37 950	29 317	24 279
Sweden	*5 278*	1 466	*1 056*	982	9 016 596	*47 570*	13 214	*9 514*	8 854
Switzerland	6 241	2 169	1 583	713	7 523 934	46 958	16 319	11 913	5 365
Turkey	3 026	558	336	53	70 413 958	213 101	39 257	23 640	3 732
The former Yugoslav Republic of Macedonia	1 402	601	559	116	2 050 554	2 876	1 232	1 146	238
United Kingdom	*3 096*	860	722	497	60 609 153	*187 646*	52 124	43 785	30 123
				Total	569 348 641	2 871 726	859 373	648 612	522 621

Note: Data in italics estimated using average ratio of coronary angiograms to PTCAs (3.6), stents to PTCAs (0.72) and pacemakers to PTCAs (0.67) as appropriate.

[a] Estimated from 2000 data using an average rate.

Table B33. 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)*	*Reference*
	I	*II*	*III*	*IV*		
1977	29	35	23	13	4 200	[U9]
1984	27	50	15	8	5 000	[U7]
1990	25	50	16	9	5 290	[U6]
1996	26	53	11	10	5 800	[U3]
2007	24	49	16	11	6 446	Present

Table B34. Physicians and health-care professionals
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country/area	*Population (thousands)*	*Number*						
		All physicians	*Physicians conducting radiological procedures*	*Radiology-technicians*	*Medical-physicists*	*Interventional cardiologists*	*Other physicians performing radiology*	*Dentists*
Health-care level I								
Albania	3 200		160	120	6	6		
Australia	20 406	59 023	1 201		392			8 800
Austria	8 200	37 000	1 030	2 200	70	200	800	4 500
Belgium	10 300	42 978	1 690		155	888		8 450
Bulgaria	8 149	27 526	815					6 778
Croatia	4 437	12 830	485	947	22	28	97	3 445
Czech Republic	10 290	35 960	1 299	3 257	199	434	522	6 429
Estonia	1 370	4 300	192	371	20	14	44	1 200
Finland	5 250	14 661	770	3 892	88	90		6 113
France	61 700	205 000	7 590	23 380	347	500	13 600	41 250
Germany	82 501	306 435	6 314	31 000	635		19 000	65 000
Greece	11 000	55 000	1 800	2 500	350	2 400		12 000
Hungary	9 981	36 907	1 171	3 000	60	65	500	5 156
Iceland	294	1 120	35	170	10	15	25	350
Japan	127 435	262 687	4 710	41 549	117			92 874
Korea, Rep.	48 497	127 158	2 434	14 291	56	294	24 021	22 366
Latvia	2 295	8 956	277	7 236	393	21		1 415
Lithuania	3 491	14 034	394	1 228	9	36	209	2 446
Luxembourg	452	1 422	54	165	5	12	183	312
Malta	400	1 407	26	164	3	5	16	195
Netherlands	15 638	46 000	730		110			6 344
New Zealand	3 737	8 615	215	1 600	32	74	200	1 591
Norway	4 640	18 404	476	2 350	75	52	756	4 140
Russian Federation	146 700	607 000	14 860	26 880	150		320	42 200
Slovenia	2 003	4 671	300	457	15		50	1 233
Spain	44 109	194 668	3 655	6 093	579	347	3 371	21 055
Sweden	8 861	32 000	1 300	3 000	200			11 000
Switzerland	7 461	28 251	517	5 100	60	205	4 500	4 500
The former Yugoslav Republic of Macedonia	2 033	5 131	113	287	13	24	74	1 602
United Kingdom	59 500	100 000	2 750	19 000	1 100			21 000
Venezuela (Bolivarian Rep. of)	27 031		1 072					208
Health-care level II								
Azerbaijan	7 962			4	3			
Brazil	186 771	466 111			299			56 995
Chile	15 116	15 195	700		10			8 748
China	1 248 100	1 999 521		126 173				
Colombia	41 468	13 471	5 544					20 328
Costa Rica	4 326	6 812	103	386	5	63		2 696
El Salvador	6 500	7 000	60	600	10	8	30	5 000
Malaysia	26 909	14 986	275	1 799	47	35	54	3 989
Mauritius	1 200		18	115	3	12		106
Oman	2 018	3 248	40	334	3		2	262

Country/area	*Population (thousands)*	*Number*						
		All physicians	*Physicians conducting radiological procedures*	*Radiology-technicians*	*Medical-physicists*	*Interventional cardiologists*	*Other physicians performing radiology*	*Dentists*
Thailand	60 607	16 569	329	3 885	98	110	860	3 414
Trinidad and Tobago	1 262	2 667	5	125	5	7	187	295
Tunisia	9 650	8 000	178	3 000	15	10		1 180
Turkey	67 800	81 988	3 500	16 000	130			14 226
Health-care level III								
Zimbabwe	12 000	13	15	180	4			200
Health-care level IV								
Maldives	300	18	3	23	0	1	0	10

Table B35. Physicians and health-care professionals per million population

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country/area	*Population (thousands)*	*Number per million population*						
		All physicians	*Physicians conducting radiological procedures*	*Radiology-technicians*	*Medical-physicists*	*Interventional cardiologists*	*Other physicians performing radiology*	*Dentists*
Health-care level I								
Albania	3 200			38	2	2		
Australia	20 406	2 892	59		19			431
Austria	8 200	4 512	126	268	9	24	98	549
Belgium	10 300	4 173	164		15	86		820
Bulgaria	8 149	3 378	100					832
Croatia	4 437	2 892	109	213	5	6	22	776
Czech Republic	10 290	3 495	126	317	19	42	51	625
Estonia	1 370	3 139	140	271	15	10	32	876
Finland	5 250	2 793	147	741	17	17		1 164
France	61 700	3 323	123	379	6	8		669
Germany	82 501	3 714	77	376	8		230	788
Greece	11 000	5 000	164	227	32	218		1 091
Hungary	9 981	3 698	117	301	6	7	50	517
Iceland	294	3 810	119	578	34	51	85	1 190
Japan	127 435	2 061	37	326	1			729
Korea, Rep.	48 497	2 622	50	295	1			461
Latvia	2 295	3 902	121	171	(3 153)	9		617
Lithuania	3 491	4 020	113	352	3	10	60	701
Luxembourg	452	3 146	119	365	11	27	405	690
Malta	400	3 518	65	410	8	13	40	488
Netherlands	15 638	2 942	47		7			406
New Zealand	3 737	2 305	58	428	9	20	54	426
Norway	4 640	3 966	103	506	16	11	163	892
Russian Federation	146 700	4 138	101	183	1		2	288
Slovenia	2 003	2 332	150	228	7		25	616
Spain	44 109	4 413	83	138	13	8	76	477

Country/area	*Population (thousands)*	*Number per million population*						
		All physicians	*Physicians conducting radiological procedures*	*Radiology-technicians*	*Medical-physicists*	*Interventional cardiologists*	*Other physicians performing radiology*	*Dentists*
Sweden	8 861	3 611	147	34	23			1 241
Switzerland	7 461	3 786	69	684	8	27	603	603
The former Yugoslav Republic of Macedonia	2 033	2 524	56	141	6	12	36	788
United Kingdom	59 500	1 681	46	319	18			353
Venezuela (Bolivarian Republic of)	27 031		40					8
Weighted average		3 530	77	370	7	40	92	540
Health-care level II								
Azerbaijan	7 962			1	0			
Brazil	186 771	2 496			2			305
Chile	15 116	1 005	46		1			579
China	1 248 100	1 602		101				
Colombia	41 468	325	134	42	0			490
Costa Rica	4 326	1 575	24	89	1	15		623
El Salvador	6 500	1 077	9	92	2	1	5	769
Malaysia	26 909	557	10	67	2	1	2	148
Mauritius	1 200		15	96	3	10		88
Oman	2 018	1 610	20	166	1		1	130
Thailand	60 607	273	5	64	2	2	14	56
Trinidad and Tobago	1 262	2 113	4	99	4	6	148	234
Tunisia	9 650	829	18	311	2	1		122
Turkey	67 800	1 209	52	236	2			210
Weighted average		1 600	45	100	1	2	12	280
Health-care level III								
Zimbabwe	12 000	1.1	1.3	15.0	0.3			16.7
Weighted average		1.1	1.3	15	0.3			17
Health-care level IV								
Maldives	300	60	10	76.7	0	3.3	0	33.3
Weighted average		60	10	77	0	3.3	0	33

Note: Value for Latvia excluded from the calculation of the population-weighted mean.

Table B36. Number of items of diagnostic X-ray equipment in various countries

Country	*X-ray generators*						*Bone densitometry*	*CT scanners*
	Medical	*Mammo-graphy*	*Dental*	*Interventional*	*General fluoroscopy*	*Angiography*		
Health-care level I								
Albania	9	10	100	1	11		1	17
Australia	3 938	400	10 100					500
Austria	2 230	420	10 000		13 000	150	120	250
Belgium	2 241	283	3 914			24	185	204
Bulgaria	1 498	79	455	11			5	32
Croatia	552	137	593	17	3	27	45	65
Czech Republic	1 981	137	4 670		323	63	52	126
Estonia	80	6	588	17	29	5	5	10
Finland	1 079	198	5 200			28	86	80
France	13 061	2 538	33 245					608
Germany	23 000	3 100	72 600		7 000	1 900		2 800
Greece	1 373	433	10 000	180	200	80	396	286
Hungary	1 800	100	2 600	35	300	50	53	60
Iceland	46	5	360		7		3	6
Japan	88 000	2 905	131 300			3 223	9 381	11 803
Korea, Rep.	15 599	1 493	24 592	119	5 939	166	1 734	1 491
Latvia	370	34	610	6	20	3	8	41
Lithuania	797	26	578					23
Luxembourg	61	10	426	6	40	6	1	12
Malta	57	13	149	3	10	3	6	10
New Zealand	665	96	2 228	23			43	45
Norway	830	87	6 400	75	200			124
Romania	1 305	114	634	5	901	24	25	107
Russian Federation	18 564	1 167	5 835	480	11 000	243	30	378
Slovakia	650	102	750	8	350	40	40	94
Slovenia	257	34	376	13		8	34	20
Spain	12 438	1 093	18 486	32	1 253		382	566
Sweden	1 200	180	12 000	30			40	130
Switzerland	5 134	239	9 846	1 337	1 300	37	135	214
The former Yugoslav Republic of Macedonia	140	15	136	66	61	5	2	13
United Kingdom								400
Venezuela (Bolivarian Republic of)	506	90	217		60	10	31	64
Health-care level II								
Azerbaijan	6	2	-					
Brazil	18 229	3 057	20 610		1 402	535	932	2 043
Chile	1 424	279	815	16	69	42	78	161
China	59 000	750	2 450					3 712
Colombia	1 833	98	2 526	5				106
Costa Rica	284	46	648	12	29	29	13	12
El Salvador	113	38	500	5	53	5	4	17
Mauritius	47	2	60	11				2

Country	*X-ray generators*						*Bone densitometry*	*CT scanners*
	Medical	*Mammo-graphy*	*Dental*	*Interventional*	*General fluoroscopy*	*Angiography*		
Oman	159	4	33	2			1	6
Thailand	2 866	100	1 678	1 700				261
Trinidad and Tobago	50	24	90	5	15		4	8
Tunisia	1 128	77	763	21			7	88
Turkey	3 915	433	1 100	181			251	685
Health-care level III								
Zimbabwe	250	2	200	2	30	15		8
Health-care level IV								
Maldives	16	1.0	2.0	0.0	1.0	0.0	1.0	1.0

Note: For some countries, the number of items of conventional equipment also includes the number of digital machines.

Table B37. Number of items of digital diagnostic equipment in various countries

Country	*Digital systems*					
	General	*Mammography*	*Dental*	*Interventional*	*General fluoroscopy*	*Angiography*
Health-care level I						
Albania	92	3		1	50	1
Australia	31					
Bulgaria	28	1	17	8		
Czech Republic				36		
Estonia	26			6	10	1
Finland						81
Hungary	15			3	15	3
Iceland	30					6
Japan	2 082				2 649	
Latvia					7	2
Luxembourg	3	0		2		
New Zealand		0	3			
Romania	59	0	0	2		2
Russian Federation	221		528			
Spain	2 548	400	1 180	273	1 110	
Sweden	400	2	200	20		
Venezuela (Bolivarian Rep. of)			43			
Health-care level II						
Costa Rica						
El Salvador	15					
Mauritius	0	0	0	0	0	0
Oman	2					
Trinidad and Tobago			20		3	4
Tunisia	10					

Note: For some countries, the number of items of conventional equipment also includes the number of digital machines.

Table B38. Number of items of diagnostic X-ray equipment in various countries per million population

Country	*X-ray generators*						*Bone densitometry*	*CT scanners*
	Medical	*Mammography*	*Dental*	*Interventional*	*General fluoroscopy*	*Angiography*		
Health-care level I								
Albania	2.8	3.1	31.3	0.3	3.4		0.3	5.3
Australia	193.0	19.6	495.0					24.5
Austria	272	51	1 220		159	18	15	31
Belgium	217.6	27.5	380.0			2.3	18.0	19.8
Bulgaria	183.8	9.7	55.8	1.3			0.6	3.9
Croatia	124.4	30.9	133.6	3.8	0.7	6.1	10.1	14.6
Czech Republic	192.5	13.3	453.8		31.4	6.1	5.1	12.2
Estonia	58.4	4.4	429.2	12.4	21.2	3.6	3.6	7.3
Finland	205.5	37.7	990.5			5.3	16.4	15.2
France	211.7	41.1	538.8					9.9
Germany	278.8	37.6	880.0		84.8	23.0		33.9
Greece	124.8	39.4	909.1	16.4	18.2	7.3	36.0	26.0
Hungary	180.3	10.0	260.5	3.5	30.1	5.0	5.3	6.0
Iceland	156.5	17.0	1 224.5		23.8		10.2	20.4
Japan	690.5	22.8	1 030.3			25.3	73.6	92.6
Korea, Rep.	321.6	30.8	507.1	2.5	122.5	3.4	35.8	30.7
Latvia	161.2	14.8	265.8	2.6	8.7	1.3	3.5	17.9
Lithuania	228.3	7.4	165.6					6.6
Luxembourg	135.0	22.1	942.5	13.3	88.5	13.3	2.2	26.5
Malta	142.5	32.5	372.5	7.5	25.0	7.5	15.0	25.0
Netherlands	179.1							
New Zealand	178.0	25.7	596.2	6.2			11.5	12.0
Norway	178.9	18.8	1 379.3	16.2	43.1			26.7
Russian Federation	126.5	8.0	39.8	3.3	75.0	1.7	0.2	2.6
Slovakia	119.5							
Slovenia	128.3	17.0	187.7	6.5		4.0	17.0	10.0
Spain	282.0	24.8	419.1	0.7	28.4		8.7	12.8
Sweden	135.4	20.3	1 354.2	3.4			4.5	14.7
Switzerland	688.1	32.0	1 319.7	179.2	174.2	5.0	18.1	28.7
The former Yugoslav Republic of Macedonia	68.9	7.4	66.9	32.5	30.0	2.5	1.0	6.4
United Kingdom								6.7
Venezuela (Bolivarian Republic of)	18.7	3.3	8.0		2.2		1.1	2.4
Weighted average	370	28	660	8.5	96	15	27	32
Health-care level II								
Azerbaijan	0.8	0.3	0.0					0.0
Brazil	97.6	16.4	110.3		7.5	2.9	5.0	10.9
Chile	94.2	18.5	53.9	1.1	4.6	2.8	5.2	10.7
China	47.3	0.6	2.0					3.0
Colombia	44.2	2.4	60.9	0.1				2.6
Costa Rica	65.6	10.6	149.8	2.8	6.7	6.7	3.0	2.8
El Salvador	17.4	5.8	76.9	0.8	8.2	0.8	0.6	2.6
Mauritius	39.2	1.7	50.0	9.2				1.7
Oman	78.8	2.0	16.4	1.0			0.5	3.0

Country	X-ray generators						Bone densitometry	CT scanners
	Medical	*Mammography*	*Dental*	*Interventional*	*General fluoroscopy*	*Angiography*		
Thailand	47.3	1.6	27.7	28.0				4.3
Trinidad and Tobago	39.6	19.0	71.3	4.0	11.9		3.2	6.3
Tunisia	116.9	8.0	79.1	2.2			0.7	9.1
Turkey	57.7	6.4	16.2	2.7			3.7	
Weighted average	47	0.9	4.4	0.6	1.2	0.5	0.7	3.1
Health-care level III								
Zimbabwe	20.8	0.2	16.7	0.2	2.5	1.3		0.7
Average	21	0.2	17	0.2	2.5	1.3		0.7
Health-care level IV								
Maldives	53.3	3.3	6.7	0.0	3.3	0.0	3.3	3.3
Average	53	3.3	6.7	0.0	3.3	0.0	3.3	3.3

Table B39. Number of items of digital diagnostic equipment in various countries per million population

Country	*Digital systems*					
	General	*Mammography*	*Dental*	*Interventional*	*General fluoroscopy*	*Angiography*
Health-care level I						
Albania	28.8	0.9		0.3	15.6	0.3
Australia	1.5					
Bulgaria	3.4	0.1	2.1	1.0		
Czech Republic				3.5		
Estonia	19.0			4.4	7.3	0.7
Finland	0.0					15.4
Hungary	1.5			0.3	1.5	0.3
Iceland	102.0					20.4
Japan	16.3				20.8	
Latvia					3.1	0.9
Luxembourg	6.6	0.0		4.4		
New Zealand		0.0	0.8			
Romania	2.7	0.0	0.0	0.1		0.1
Russian Federation	1.5		3.6			
Spain	57.8	9.1	26.8	6.2	25.2	
Sweden	45.1	0.2	22.6	2.3		
Venezuela (Bolivarian Republic of)	0.0	0.0	1.6			
Weighted average	14	4.5	7.6	3.2	20	2.2
Health-care level II						
El Salvador	2.3					
Mauritius	0.0	0.0	0.0	0.0	0.0	0.0
Trinidad and Tobago			15.8		2.4	3.2
Tunisia	1.0					
Weighted average	1.4	0.0	8.1	0.0	1.2	1.6

Table B40. Trends in average provision of medical radiology per million population
Data from the UNSCEAR Global Surveys of Medical Radiation Usage and Exposures

Resource	*Years*	*Number per million population at health-care level*			
		I	*II*	*III*	*IV*
Physicians	1985–1990	2 600	550	180	53
	1991–1996	2 780	695	210	45
	1997–2007	3 530	1 580	1.1	60
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
	1997–2007	77	45	1	10
Dentists	1991–1996	530	87	49	3
	1997–2007	540	280	17	33
Medical physicists	1997–2007	7	1.5	0.3	0
Radiology technicians	1997–2007	370	100	15	77
Diagnostic radiology physicians	1997–2007	77	45	1.3	10
Interventional cardiologists	1997–2007	40	2.2		3.3
Medical X-ray generators, conventional	1970–1974	450	14		0.6
	1980–1984	380	71	16	10
	1985–1990	350	86	18	4
	1991–1996	290	60	40	4
	1997–2007	370	47	21	53
Mammography X-ray generators, conventional	1991–1996	24	0.5	0.2	0.1
	1997–2007	28	0.9	0.2	3.3
Dental X-ray generators, conventional	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
	1997–2007	660	4	17	6.7
Interventional radiology systems, conventional	1997–2007	8.5	0.6	0.2	0.0
CT scanners	1991–1996	17	2.4	0.4	0.1
	1997–2007	32	3.1	0.7	3.3
General X-ray generators, digital	1997–2007	14	1.4		
Mammography, digital	1997–2007	4.5	0.0		
Dental, digital	1997–2007	7.6	8.1		
Interventional radiology, digital	1997–2007	3.2	0.0		
Bone mineral densitometry	1997–2007	27	0.7		3.3

Table B41a. Annual number of medical radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photo-fluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
I	Australia	2 208 100	1 464 300			3 256 400	822 100		455 900		523 200	
	Austria	1 977 000	1 200 000			1 718 000	400 000	392 000	222 000	207 000	332 000	325 000
	Belgium	2 533 800	1 637 700	412		2 811 900	391 400	391 400	195 700	195 700	350 200	350 200
	Bulgaria	569 187	243 937	94 126	33 745	635 511	45 880	107 056	15 746	63 058	30 242	56 165
	Croatia	676 834	378 674		32 381	1 545 721						
	Czech Republic	1 060 106	58 102		43 489	1 572 134	268 128	200 112	16 100	8 414	112 621	143 114
	Finland	1 173 914				1 102 625	156 261		31 310		76 736	
	France	5 600 000				14 000 000	7 900 000					
	Germany	17 134 400				21 195 500	3 940 700		2 055 100		4 491 500	
	Greece	3 400 000				1 500 000	800 000					
	Hungary	4 794 000	463 000	301 000	550 000	2 161 000	14 000	442 000	13 000	244 000	13 000	287 000
	Iceland	47 992				55 062	6 017		2 503		3 540	
	Japan	83 271 000			397 000	20 817 000	10 060 000		2 488 000		6 609 000	
	Korea, Rep.	18 408 379	2 125 281				3 542 052	2 727 445	873 330	875 428	2 101 582	2 083 825
	Latvia	464 404		320 196		734 261						
	Lithuana	440 451		1 142 015	170 753	1 414 331						
	Luxembourg	53 412	21 419			109 353	25 138		7 915		12 812	
	Malta	33 053	574	0	0	23 603	2 962	2 962	732	732	1 666	1 656
	Netherlands	2 600 000										
	Norway	185 256	545 050			886 887	161 058		40 018		92 562	
	Romania	997 265	314 207	1 385 085	1 962 670	1 740 362	183 739	341 123	71 400	144 964	214 543	143 028
	Russian Federation	10 500 000	8 540 000	59 700 000	2 600 000	2 940 000	2 770 000	1 700 000	2 230 000	759 000	2 360 000	1 940 000
	Slovenia	388 000	121 000			452 000	117 000	125 000	51 000	51 000	145 000	151 000
	Spain	14 391 203	6 460 927			1 919 608	1 066 753	787 090	869 715	602 227	1 988 509	628 466
	Sweden	841 000	841 000	0	0	1 338 000	170 000	170 000	76 000	76 000	90 700	90 700
	Switzerland	1 400 000	350 000	51 000	3 200	1 940 000	279 000	279 000	82 000	82 000	195 000	195 000
	The former Yugoslav Republic of Macedonia	4 320				5 760						
	United Kingdom	8 300 000	-	-		7 700 000	825 000		281 000		859 000	

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photo-fluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
II	Costa Rica	60 629	45 897	0	6	34 088	7 020	7 020	3 500	3 500	3 516	3 516
	El Salvador	1 823 400	455 800		386	189 800	34 200	34 200	5 700	5 700	17 100	17 100
	Mauritius	64 500	3 200	0	0	163 600	38 760					
	Oman	163 677				216 475				77 169		
	Trinidad and Tobago	65 764	17 764				27 363		13 048		24 514	
III	Zimbabwe	20 000	4 000	10 000	0	3 500	10 000	10 000	8 000	8 000	15 000	15 000
IV	Maldives	494	237			8 456	1 550	1 551	270	269	716	781

Table B41b. Annual number of medical radiological examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography*	
									Screening	*Clinical diagnosis*
I	Australia	953 300	385 500	242 000			2 790	52 200	800 000	337 000
	Austria	498 000	338 000	156 000	113 000	149 000	20 000	131 000	630 000	410 000
	Belgium	906 400	319 300	494 400	91 670	81 370	7 210	97 850	72 100	947 600
	Bulgaria	123 631	157 725	81 449	105 328	59 267	3 521	31 572	57 066	40 244
	Croatia			68 188	85 611	28 271	1 363	66 464		250 962
	Czech Republic	317 354	417 220	156 953	34 553	52 867	10 954	66 703		248 602
	Finland	180 644	396 993	55 159	5 361	13 625	4 321	7 037	197 712	93 117
	France	4 300 000	2 300 000	2 500 000					5 600 000	
	Germany	6 975 000	3 751 100	2 570 000	302 400	571 800	95 000	1 208 300	5 150 300	
	Greece	320 000	430 000		170 000					195 000
	Hungary	533 000	633 000	471 000	99 000	22 000	1 600	47 000	253 000	1 506 000
	Iceland	2 517	6 297	3 996	1 161	1 437		2 146	14 872	500
	Japan	3 589 000	8 461 000	16 210 000	15 000 000	2 270 000	553 000	1 442 000		844 000
	Korea, Rep.	2 249 892	4 314 452	4 323 800						
	Latvia			277 873	24 969	9 044	754	44 977	85 915	
	Lithuania			264 046				90 888	85 944	

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography*	
									Screening	*Clinical diagnosis*
I	Luxembourg	29 612	9 582	8 880	2 396	1 095	158	6 921	12 252	11 271
	Malta	1 238	3 713	8 473	1 850	1 622	0	1 632	5 059	1 604
	Netherlands								700 000	250 000
	Norway	340 969	31 300	45 808	10 733	28 245		24 628	1 485 263	2 005 303
	Romania	274 433	601 641	70 604	749 516	252 805	19 658	248 250		90 388
	Russian Federation	2 420 000	6 060 000	808 000	1 710 000	855 000	162 000	804 000	239 000	871 000
	Slovenia	219 000	182 000	40 000						60 000
	Spain	981 484	628 316	933 446	446 020	359 087	38 858	272 681	1 368 981	1 473 994
	Sweden	420 000	73 000	63 000	63 600	70 000		75 000	520 000	260 000
	Switzerland	312 000	160 000	92 000	13 000	16 000	6 000	42 000		265 000
	The former Yugoslav Republic of Macedonia			2 880				1 728	8 640	
	United Kingdom	1 773 000	1 118 000	1 217 000	222 000	400 000	68 000	258 000	1 334 000	390 000
II	Costa Rica	5 267	11 456	10 326	891	1 629	251	736	5 250	5 250
	El Salvador	28 500	61 940	61 940	171 000	114 000	142 500	142 500	158 680	68 000
	Mauritius		49 800	20 900	2 320			760	0	253
	Oman	19 064	64 589	47 044	4 761		193	3 817	1 206	
	Trinidad and Tobago	16 673	14 015	24 380	1 990	1 317		1 758	2 196	
III	Zimbabwe	25 000	30 000	20 000	5 000	5 000	0	10 000	10 000	10 000
IV	Maldives	586	1 688	1 333	56	52		19		

Table B41c. Annual number of medical radiological examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*CT*							*Interventional procedures*				*Angiography*	
		Head	*Thorax*	*Abdomen*	*Spine*	*Pelvis*	*Inter-ventional*	*Other*	*PTCA*	*Cerebral*	*Vascular*	*Others*	*Non-cardiac*	*Cardiac*
I	Australia												67 400	31 500
	Austria	218 000	101 000	96 000	40 000	44 000		112 000	30 000	3 000	16 000	23 000	73 000	7 000
	Belgium	432 600	669 500	669 500					19 570		9 270		133 900	19 570
	Bulgaria									5 400	5 488		1 601	
	Croatia	89 444			24 247	105 521			14 800				11 978	

Health-care level	*Country*	*CT*							*Interventional procedures*				*Angiography*	
		Head	*Thorax*	*Abdomen*	*Spine*	*Pelvis*	*Inter-ventional*	*Other*	*PTCA*	*Cerebral*	*Vascular*	*Others*	*Non-cardiac*	*Cardiac*
I	Czech Republic	187 427	44 753	78 114	58 200	44 741			8 030	4 512	3 200	1 203	4 424	92 196
	Finland	136 512	33 078	62 948	14 158	1 177	2 091	17 107	9 854	436	7 276	14 416	12 432	16 556
	France	1 900 000	620 000	930 000	1 300 000			350 000	105 553	12 183	354 000	420 000		
	Germany	3 267 700	1 488 600	2 269 300	1 588 500	372 200		90 800	189 700	137 400			1 047 500	1 280 300
	Greece	210 000	180 000	200 000	85 000	200 000	0	36 000					35 000	35 000
	Hungary	276 000	199 000	225 000	58 000	54 000	1 100	55 000					82 000	
	Iceland	10 718	2 936	6 024	3 229	231	0	1 475	580		193	120	793	2 121
	Japan	16 613 000	11 167 000	12 878 000		3 796 000		195 000					1 102 000	
	Korea, Rep.	881 008	188 804	278 096										
	Latvia	62 497	19 984	28 800	29 271			3 677	2 798	142	124	241	3 913	6 107
	Lithuania	104 650							7 633					
	Luxembourg	19 795	6 035	11 879	16 807			6 378	698	32	634	235	3 163	1 545
	Malta	5 673	1 351	2 707	220	1 036	40	636	578	0	75	290	370	2 051
	Netherlands	300 000	210 000	305 000						19 000			130 000	
	Norway	183 922	49 631	81 279	76 871	51 991		10 457	2 517	357	10 930		28 732	17 032
	Romania	235 723	225 355						15 942				34 162	19 358
	Russian Federation	714 000	102 000	204 000					80 000	60 100	50 000	40 000	130 000	35 000
	Slovakia	30 000	30 000	30 000	30 000				3 600					1 800
	Spain	719 523	247 082	645 489	219 030	149 713	65 404	132 227	28 757	7 419	67 442	132 484	75 158	56 330
	Sweden	324 000	97 000	128 000	12 000	25 000		24 000						
	Switzerland	196 000	84 000	166 000	80 000	120 000		20 000	7 800	650	9 500	3 500	22 000	20 000
	The former Yugoslav Republic of Macedonia	11 520							1 728					
	United Kingdom	618 000	193 000	297 000				8 000	26 000	2 000	65 000	97 000	158 000	163 000
II	Costa Rica	8 868	786	1 770	1 180	590		721					125	
	El Salvador	17 000	7 480	20 400	2 176	9 520		11 424	770	462	77	231	721 772	37 988
	Mauritius	0	0	0					0	0	0	0	0	280
	Oman	14 625											183	1 363
	Trinidad and Tobago	4 143	1 875	1 778	581	1 441		226						
III	Zimbabwe	10 000	8 000	8 000	6 000	4 000	1 000		0	0	0	0	0	0
IV	Maldives	992	98	110	58	76								

Table B41d. Annual number of various medical and dental radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvimetry*	*Other medical*	*Total medical*	*Intraoral*	*Panoramic*	*Dental CT*	*Total dental*
I	Austria			8 770 000	5 500 000	1 350 000	400	6 850 000
	Belgium	6 180	1 050 600	14 887 002				
	Bulgaria	11 808	136 808	3 014 561	260 309	12 265		272 574
	Croatia				314 843	68 944		383 787
	Czech Republic			5 773 618	2 094 778	367 660		2 462 438
	Finland	1 860	25 872	3 583 517	1 656 000	300 000		1 956 000
	France			47 000 000	15 700 000	2 300 000		18 000 000
	Germany		5 873 400	87 046 500				47 925 500
	Greece					22 000		
	Iceland	198	6 561	182 719				
	Japan	60 000	19 524 000	237 346 000	61 443 000	11 975 000		73 418 000
	Korea, Rep.			44 994 733				
	Latvia	100 054	320 215	2 540 216				114 960
	Lithuania							356 199
	Luxembourg	1	2 702	397 239	108 158	21 444		175 767
	Malta	0	0	108 158	42 321	1 146	0	43 467
	Netherlands			8 400 000				8 200 000
	Norway			3 377 606	1 790 000	56 500		1 865 500
	Romania	9 110	61 742	10 555 115	327 406	15 537		342 943
	Russian Federation	16 000	45 700 000	157 800 000	13 300 000	2 100 000		14 100 000
	Slovenia							375 000
	Spain	245 346	56 356	38 055 077	3 753 836	1 181 763	449	4 936 048
	Switzerland		43 600	6 400 000	3 800 000	231 000		4 031 000
	The former Yugoslav Republic of Macedonia			36 576				
	United Kingdom	6 000		29 000 000	9 500 000	3 000 000		12 500 000
II	Costa Rica	0		223 778		5 000		
	El Salvador	5 698		4 367 444	83 300	36 000		119 300
	Mauritius	0	0	383 100				320
	Oman				19 508	5 965		25 473
III	Zimbabwe	0			30 000	1 000		
IV	Maldives			77 580				

Table B42. Total annual number of diagnostic medical and dental radiological examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Diagnostic examinations*	
		Medical	*Dental*
I	Austria	8 770 000	6 850 000
	Belgium	14 887 002	14 887 002
	Bulgaria	3 014 561	272 574
	Croatia		383 787
	Czech Republic	5 773 618	2 462 438
	Finland	3 583 517	1 956 000
	France	47 000 000	18 400 000
	Germany	87 046 500	47 925 500
	Iceland	182 719	
	Japan	237 346 000	73 418 000
	Korea, Rep.	44 994 733	
	Latvia	2 540 216	114 960
	Lithuana		356 199
	Luxembourg	397 239	175 767
	Malta	108 158	43 467
	Netherlands	9 900 000	4 920 000
	Romania	10 555 115	342 943
	Russian Federation	157 800 000	14 100 000
	Slovenia		375 000
	Spain	38 055 077	4 936 048
	Sweden	5 120 000	
	Switzerland	6 400 000	4 031 000
	The former Yugoslav Republic of Macedonia	36 576	
	United Kingdom	29 000 000	12 500 000
II	Costa Rica	223 778	
	El Salvador	4 367 444	119 300
	Mauritius	383 100	320
	Oman		25 473
IV	Maldives	77 580	

Table B43a. Annual number of various medical examinations per 1,000 population

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photo-fluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
I	Australia	108.21	71.76			159.58	40.29		22.34		25.64	
	Austria	241.1	146.34			209.51	48.78	47.80	27.07	25.24	40.49	39.63
	Belgium	246.00	159.00	0.04		271.00	38.00	38.00	19.00	19.00	34.00	34.00
	Bulgaria	69.85	29.93	11.55	4.14	77.99	5.63	13.14	1.93	7.74	3.71	6.89
	Croatia	152.54	85.34		7.30	348.37						
	Czech Republic	103.02	5.65	0.00	4.23	152.78	26.06	19.45	1.56	0.82	10.94	13.91
	Finland	223.60				210.02	29.76		5.96		14.62	
	France	90.76				226.90	128.04					
	Germany	207.69				256.91	47.77		24.91		54.44	
	Greece	309.09				136.36	72.73					
	Hungary	480.31	46.39	30.16	55.10	216.51	1.40	1.30	1.30	24.45	1.30	28.75
	Iceland	163.24				187.29	20.47	8.51	8.51		12.04	
	Japan	653.44			3.12	163.36	78.94		19.52		51.86	
	Korea, Rep.	391.60	45.21				75.35	58.02	18.58	18.62	44.71	44.33
	Latvia	202.35		139.52		319.94						
	Lithuania	126.17		327.13	48.91	405.14						
	Luxembourg	118.17	47.39			241.93	55.62		17.51		28.35	
	Malta	82.63	1.44			59.01	7.41	7.41	1.83	1.83	4.17	4.14
	Netherlands	166.26										
	Norway	39.93	117.47			191.14	34.71		8.62		19.95	
	Romania	45.93	14.47	63.80	90.40	80.16	8.46	15.71	3.	6.68	9.88	6.59
	Russian Federation	71.57	58.21	406.95	17.72	20.04	18.88	11.59	15.20	5.17	16.09	13.22
	Slovenia	193.71	60.41			225.66	58.41	62.41	25.46	25.46	72.39	75.39
	Spain	326.26	146.48			43.52	24.18	17.84	19.72	13.65	45.08	14.25
	Sweden	94.91	94.91			151	19.19	19.19	8.58	8.58	10.24	10.24
	Switzerland	187.64	46.91	6.84	0.43	260.02	37.39	37.39	10.99	10.99	26.14	26.14
	The former Yugoslav Republic of Macedonia	2.12				2.83						
	United Kingdom	139.50				129.41	13.87		4.72		14.44	
	Weighted average	168	70	287	17	140	31	23	16	9.8	32	19

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photo-fluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
II	Azerbaijan	0.48		0.01		0.09	0.01		0.00		0.00	
	Costa Rica	14.02	10.61		0.00	7.88	1.62	1.62	0.81	0.81	0.81	0.81
	El Salvador	280.52	70.12		0.06	29.20	5.26	5.26	0.88	0.88	0.88	2.63
	Mauritius	53.75	2.67			136.33	32.30					
	Oman	81.11				107.27				38.24		
	Trinidad and Tobago	52.11	14.08				21.68		10.34		19.42	
	Weighted average	140	39	0.01	0.03	27	3.8	3.8	0.85	6.7	1.9	1.9
III	Zimbabwe	1.7	0.33	0.83	0.00	0.29		0.83	0.67	0.67	1.3	1.3
	Average	1.7	0.33	0.83	0.00	0.29		0.83	0.67	0.67	1.3	1.3
IV	Maldives	0.04	0.02			0.70	0.13	0.13	0.02	0.02	0.06	0.07
	Average	0.04	0.02			0.70	0.13	0.13	0.02	0.02	0.06	0.07

Table B43b. Annual number of various medical examinations per 1,000 population
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography*	
									Screening	*Clinical diagnosis*
I	Australia	46.72	18.89	11.86			0.14	2.56	39.20	16.51
	Austria	60.73	41.22	19.02	13.78	18.17	2.44	15.98	76.83	50.00
	Belgium	88.00	31.00	48.00	8.90	7.90	0.70	9.50	7.00	92.00
	Bulgaria	15.17	19.36	9.99	12.93	7.27	0.43	3.87	7.00	4.94
	Croatia	0.00		15.37	19.29	6.37	0.31	14.98		56.56
	Czech Republic	30.84	40.55	15.25	3.36	5.14	1.06	6.48		24.16

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography*	
									Screening	*Clinical diagnosis*
I	Finland	34.41	75.62	10.51	1.02	2.60	0.82	1.34	37.66	17.74
	France	69.69	37.28	40.52					90.76	
	Germany	84.54	45.47	31.15	3.67	6.93	1.15	14.65	62.43	
	Greece	29.09	39.09		15.45					17.73
	Hungary	53.40	63.42	47.19	9.92	2.20	0.16	4.71	25.35	150.89
	Iceland	8.56	21.42	13.59	3.95	4.89		7.30	50.59	1.70
	Japan	28.16	66.40	127.20	117.71	17.81	4.34	11.32		6.62
	Korea, Rep.	47.86	91.78	91.98						
	Latvia			121.08	10.88	3.94	0.33	19.60	37.44	
	Lithuania							26.03	24.62	
	Luxembourg	65.51	21.20	19.65	5.30	2.42	0.35	15.31	27.11	24.94
	Malta	3.10	9.28	21.18	4.63	4.06	0.00	4.08	12.65	4.01
	Netherlands								44.76	15.99
	Norway	73.48	6.75	9.87	2.31	6.09		5.31	320.10	432.18
	Romania	12.64	27.71	3.25	34.52	11.64	0.91	11.43		4.16
	Russian Federation	16.50	41.31	5.51	11.66	5.83	1.10	5.48	1.63	5.94
	Slovenia	109.34	90.86	19.97						29.96
	Spain	22.25	14.24	21.16	10.11	8.14	0.88	6.18	31.04	33.42
	Sweden	47.40	8.24	7.11	7.18	7.90		8.46	58.68	29.34
	Switzerland	41.82	21.44	12.33	1.74	2.14	0.80	5.63		35.52
	The former Yugoslav Republic of Macedonia							0.85		
	United Kingdom	29.80	18.79	20.45	3.73	6.72	1.14	4.34	22.42	6.55
	Weighted average	40	44	45	34	9.3	1.7	8.5	23	20
II	Costa Rica	1.22	2.65	2.39					1.21	1.21
	El Salvador	4.38	9.53	9.53	26.31	17.54	21.92	21.92	24.41	10.46
	Mauritius		41.50	17.42	1.93			0.63	0.00	0.21
	Oman	9.45	32.01	23.31	2.36		0.10	1.89	0.60	
	Trinidad and Tobago	13.21	11.11	19.32	1.58	1.04		1.39	1.74	
	Weighted average	4.9	13	11	12	9.7	11	9.8	14	6.1
III	Zimbabwe	2.08	2.50	1.67				0.83	0.83	0.83
	Average	2.1	2.5	1.7				0.83	0.83	0.83
IV	Maldives	1.95	5.63	4.44	0.52	0.17		0.06		
	Average	1.9	5.6	4.4	0.52	0.17		0.06		

Table B43c. Annual number of various medical examinations per 1,000 population

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*CT*							*Interventional procedures*				*Angiography*	
		Head	*Thorax*	*Abdomen*	*Spine*	*Pelvis*	*Interventional*	*Other*	*PTCA*	*Cerebral*	*Vascular*	*Others*	*Non-cardiac*	*Cardiac*
I	Australia												3.30	1.54
	Austria	26.59	12.32	11.71	4.88	5.37		13.66	3.66	0.37	1.95	2.80	8.90	0.85
	Belgium	42.00	65.00	65.00					1.90		0.90		13.00	1.90
	Bulgaria									0.66	0.67		0.20	
	Croatia	20.16	0.00	0.00	5.46	23.78			3.34				2.70	
	Czech Republic	18.21	4.35	7.59	5.66	4.35			0.78	0.44	0.31	0.12	0.43	8.96
	Finland	26.00	6.30	11.99	2.70	0.22	0.40	3.26	1.88	0.08	1.39	2.75	2.37	3.15
	France	30.79	10.05	15.07	21.07			5.67	1.71	0.20	5.74	6.81		
	Germany	39.61	18.04	27.51	19.25	4.51		1.10	2.30	1.67			12.70	15.52
	Greece	19.09	16.36	18.18	7.73	18.18	0.00	3.27					3.18	3.18
	Hungary	27.65	19.94	22.54	5.81	5.41	0.11	5.51						
	Iceland	36.46	9.99	20.49	10.98	0.79	0.00	5.02	1.97		0.66	0.41	2.70	7.21
	Japan	130.36	87.63	101.06		29.79		1.53					8.65	
	Korea, Rep.	18.74	4.02	5.92										
	Latvia	27.23	8.71	12.55	12.75			1.60						
	Lithuania	29.98							2.19					
	Luxembourg	43.79	13.35	26.28	37.18			14.11	1.54	0.07	1.40	0.52	7.00	3.42
	Malta	14.18	3.38	6.77	0.55	2.59	0.10	1.59	1.45	0.00	0.19	0.73	0.93	5.13
	Netherlands	19.18	13.43	19.50						1.21			5.12	
	Norway	39.64	10.70	17.52	16.57	11.20		2.25	0.54	0.08	2.36		6.19	3.67
	Romania	10.86	10.38						0.73				1.57	0.89
	Russian Federation	4.87	0.70	1.39					0.55	0.41	0.34	0.27	0.89	0.24
	Slovenia	14.98	14.98	14.98	14.98				1.80					0.90
	Spain	16.31	5.60	14.63	4.97	3.39	1.48	3.00	0.65	0.17	1.53	3.00	1.70	1.28
	Sweden	36.56	10.95	14.45	1.35	2.82		2.71						
	Switzerland	26.27	11.26	22.25	10.72	16.08		2.68	1.05	0.09	1.27	0.47	2.95	2.68
	United Kingdom	10.39	3.24	4.99				0.13	0.44	0.03	1.09	1.63	2.66	2.74
	Weighted average	40	24	30	11	19	0.97	2.8	0.92	0.31	1.6	1.1	2.6	1.5

Health-care level	*Country*	*CT*							*Interventional procedures*				*Angiography*	
		Head	*Thorax*	*Abdomen*	*Spine*	*Pelvis*	*Interventional*	*Other*	*PTCA*	*Cerebral*	*Vascular*	*Others*	*Non-cardiac*	*Cardiac*
II	Costa Rica	2.05	0.18	0.41	0.27	0.14		0.17					0.03	
	El Salvador	2.62	1.15	3.14	0.33	1.46		1.76	0.12	0.07	0.01	0.04	(111.04)	5.84
	Mauritius	0.00	0.00	0.00					0.00	0.00	0.00	0.00	0.00	0.23
	Oman	7.25												
	Trinidad and Tobago	3.28	1.49	1.41	0.46	1.14		0.18						
	Weighted average	2. 3	0.76	1.8	0.33	0.96		1.0	0.10	0.06	0.01	0.03	0.02	5.0
III	Zimbabwe	0.83	0.67	0.67	0.50	0.33	0.08		0.00	0.00	0.00	0.00	0.00	0.00
	Average	0.83	0.67	0.67	0.50	0.33	0.08		0.00	0.00	0.00	0.00	0.00	0.00
IV	Maldives	3.31	0.33	0.37	0.19	0.25								
	Average	3.3	0.33	0.37	0.19	0.25								

Note: Data for El Salvador in parentheses were excluded from the calculation of the weighted average for non-cardiac angiography.

Table B43d. Annual number of various medical and dental radiological examinations per 1,000 population
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvimetry*	*Other medical*	*Total medical*	*Intraoral*	*Panoramic*	*Dental CT*	*Total dental*
I	Austria			1 069.51	670.73	164.63	0.05	835.37
	Belgium	0.60	102.00	1 445.34				
	Bulgaria	1.45	16.79	369.93	31.94	1.51		33.45
	Croatia				70.96	15.54		86.50
	Czech Republic			561.09	203.57	35.73		239.30
	Finland	0.35	4.93	682.57	315.43	57.14		372.57
	France			761.75	254.46	37.28		291.73
	Germany		71.19	1 055.1				580.91
	Greece					2.00		
	Iceland	0.67	22.32	621.49				
	Japan	0.47	153.21	1 862.49	482.07	93.97		576.12
	Korea, Rep.			957.17				
	Latvia	43.60	139.53	1 106.85				50.09
	Lithuania							102.03
	Luxembourg	0.00	5.98	878.85	239.29	47.44		388.87
	Malta	0.00	0.00	270.40	105.80	2.87	0.00	108.67
	Netherlands			633.07	306.94	7.67		314.62
	Norway			727.93	385.78	12.18		402.05
	Romania	0.42	2.84	486.16	15.08	0.72		15.80
	Russian Federation	0.11	311.52	1 075.66	90.66	14.31		96.11
	Slovenia							187.22
	Spain	5.56	1.28	862.75	85.10	26.79	0.01	111.91
	Switzerland		5.84	857.79	509.32	30.96		540.28
	United Kingdom	0.10		487.39	159.66	50.42		210.08
	Weighted average	1.1	159	1 176	230	49	0.02	316
II	Costa Rica	0.00		51.73		1.16		
	El Salvador	0.88		671.91	12.82	5.54		18.35
	Mauritius	0.00	0.00	319.25				0.27
	Oman				9.67	2.96		12.62
	Weighted average	0.47	0.00	410	12	3.6		15
III	Zimbabwe	0.00			2.50	0.08		
	Average	0.00			2.5	0.08		
IV	Maldives			258.60				
	Average			260				

Table B44. Total annual numbers of medical and dental radiological examinations per 1,000 population
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Total medical*	*Total dental*	*Total diagnostic*
I	Austria	1 069.51	835.37	1 904.88
	Belgium	1 445.34		1 445.34
	Bulgaria	369.93	33.45	403.38
	Croatia		86.50	
	Czech Republic	561.09	239.30	800.39
	Finland	682.57	372.57	1 055.15
	France	761.75	291.73	1 053.48
	Germany	1 055.1	580.91	1 636.01
	Iceland	621.49		
	Japan	1 862.49	576.12	2 438.61
	Korea, Rep.	957.17		
	Latvia	1 106.85	50.09	1 156.94
	Lithuania		102.03	
	Luxembourg	878.85	388.87	1 267.71
	Malta	270.40	108.67	379.06
	Netherlands	537.15	314.62	851.77
	Norway	727.93	402.05	1 129.98
	Romania	486.16	15.80	501.96
	Russian Federation	1 075.66	96.11	1 171.78
	Slovenia		187.22	
	Spain	862.75	111.91	974.66
	Sweden	566		
	Switzerland	857.79	540.28	1 398.07
	United Kingdom	487.39	210.08	697.48
	Weighted average	1 176.38	351.62	1 492.80
II	Costa Rica	51.73		
	El Salvador	671.91	18.35	690.27
	Mauritius	319.25	0.27	319.52
	Oman		12.62	
	Weighted average	410	15	430
IV	Maldives	258.60		
	Average	260		

Table B45a. Mean patient dose[a] for various medical and dental radiological examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photo-fluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
I	Australia	0.16	0.73				4.60	13.10	3.10	7.80	0.71	0.55
	Belgium	0.15	1.23				6.10	10.50				
	Czech Republic	0.40	1.20				11.10	15.00	7.00	11.00	6.90	7.20
	Germany	**0.13**	0.46				2.31	4.76	1.46	1.64	0.39	0.20
	Greece	0.50					10.00	30.00			1.30	
	Hungary	0.52	0.91	4.18			5.86	12.40	4.14	6.05	1.48	1.45
	Iceland	**0.57**					**9.60**		**4.20**		**0.90**	
	Japan	0.33	0.44		22.00	0.33	2.70	15.89	2.37	3.80	0.45	
	Lithuania	0.44	1.60	4.40			9.20	27.00	3.30	9.00	1.40	1.00
	Malta	0.20	0.45				5.07	5.80	2.50	5.80	0.25	0.22
	Netherlands	0.04										
	Norway	**0.64**	**0.82**				**4.20**		**3.79**		**1.49**	
	Romania	1.30	3.50	7.20	**5.40**	4.50	17.40	37.40	15.50	26.90	5.90	7.10
	Slovenia	0.29	0.96				6.06	15.52	5.75	6.43	1.40	1.40
	Spain	0.17	0.49			0.13	4.40	10.80	3.10	1.96	1.50	1.40
	Sweden	**0.40**	**0.40**				**6.5**	**6.5**				
	Switzerland	0.10	0.20	0.40	**11.00**	1.00	4.40	17.00	3.00	14.00	1.60	1.80
	United Kingdom	0.16				0.10	6.00	14.00	4.00	11.00	1.70	0.30
II	Chile	0.20	0.70									
	Mauritius	0.40	1.50				AP 10; LAT 30					
	Oman	0.44					16.59					
	Thailand	0.20										
	Tunisia	0.20	11.00				6.30	15.90				
	Turkey	0.38	1.68				4.35	17.60	2.85	11.20		
IV	Maldives	0.20	0.20			0.01	1.30		0.70		0.08	

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[a] Values in regular type are for entrance air kerma in mGy; values in bold type are for DAP in Gy cm^2.

Table B45b. Mean patient dose[a] for various medical and dental radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography (mean glandular dose)*	
									Screening	*Clinical diagnosis*
I	Australia								2.00	2.00
	Belgium			*8.25*					*1.54*	
	Czech Republic	9.90	5.10	9.30	10.20	**19.00**	**12.00**	**11.00**		2.00
	Germany	**1.96**	**0.44**	**2.64**	**23.53**	**57.43**				5.00
	Greece		3.00							7.00
	Hungary	4.78	2.27	3.36						
	Iceland	**2.40**	**1.20**	**7.80**	**31.90**	**89.00**		**19.40**		
	Japan	3.16	2.37	2.37	2.90	2.90	2.84			
	Lithuania	6.10	2.40	7.50						
	Malta	2.65	0.67	2.65	1.87	2.03			3.04	4.17
	Netherlands				**21.00**	**29.00**				
	Norway	**5.17**								
	Romania	15.60	16.30	16.70	**21.50**	**36.80**	32.10	51.60		44.80
	Slovenia	3.95	1.98	4.43						1.27
	Spain	7.00	2.70	5.40	**19.00**	**38.00**	**1.41**	**33.20**	6[b]	6.7[b]
	Sweden	**1.60**				**30.00**		**15.00**	2.1	2.7
	Switzerland	10.00	3.30	3.30	20.00	20.00	33.00	24.00		
	United Kingdom	4.00	2.00	5.00	**9.00**	**20.00**	**15.00**	**10.00**		
II	Chile	4.00	4.30							10.00
	Mauritius	10.00	5.00	10.00			10.00	10.00		
	Oman		17.50							
	Thailand			2.20						7.80
	Tunisia			7.60						
	Turkey	3.10	4.00							1.65
IV	Maldives	0.70	0.07	0.70	3.00	7.00		2.50		

[a] Values in regular type are for entrance air kerma in mGy; values in bold type are for DAP in Gy cm^2; values in italic type are for ESD.

[b] ESD in mammography.

Table B45c. Mean patient dose^a for various medical and dental radiological examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*CT*							*Interventional procedures*				*Angiography*	
		Head	*Thorax*	*Abdomen*	*Spine*	*Pelvis*	*Interventional*	*Other*	*PTCA*	*Cerebral*	*Vascular*	*Others*	*Non-cardiac*	*Cardiac*
I	Czech Republic	39.00	22.00	28.00	36.00	39.00			**120.00**	**52.00**	**29.00**		**38.00**	**68.00**
	Germany	**980**	**508**	**1 239**	**248**								**77.46**	
	Greece	90.00	65.00	72.00	90.00	70.00		170.00						
	Iceland								**78.10**					**298.00**
	Japan	145.00	18.80	25.60		23.50							2.72	
	Malta	1 036.53	256.40	410.00	170.57	201.56	85.70		**57.20**		**6.00**	**10.00**	**58.10**	**26.50**
	Netherlands	71.00	22.00	27.00										
	Romania												**29.00**	
	Slovenia	348.40	349.50	700.90										
	Spain	560.00	238.00	290.00	372.00	451.00			**67.80**	**77.40**	**113.40**	**63.60**	**47.30**	**30.30**
	Sweden	**1 000.00**	**390**	**670**	**510**									**44**
	Switzerland	1 200.00	400.00	800.00					**85.00**	**50.00**	**170.00**	**70.00**	**85.00**	**85.00**
II	Chile								80.00	`				36.00
IV	Maldives	2.00	8.00	10.00	8.00	6.00								

[a] Values in regular type are for entrance air kerma in mGy; values in bold type are for DAP in Gy cm^2; values underlined are for CTDI in mGy cm; values underlined and in bold type are for DLP in mGy cm.

Table B45d. Mean patient dose^a for various medical and dental radiological examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvimetry*	*Other medical*	*Intraoral*	*Panoramic*	*Dental CT*
I	Finland			2.50	**0.09**	
	Japan	3.98				
	Malta			2.17	3.90	
	Romania	36.20	19.40	7.90		
	Spain			3.10	1.6	
	Switzerland		0.20	3.00	**0.10**	

[a] Values in regular type are for entrance air kerma in mGy; values in bold type are for DAP in Gy cm^2.

Table B46a. Mean effective dose and variation on the mean for various medical and dental radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photofluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
Mean effective dose (mSv)												
I	Australia	0.03	0.07			0.10	0.43	0.31	0.29	0.20	0.04	0.01
	Austria	0.06	0.07			0.003	0.32	0.36	0.18	0.22	0.02	0.02
	Belgium	0.03	0.12				0.69	0.28				
	Bulgaria	0.02	0.05									
	Czech Republic	0.06	0.09				1.70	1.00	0.80	0.90	0.40	0.30
	France	0.05				0.02						
	Germany	0.03	0.08			0.05	0.60	0.60	0.40	0.20	0.11	0.07
	Japan	0.09			3.60	0.00	0.75		0.37		0.07	
	Korea, Rep.	0.02	0.13				0.27	0.40	0.18	0.18	0.06	0.00
	Malta	0.03	0.05									
	Netherlands	0.02				<0.001	0.40		0.20		0.02	
	Norway	0.12	0.15			0.02	1.73		0.72		0.18	
	Romania	0.14	0.28	0.84	0.76	0.04	2.10	1.23	1.43	0.81	0.25	0.04
	Russian Federation	0.11	0.37	0.80	0.91	0.10	1.92	1.40	0.69	0.47	0.14	0.31
	Spain	0.09	0.14			0.12	1.20	0.90	0.60	0.60	0.40	0.01
	Sweden	0.07	0.07				1.4	1.4				
	Switzerland	0.04	0.11	0.11	2.60	0.02	1.60	3.30	0.80	2.90	0.20	0.10
	United Kingdom	0.02				0.00	1.00		0.70		0.07	
	Weighted average	0.07	0.20	0.78	2.1	0.05	1.2	1.0	0.51	0.35	0.13	0.13
IV	Maldives	0.02	0.02			0.01	1.30	1.80	0.70		0.08	
	Average	0.02	0.02			0.01	1.30	1.80	0.70		0.08	
Standard deviation or range of mean effective dose (mSv)												
I	Australia	0.04	0.10			0.10	0.40	0.30	0.38	0.26	0.03	0.02
	Belgium	0.01	0.09				0.34	0.16				
	Bulgaria	0.012–0.026	0.042–0.055									
	Germany	0.02–0.05	0.04–0.1			0.001–0.1	0.3–1	0.4–1	0.2–0.5	0.1–0.4	0.05–0.15	0.05–0.1
	Korea, Rep.	0.02	0.13				0.13	0.18	0.08	0.08	0.03	0.00
	Netherlands	0.005–0.137					0.12–0.73		0.07–0.3		0.01–0.02	
	Romania	0.09	0.12	0.41	0.40	0.03	1.18	0.53	0.80	0.53	0.16	0.02
	Spain	0.03–0.2	0.05–0.26			0.01–0.1	0.5–1.3	0.3–1.3	0.3–0.7	0.5–0.7	0.04–0.7	

Health-care level	*Country*	*Chest*				*Limbs and joints*	*Spine*					
		Chest PA	*Chest LAT*	*Photofluorography*	*Fluoroscopy*		*Lumbar AP/PA*	*Lumbar LAT*	*Thoracic AP*	*Thoracic LAT*	*Cervical AP*	*Cervical LAT*
I	Sweden	0.02–0.27	0.02–0.27				0.27–4.4	0.27–4.4				
	Switzerland	0.03	0.05	0.05	2.00	0.02	1.00	2.00	0.50	2.00	0.10	0.05
IV	Maldives	0.01	0.01			0.00	0.01	0.02	0.02		0.01	

Table B46b. Mean effective dose and variation on the mean for various medical and dental radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography*	
									Screening	*Clinical diagnosis*
Mean effective dose (mSv)										
I	Australia	0.58	0.03	1.00			1.32	3.97	0.40	
	Austria	0.52	0.02	0.31	4.10	5.35	14.85	4.8	0.35	0.35
	Belgium			0.99						
	Czech Republic	1.40	0.20	1.10	1.90	3.50	2.90	2.90		1.20
	France	0.60	0.07							
	Germany	0.50	0.04	0.60	6.00					0.50
	Japan	0.77	0.04	0.58	0.31	0.40	0.15			
	Korea, Rep.	0.28	0.02	0.25						
	Malta	0.45	0.01	0.39						
	Netherlands	0.20			7.00	5.00			0.21	0.40
	Norway	0.60	0.03	3.62	5.17	12.57		3.81	0.13	0.13
	Romania	2.68	0.17	2.39	4.32	10.30	2.86	7.00		0.52
	Russian Federation	2.23/1.47	0.14	0.90	3.80	8.50	1.00	0.60	0.15	0.30
	Spain	0.80	0.07	0.80	7.80	7.80			0.70	0.40
	Sweden	0.46				8.4		2.7	0.1	0.14
	Switzerland	1.60	0.40	2.10	13.00	14.00	12.00	5.30		
	United Kingdom	0.50	0.06	0.70	2.00	7.00	4.00	2.00	0.20	0.30
	Weighted average	1.2	0.08	0.82	3.4	7.4	2.0	2.6	0.26	0.39

Health-care level	*Country*	*Pelvis/hip*	*Head*	*Abdomen*	*Upper GI*	*Lower GI*	*Cholecystography*	*Urography*	*Mammography*	
									Screening	*Clinical diagnosis*
IV	Maldives	0.70	0.07	0.70	3.00	7.00		2.50		
	Average	0.70	0.07	0.70	3.00	7.00		2.50		
Standard deviation or range of mean effective dose (mSv)										
I	Australia	0.60	0.03	1.50			1.19	3.57		
	Belgium			1.56						
	Germany	0.4–1.0	0.02–0.06	0.5–1	2.0–12					0.2–0.8
	Korea, Rep.	0.12	0.01	0.10						
	Netherlands	0.1–0.32			3.0–19	3.0–8				
	Romania	1.68	0.11	1.35	2.14	4.00	1.25	4.80		0.18
	Spain			0.5–1	3–12.7	7–16.7				
	Sweden	0.06–2.3				1.9–20		0.7–8.5	0.03–0.16	0.05–0.3
	Switzerland	1.00	0.20	1.00	5.00	5.00	2.00	2.00		
IV	Maldives	0.01	0.00	0.02	0.10	0.30		0.50		

Table B46c. Mean effective dose and variation on the mean for various medical and dental radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*CT*							*Interventional procedures*				*Angiography*	
		Head	*Thorax*	*Abdomen*	*Spine*	*Pelvis*	*Interventional*	*Other*	*PTCA*	*Cerebral*	*Vascular*	*Others*	*Non-cardiac*	*Cardiac*
Mean effective dose (mSv)														
I	Australia	2	10	20.00										
	Austria	2.22	1.72	14.7	4.99	8.02		4.95	5.67		15.85	21.44	8	5
	Belgium		4.14	11.30										
	Czech Republic	2.1	8.8	8.9	8.1	8.5								
	France	2	5	6.7	4				9	5.7	9	9		
	Germany	2.7	7.7	21.4	2.7								15	
	Greece	7.8	7.2	7										
	Hungary	0.83	6.64	3.73		6.98		2.88						
	Iceland								14.3					5.5
	Japan	2.4	9.1	12.9		10.5								
	Korea, Rep.	0.81	7.4	6.6										
	Netherlands	3	10	16										
	Norway	1.83	11.50	12.7	4.32	9.29			10.8	3.31	13.8		5.38	9.3
	Romania												0.32	
	Spain	1.8	6.6	8.5	5	7.2								
	Sweden	2.2	6.6	10	8.5									8
	Switzerland	5	10	14					19	5	15	18	10	17
	United Kingdom	2	8	10					15	6	7		5	7
	Weighted average	2.4	7.8	12	5.0	9.4	0.0	3.8	12	5.7	9.0	11	9.3	7.9
Standard deviation or range of mean effective dose (mSv)														
I	Belgium		1.21	7.8										
	Germany	2.0–4.0	6.0–10	10.0–25	2.0-5.0								10.0–20.0	
	Greece	0.6	3.5	3.5										
	Iceland								7.8					3.4
	Netherlands	1.0–5	4.0–19	7.0–26										
	Romania												0.12	
	Spain	1.1–2.3	2.6–8	6.5–10		4.4–10								
	Sweden	1.0–4.0	2.1–19	4–21	2.2–21									2.7–20
	Switzerland	1	4	5					5	2	4	5	3	5

Table B46d. Mean effective dose and variation on the mean for various medical and dental radiological examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Pelvimetry*	*Other medical*	*Total medical*	*Intraoral*	*Panoramic*	*Dental CT*	*Total dental*
Mean effective dose (mSv)								
I	Austria				0.01	0.026	0.32	
	Czech Republic				0.10			
	France			0.97	0.01	0.01		0.01
	Germany			1.75	0.01			0.01
	Japan	0.83			0.02	0.01		
	Netherlands			0.87	0.00	0.01		0.00
	Norway			1.47				
	Romania	6.20	3.33	1.25	0.03			0.03
	Russian Federation			0.86	0.02	0.15		0.03
	Switzerland			1.30	0.01	0.05		0.01
	United Kingdom	0.80		0.70	0.01	0.01		0.01
	Weighted average	1.4	3.3	1.0	0.02	0.06	0.32	0.02
IV	Maldives					0.01		
	Average					0.01		
Standard deviation or range of mean effective dose								
I	Germany							0.001–1
	Romania	2.40	2.10	0.65	0.02			0.02
	Switzerland		0.00	0.20	0.01	0.02		0.01

Table B47. Distribution by age and sex of patients undergoing various types of diagnostic radiological examination (1997–2007)

Data from the UNSCEAR Global 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*
Chest PA						
I	Australia	7	20	73	50	50
	Bulgaria	19	34	46	51	49
	Czech Republic	7	17	76	50	50
	Iceland	12	10	78	53	47
	Japan	6	18	86	55	45
	Korea, Rep.	20	34	46	54	47
	Luxembourg	6	14	80	54	46
	Romania	22	24	54	56	44
	Russian Federation	7	49	44	48	52
	Spain	10	10	80	51	49
	Switzerland	5	15	80	53	47
	Weighted average	9.0	30	64	51	49
II	Trinidad and Tobago	23	28	49	59	41
	Tunisia	7	35	58	44	56
	Turkey	2	14	84	45	55
	Weighted average	3	17	80	45	55
III	Zimbabwe	50	40	10	50	50
	Average	50	40	10	50	50
IV	Maldives	9	38	54	50	50
	Average	9	38	54	50	50
Chest LAT						
I	Australia	7	20	73	50	50
	Bulgaria	19	34	46	51	49
	Iceland	12	10	78	53	47
	Japan	6	18	76	55	45
	Korea, Rep.	17	29	55	56	44
	Luxembourg	2	16	82	52	48
	Romania	22	24	54	56	44
	Spain	10	11	80	55	45
	Switzerland	5	15	80	53	47
	Weighted average	10	20	71	55	46
II	Trinidad and Tobago	12	34	54	55	45
	Tunisia	0	0	100	100	0
	Weighted average	1	4	95	95	5
III	Zimbabwe	0	100	0	50	50
	Average	0	100	0	50	50
IV	Maldives	3	43	55	71	29
	Average	3	43	55	71	29
Chest photofluorography						
I	Bulgaria	14	46	42	31	69
	Romania	4	55	41	52	48
	Russian Federation	0	41	59	52	48
	Weighted average	1	43	56	51	49

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
III	Zimbabwe	0	100	0	50	50
	Average	0	100	0	50	50
Chest fluoroscopy						
I	Bulgaria	5	46	49	44	56
	Czech Republic	0	29	71	50	50
	Japan	11	17	72	63	37
	Romania	7	35	58	50	50
	Russian Federation	1	28	71	56	44
	Weighted average	6	25	70	58	43
Limbs and joints						
I	Australia	14	32	54	46	54
	Bulgaria	21	32	46	49	51
	Czech Republic	19	30	51	50	50
	Iceland	32	18	51	47	53
	Japan	14	23	63	43	57
	Luxembourg	11	31	58	49	51
	Romania	20	33	47	55	45
	Russian Federation	15	30	55	39	61
	Spain	14	22	64	44	56
	Switzerland	16	30	54	50	50
	Weighted average	15	27	58	43	57
III	Zimbabwe	43	29	28	51	49
	Average	43	29	28	51	49
IV	Maldives	22	29	49	48	52
	Average	22	29	49	48	52
Lumbar spine AP/PA						
I	Australia	2	29	69	42	58
	Czech Republic	6	32	62	50	50
	Iceland	7	15	78	41	59
	Japan	3	18	79	43	57
	Korea, Rep.	10	36	54	51	49
	Luxembourg	5	31	64	44	56
	Romania	6	33	62	49	51
	Russian Federation	11	36	53	58	42
	Spain	6	13	91	42	58
	Switzerland	2	29	69	47	53
	Weighted average	7	28	67	49	51
II	Trinidad and Tobago	6	47	47	50	50
	Tunisia	0	18	82	18	82
	Turkey	3	17	80	45	55
	Weighted average	3	18	80	42	58
III	Zimbabwe	0	50	50	60	40
	Average	0	50	50	60	40
IV	Maldives	5	25	70	57	43
	Average	5	25	70	57	43

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Lumbar spine LAT						
I	Australia	2	29	69	42	58
	Iceland	7	15	78	41	59
	Japan	3	18	79	43	57
	Korea, Rep.	9	53	38	66	34
	Romania	6	33	53	49	51
	Spain	2	13	85	42	58
	Switzerland	2	29	69	47	53
	Weighted average	4	26	70	47	53
II	Trinidad and Tobago	6	47	47	50	50
	Tunisia	0	18	82	18	82
	Turkey	3	17	80	45	55
	Weighted average	3	18	80	42	58
III	Zimbabwe	0	50	50	60	40
	Average	0	50	50	60	40
IV	Maldives	5	25	70	57	43
	Average	5	25	70	57	43
Thoracic spine AP						
I	Australia	4	21	74	31	69
	Czech Republic	0	14	86	50	50
	Iceland	11	15	74	44	56
	Japan	9	23	68	56	44
	Korea, Rep.	14	34	52	51	49
	Luxembourg	4	34	62	43	57
	Romania	12	37	51	49	51
	Russian Federation	13	37	50	60	40
	Spain	10	23	68	44	56
	Switzerland	6	36	58	42	58
	Weighted average	12	32	57	53	47
II	Trinidad and Tobago	15	47	38	47	53
	Turkey	3	17	80	45	55
	Weighted average	4	21	75	45	55
III	Zimbabwe	0	50	50	50	50
	Average	0	50	50	50	50
IV	Maldives	4	25	71	54	46
	Average	4	25	71	54	46
Thoracic spine LAT						
I	Australia	4	21	74	31	69
	Iceland	11	15	74	44	56
	Korea, Rep.	12	33	54	50	50
	Romania	12	37	51	49	51
	Spain	13	21	65	44	56
	Switzerland	6	36	58	42	58
	Weighted average	12	30	58	47	53
II	Trinidad and Tobago	15	47	38	47	53
	Turkey	3	17	80	45	55
	Weighted average	4	21	75	45	55

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
III	Zimbabwe	0	50	50	50	50
	Average	0	50	50	50	50
IV	Maldives	4	25	71	54	46
	Average	4	25	71	54	46
Cervical spine AP						
I	Australia	3	31	66	44	56
	Czech Republic	7	31	63	50	50
	Iceland	15	20	65	42	58
	Japan	4	26	70	47	53
	Korea, Rep.	12	39	48	55	45
	Luxembourg	2	35	63	43	57
	Romania	4	27	69	53	47
	Russian Federation	15	32	53	47	53
	Spain	7	18	75	39	61
	Switzerland	4	32	64	42	58
	Weighted average	9	29	62	47	53
II	Trinidad and Tobago	6	51	43	35	65
	Turkey	3	17	80	45	55
	Weighted average	3	21	76	44	56
III	Zimbabwe	0	53	47	50	50
	Average	0	53	47	50	50
IV	Maldives	6	45	49	51	49
	Average	6	45	49	51	49
Cervical spine LAT						
I	Australia	3	31	66	44	56
	Iceland	15	20	65	42	58
	Korea, Rep.	12	40	48	54	46
	Romania	4	27	69	53	47
	Spain	13	15	72	41	59
	Switzerland	4	32	64	42	58
	Weighted average	11	33	54	50	50
II	Trinidad and Tobago	6	51	43	35	65
	Turkey	3	17	80	45	55
	Weighted average	3	21	76	44	56
III	Zimbabwe	0	53	47	50	50
	Average	0	53	47	50	50
IV	Maldives	6	45	49	51	49
	Average	6	45	49	51	49
Pelvis/hip						
I	Australia	7	22	71	44	56
	Bulgaria	18	29	53	42	58
	Czech Republic	14	12	74	50	50
	Iceland	5	12	83	39	61
	Japan	6	19	75	44	56
	Korea, Rep.	10	21	69	55	46
	Luxembourg	4	15	81	38	62
	Romania	23	24	53	52	48

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Russian Federation	16	17	53	44	56
	Spain	9	9	82	41	59
	Switzerland	5	16	79	44	56
	Weighted average	9	19	73	45	55
II	Trinidad and Tobago	14	40	46	49	51
	Turkey	3	17	80	45	55
	Weighted average	4	20	76	46	55
III	Zimbabwe	0	50	50	48	52
	Average	0	50	50	48	52
IV	Maldives	8	27	65	50	50
	Average	8	27	65	50	50
Head						
I	Bulgaria	24	33	43	45	55
	Czech Republic	27	36	38	50	50
	Iceland	33	24	43	42	58
	Japan	17	29	53	51	49
	Korea, Rep.	24	35	41	58	42
	Luxembourg	23	36	41	50	50
	Romania	21	37	42	57	43
	Russian Federation	16	44	40	52	48
	Spain	20	20	60	46	54
	Switzerland	21	40	39	54	46
	Weighted average	19	35	46	52	48
II	Trinidad and Tobago	19	39	42	50	50
	Turkey	3	17	80	45	55
	Weighted average	5	20	76	46	54
III	Zimbabwe	33	33	34	50	50
	Average	33	33	34	50	50
IV	Maldives	10	35	55	48	52
	Average	10	35	55	48	52
Abdomen						
I	Australia	18	24	58	46	54
	Bulgaria	11	31	58	36	64
	Czech Republic	4	17	79	50	50
	Iceland	19	12	70	47	53
	Japan	6	14	80	57	43
	Korea, Rep.	23	31	47	52	48
	Luxembourg	10	23	67	48	52
	Romania	13	25	63	51	49
	Russian Federation	19	21	60	43	57
	Spain	7	13	80	51	49
	Switzerland	7	22	71	47	53
	Weighted average	13	20	67	50	51
II	Trinidad and Tobago	21	29	50	51	49
	Tunisia	6	25	69	75	25
	Turkey	3	17	80	45	55
	Weighted average	4	18	78	49	51

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
III	Zimbabwe	25	50	25	50	50
	Average	25	50	25	50	50
IV	Maldives	30	36	34	52	48
	Average	30	36	34	52	48
Upper gastrointestinal tract						
I	Bulgaria	9	31	60	35	66
	Czech Republic	3	23	75	50	50
	Iceland	20	20	60	43	57
	Japan	0	17	83	65	35
	Luxembourg	3	25	73	42	58
	Romania	8	32	61	50	50
	Russian Federation	3	29	68	42	58
	Spain	9	19	82	43	57
	Switzerland	4	12	84	43	57
	Weighted average	3	23	75	51	50
II	Trinidad and Tobago	7	39	54	53	47
	Turkey	1	22	77	47	53
	Weighted average	2	24	74	48	52
III	Zimbabwe	0	29	71	50	50
	Average	0	29	71	50	50
IV	Maldives	18	27	55	52	48
	Average	18	27	55	52	48
Lower gastrointestinal tract						
I	Bulgaria	7	30	64	34	65
	Czech Republic	3	15	82	50	50
	Iceland	4	10	86	43	57
	Japan	2	11	88	61	39
	Luxembourg	2	10	88	39	61
	Romania	10	17	73	49	51
	Russian Federation	3	31	66	40	60
	Spain	1	16	83	40	61
	Switzerland	2	13	85	42	58
	Weighted average	3	20	77	48	52
II	Trinidad and Tobago	5	32	63	49	51
	Tunisia	1	22	77	47	53
	Weighted average	2	23	75	47	53
III	Zimbabwe	0	29	71	50	50
	Average	0	29	71	50	50
IV	Maldives	20	29	51	54	46
	Average	20	29	51	54	46
Cholecystography						
I	Bulgaria	6	27	68	31	69
	Czech Republic	6	12	82	50	50
	Japan	0	6	94	64	36
	Luxembourg	1	15	84	35	65
	Romania	0	23	76	62	38
	Russian Federation	3	20	77	44	56

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Spain	0	9	90	54	46
	Switzerland	0	13	87	37	63
	Weighted average	2	14	85	53	47
Urography						
I	Bulgaria	14	30	54	40	60
	Czech Republic	8	18	74	50	50
	Iceland	4	27	79	59	41
	Japan	3	18	80	62	39
	Luxembourg	7	24	69	54	46
	Romania	9	25	67	59	41
	Russian Federation	9	31	60	46	54
	Spain	6	18	77	49	51
	Switzerland	16	25	59	51	49
	Weighted average	7	24	70	53	48
II	Trinidad and Tobago	5	47	48	52	48
	Turkey	3	28	69	50	50
	Weighted average	3	30	67	50	50
IV	Maldives	5	35	60	48	52
	Average	5	35	60	48	52
Mammography screening						
I	Australia	0	0	100	0	100
	Bulgaria	3	43	54	7	93
	Luxembourg	0	0	100	0	100
	Russian Federation	0	30	70	0	100
	Spain				0	100
	Weighted average	0	27	73	0	100
II	Trinidad and Tobago	0	8	92	0	100
	Turkey	0	50	50	0	100
	Weighted Average	0	45	55	0	100
IV	Maldives	0	10	90	0	100
	Average	0	10	90	0	100
Mammography clinical diagnosis						
I	Australia	0	30	70	0	100
	Bulgaria	0	45	55	0	100
	Czech Republic	0	2	98		
	Japan	0	13	88	0	100
	Luxembourg	0	15	85	1	99
	Romania	5	40	55	21	79
	Russian Federation	0	20	80	0	100
	Spain	0	28	72	1	99
	Weighted average	0	20	80	2	99
II	Turkey	0	50	50	0	100
	Average	0	50	50	0	100
CT head						
I	Australia	5	32	63	42	58
	Bulgaria	10	37	53	53	47
	Czech Republic	5	18	77	50	50
	Iceland	15	13	73	46	54

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Japan	6	94		52	48
	Korea, Rep.	17	33	50	52	48
	Luxembourg	4	27	70	46	54
	Romania	12	25	63	53	47
	Russian Federation	5	25	70	52	48
	Spain	8	18	74	49	51
	Switzerland	4	23	73	51	49
	Weighted average	8	26	66	51	49
II	Trinidad and Tobago	23	33	44	51	49
	Turkey	7	29	64	49	51
	Weighted average	9	30	62	49	51
III	Zimbabwe	10	30	60	53	47
	Average	10	30	60	53	47
IV	Maldives	8	40	52	48	52
	Average	8	40	52	48	52
CT abdomen						
I	Australia	0	19	81	46	54
	Bulgaria	5	41	55	49	51
	Czech Republic	5	15	80	50	50
	Iceland	3	12	85	47	53
	Japan	1	99		55	45
	Korea, Rep.	8	23	69	58	42
	Luxembourg	1	17	83	49	52
	Russian Federation	3	25	72	52	48
	Spain	5	10	85	57	43
	Switzerland	1	17	82	55	46
	Weighted average	4	22	74	54	46
II	Trinidad and Tobago	4	38	58	48	52
	Turkey	7	29	64	49	51
	Weighted average	7	30	63	49	51
III	Zimbabwe	25	63	12	44	56
	Average	25	63	12	44	56
IV	Maldives	5	25	70	54	46
	Average	5	25	70	54	46
CT thorax						
I	Australia	0	13	87	55	45
	Bulgaria	11	41	49	49	51
	Czech Republic	3	16	81	50	50
	Iceland	4	13	84	53	47
	Japan	1	99		56	44
	Korea, Rep.	11	27	62	61	39
	Luxembourg	1	13	86	58	42
	Romania	11	21	68	57	43
	Russian Federation	3	25	72	52	48
	Spain	5	11	84	62	38
	Switzerland	2	20	78	51	49
	Weighted average	5	22	73	55	45

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
II	Trinidad and Tobago	2	39	59	56	44
	Turkey	7	29	64	49	51
	Weighted average	6	30	63	50	50
III	Zimbabwe	12	76	12	65	35
	Average	12	76	12	65	35
IV	Maldives	5	20	75	52	48
	Average	5	20	75	52	48
CT spine						
I	Bulgaria	5	41	55	49	51
	Czech Republic	1	21	78	50	50
	Luxembourg	0	27	73	48	52
	Spain	3	22	75	54	46
	Switzerland	0	24	76	50	50
	Weighted average	3	24	73	52	48
II	Trinidad and Tobago	8	53	39	66	34
	Average	8	53	39	66	34
III	Zimbabwe	17	66	17	66	34
	Average	17	66	17	66	34
IV	Maldives	4	35	61	50	50
	Average	4	35	61	50	50
CT pelvis						
I	Bulgaria	5	41	55	49	51
	Czech Republic	2	20	78	50	50
	Japan	1	99		53	47
	Spain	6	12	82	55	45
	Switzerland	4	32	64	47	53
	Weighted average	5	18	78	53	47
II	Trinidad and Tobago	6	34	60	46	54
	Average	6	34	60	46	54
III	Zimbabwe	0	50	50	75	25
	Average	0	50	50	75	25
IV	Maldives	3	23	74	57	43
	Average	3	23	74	57	43
CT interventional						
I	Bulgaria	5	41	55	49	51
	Spain	0	6	94	70	30
	Weighted average	1	11	88	66	34
III	Zimbabwe	0	100	0	50	50
	Average	0	100	0	50	50
CT other						
I	Bulgaria	5	41	55	49	51
	Iceland	5	13	82	49	51
	Japan	5	95		51	49
	Luxembourg	2	26	72	53	47
	Spain	2	18	81	59	41
	Weighted average	2	21	77	53	47

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Non-cardiac angiography						
I	Czech Republic	1	11	88	50	50
	Japan	0	0	100	60	40
	Luxembourg	0	9	91	53	47
	Romania	3	22	75	69	31
	Russian Federation	4	11	85	56	44
	Spain	0	7	93	62	38
	Switzerland	2	26	72	50	50
	Weighted average	2	8	91	59	41
Cardiac angiography						
I	Czech Republic	1	8	92	50	50
	Iceland	0	2	99	69	32
	Luxembourg	0	3	97	65	35
	Romania	4	11	85	63	37
	Russian Federation	6	5	89	56	44
	Spain	0	6	94	44	56
	Switzerland	1	11	88	62	38
	Weighted average	4	6	90	54	46
Cardiac PTCA						
I	Czech Republic	0	4	96	50	50
	Iceland	0	1	99	79	21
	Luxembourg	0	3	97	73	28
	Romania	0	28	71	44	56
	Spain	0	6	94	44	56
	Switzerland	0	3	97	79	21
	Weighted average	0	11	89	48	52
Cerebral angiography						
I	Czech Republic	1	18	81	50	50
	Luxembourg	0	0	100	66	34
	Spain	2	18	80	67	33
	Switzerland	4	38	58	50	50
	Weighted average	2	20	78	62	38
Vascular angiography (non-cardiac)						
I	Czech Republic	19	13	69	50	50
	Luxembourg	0	2	98	69	31
	Spain	0	7	93	62	39
	Switzerland	4	10	86	50	50
	Weighted average	4	8	88	56	42
Other interventional						
I	Luxembourg	0	8	92	46	54
	Spain	0	11	89	56	44
	Switzerland	4	10	86	50	50
	Weighted average	1	11	89	55	45
Pelvimetry						
I	Bulgaria	7	40	54	0	100
	Iceland	3	97	0	0	100
	Japan	0	98	2	0	100
	Luxembourg	0	100	0	0	100
	Romania	14	20	66	0	100
	Spain	0	60	40	0	100
	Weighted average	2	79	19	0	100

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Other diagnostic						
I	Bulgaria	7	38	55	0	100
	Japan	15	24	61	51	49
	Luxembourg	0	3	97	12	88
	Romania	1	41	58	56	44
	Spain	10	11	80	28	72
	Weighted average	12	23	65	44	56
Intraoral dental						
I	Bulgaria	10	50	40	46	54
	Czech Republic	22	37	42	50	50
	Japan	9	28	63	45	56
	Luxembourg	5	48	47	47	53
	Romania	15	43	43	46	54
	Spain	20	40	41	51	49
	Switzerland	5	38	57	45	55
	Weighted average	12	32	55	46	54
III	Zimbabwe	7	73	20	50	50
	Average	77.0	73	20	50	50
Panoramic dental radiology						
I	Bulgaria	20	45	35	49	51
	Czech Republic	22	37	42	50	50
	Japan	6	36	58	45	55
	Luxembourg	36	37	28	47	53
	Romania	28	34	37	50	50
	Spain	16	51	33	62	38
	Switzerland	21	39	40	44	56
	Weighted average	12	39	49	49	51
III	Zimbabwe	80	14	6	50	50
	Average	80	14	6	50	50
IV	Maldives	15	50	35	20	80
	Average	15	50	35	20	80
Dental CT						
I	Luxembourg	3	38	59	42	59
	Average	3	38	59	42	59

Table B48. Frequencies, population-weighted average effective doses and collective doses assumed in the global model for diagnostic practice with medical and dental radiological examinations (1997–2007)

Examinations	*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*
Chest PA	168	142	1.6	110	0.1	*0.1*	0.02	0.05	17 000	30 000	57	48 000
Chest LAT	70	39	0.3	36	0.2	*0.2*	0.02	0.2	22 000	25 000	11	47 000
Chest photofluorography	287	0.0	0.8	69	0.8	*0.8*	0.8	0.8	340 000	19	1 100	340 000
Chest fluoroscopy	17	0.0	0.0	4.0	2.1	*2.1*	*2.1*	2.1	53 000	210	0.0	53 000
Limbs and joints	140	28	0.3	47	0.0	*0.0*	*0.01*	0.04	10 000	4 100	5.3	14 000
Lumbar spine AP/PA	31	3.8	0.1	9.2	1.2	*1.2*	1.3	1.2	58 000	15 000	300	73 000
Lumbar spine LAT	23	3.8	0.8	7.6	1.0	*1.0*	1.8	1.2	35 000	12 000	2 600	50 000
Thoracic spine AP/PA	16	0.8	0.7	4.5	0.5	*0.5*	0.7	0.6	13 000	1 400	800	15 000
Thoracic spine LAT	9.8	6.7	0.7	5.8	0.3	*0.3*	*0.3*	0.3	5 200	7 400	400	13 000
Cervical spine AP/PA	32	1.9	1.2	8.9	0.1	*0.1*	0.1	0.1	6 600	810	170	7 500
Cervical spine LAT	19	1.9	1.2	5.9	0.1	*0.1*	*0.1*	0.1	3 900	800	290	5 000
Pelvis/hip	40	4.9	2.1	13	1.1	*1.1*	0.7	1.0	70 000	18 000	2 500	91 000
Head	44	13	2.6	18	0.1	*0.1*	0.1	0.1	5 700	3 500	320	9 600
Abdomen	45	11	1.7	17	0.8	*0.8*	0.7	0.8	56 000	28 000	2 100	86 000
Upper GI tract	34	12	0.5	14	3.4	*3.4*	3.0	3.3	180 000	130 000	2 700	310 000
Lower GI tract	9.3	9.7	0.2	7.0	7.4	*7.4*	7.0	7.3	110 000	230 000	2 100	340 000
Cholecystography	1.7	11	0.0	5.9	2.0	*2.0*	*2.0*	2.0	5 400	71 000	0.0	76 000
Urography	8.5	9.8	0.8	7.1	2.6	*2.6*	2.5	2.6	34 000	80 000	3 600	120 000
Mammography screening	23	14	0.8	12	0.3	*0.3*	*0.3*	0.3	9 100	13 000	380	22 000
Mammography clinical diagnosis	20	6.1	0.8	8.0	0.4	*0.4*	*0.4*	0.4	12 000	7 400	560	20 000
CT head	40	2.3	0.9	11	2.4	*2.4*	*2.4*	2.4	150 000	17 000	3 800	170 000
CT thorax	24	0.8	0.7	6.3	7.8	*7.8*	*7.8*	7.8	290 000	19 000	9 000	310 000
CT abdomen	30	1.8	0.7	8.2	12.4	*12.4*	*12.4*	12.4	570 000	70 000	14 000	650 000

Examinations	*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*
CT spine	11	0.3	0.5	3.0	5.0	*5.0*	*5.0*	5.0	87 000	5 100	4 300	96 000
CT pelvis	19	1.0	0.3	5.1	9.4	*9.4*	*9.4*	9.4	270 000	28 000	5 400	310 000
CT interventional	1.0	0.0	0.1	0.3	3.8	*3.8*	*3.8*	3.8	5 700	0.0	530	6 200
CT other	2.8	1.0	0.0	1.2	3.8	*3.8*	*3.8*	3.8	16 000	12 000	0.0	29 000
Non-cardiac angiography	2.6	0.0	0.0	0.6	9.3	*9.3*	*9.3*	9.3	38 000	660	0	38 000
Cardiac angiography	1.5	5.0	0.0	2.8	11.2	*11.2*	*11.2*	11.2	26 000	180 000	0	200 000
Cardiac PTCA	0.9	0.1	0.0	0.3	11.9	*11.9*	*11.9*	11.9	17 000	3 800	0	21 000
Cerebral angiography	0.3	0.1	0.0	0.1	5.7	*5.7*	*5.7*	5.7	2 700	1 100	0	3 800
Vascular angiography (non-cardiac)	1.6	0.0	0.0	0.4	9.0	*9.0*	*9.0*	9.0	23 000	280	0	23 000
Other interventional	1.1	0.0	0.0	0.3	11.2	*11.2*	*11.2*	11.2	19 000	1 100	0.0	20 000
Pelvimetry	1.1	0.5	0.0	0.5	1.4	*1.4*	*1.4*	1.4	2 300	2 100	0.0	4 300
Other diagnostic	159	0.0		38	1.6	*1.6*	*1.6*	1.6	390 000	0.0	0.0	390 000
Total diagnostic	1 332	332	20	488					2 900 000	1 000 000	57 000	4 000 000
Intraoral dental	227	12	2.5	61	0.02	*0.02*	*0.02*	0.02	5 500	600	88	6 200
Panoramic dental	49	3.7	0.08	13	0.06	*0.06*	0.01	0.05	4 500	690	1.5	5 100
Dental CT	0.02	0.00		0.00				0.00	0.00	0.00	0.00	0.00
Total dental	275	16	3	74					9 900	1 300	89	11 000
Average effective dose per caput from medical radiological examinations (mSv)									1.91	0.32	0.03	0.62
Average effective dose per caput from dental radiological examinations (mSv)									0.006 4	0.004	5.1×10^{-5}	0.001 8
Average effective dose per medical radiological examination (mSv)									1.44	0.96	1.60	1.28
Average effective dose per dental radiological examination (mSv)									0.023	0.026	0.020	0.024

Note: Values in italics have been estimated in the absence of data from the UNSCEAR survey.

Table B49. Estimated global number of procedures, collective effective dose and per caput effective dose for various categories of radiographic (excluding dental) nuclear medicine procedures using ionizing radiation in the United States [N26]

Type of procedure	*Number of procedures (millions)*	*Collective effective dose (man Sv)*	*Per caput effective dose (mSv)*
Conventional radiography and fluoroscopy	293	100 000	0.3
Interventional	17	128 000	0.4
CT	67	440 000	1.5
Nuclear medicine	18	231 000	0.8
Total	395	899 000	3.0

Table B50. Contribution to the frequency of various types of diagnostic medical and dental radiological examination

Examinations	*Contribution (%)*			
	Level I	*Level II*	*Levels III–IV*	*World*
Chest PA	10	41	7.1	20
Chest LAT	4.3	11	1.4	6.4
Chest photofluorography	18	0.00	3.6	12
Chest fluoroscopy	1.0	0.01	0.00	0.71
Limbs and joints	8.7	7.9	1.3	8.4
Lumbar spine AP/PA	1.9	1.1	0.56	1.6
Lumbar spine LAT	1.4	1.1	3.5	1.4
Thoracic spine AP/PA	1.0	0.24	2.8	0.79
Thoracic spine LAT	0.6	1.9	2.8	1.0
Cervical spine AP/PA	2.0	0.55	5.3	1.6
Cervical spine LAT	1.2	0.55	5.3	1.0
Pelvis/hip	2.5	1.4	9.0	2.2
Head	2.7	3.8	11	3.2
Abdomen	2.8	3.1	7.6	3.0
Upper GI tract	2.1	3.4	2.3	2.5
Lower GI tract	0.6	2.8	0.74	1.3
Cholecystography	0.1	3.2	0.00	1.0
Urography	0.5	2.8	3.5	1.3
Mammography screening	1.4	3.9	3.6	2.2
Mammography clinical diagnosis	1.2	1.8	3.6	1.4
CT head	2.5	0.65	3.9	2.0
CT thorax	1.5	0.22	2.9	1.1
CT abdomen	1.8	0.52	2.9	1.5
CT spine	0.7	0.09	2.2	0.53
CT pelvis	1.2	0.27	1.4	0.91
CT interventional	0.1	0.00	0.35	0.05
CT other	0.2	0.29	0.00	0.21
Non-cardiac angiography	0.1	0.1	0.00	0.1
Cardiac angiography	0.1	1.4	0.00	0.5
Cardiac PTCA	0.1	0.03	0.00	0.05
Cerebral	0.0	0.02	0.00	0.02
Vascular angiography (non-cardiac)	0.1	0.00	0.00	0.07
Other interventional	0.1	0.01	0.00	0.05
Pelvimetry	0.1	0.14	0.00	0.09
Other medical	9.9	0.00	0.00	6.8
Total medical	83	96	89	87

Examinations	*Contribution (%)*			
	Level I	*Level II*	*Levels III–IV*	*World*
Intraoral dental	14	3.5	11	11
Panoramic dental	3.0	1.1	0.36	2.4
Dental CT	0.00	0.00	0.00	0.00
Total dental	17	4.5	11	13
Total diagnostic examinations	100.00	100.00	100.00	100.00

Table B51. Contribution to the collective effective dose of various types of diagnostic medical and dental radiological examination

Examinations	*Contribution (%)*			
	Level I	*Level II*	*Levels III–IV*	*World*
Chest PA	0.59	3.0	0.10	0.93
Chest LAT	0.74	2.5	0.02	0.98
Chest photofluorography	12	0.00	2.0	9.9
Chest fluoroscopy	1.8	0.02	0.00	1.5
Limbs and joints	0.35	0.41	0.01	0.35
Lumbar spine AP/PA	2.0	1.5	0.52	1.9
Lumbar spine LAT	1.2	1.2	4.5	1.3
Thoracic spine AP/PA	0.43	0.14	1.4	0.40
Thoracic spine LAT	0.18	0.73	0.69	0.26
Cervical spine AP/PA	0.22	0.08	0.30	0.20
Cervical spine LAT	0.13	0.08	0.50	0.13
Pelvis/hip	2.4	1.8	4.4	2.3
Head	0.20	0.35	0.55	0.22
Abdomen	1.9	2.7	3.7	2.1
Upper GI tract	6.0	13	4.8	7.0
Lower GI tract	3.6	22	3.6	6.3
Cholecystography	0.18	7.1	0.00	1.2
Urography	1.2	7.9	6.2	2.2
Mammography screening	0.31	1.3	0.66	0.45
Mammography clinical diagnosis	0.40	0.74	0.98	0.46
CT head	5.0	1.7	6.6	4.6
CT thorax	9.7	1.9	16	8.7
CT abdomen	19	7.0	25	18
CT spine	2.9	0.51	7.5	2.7
CT pelvis	9.3	2.8	9.4	8.4
CT interventional	0.19	0.00	0.93	0.18
CT other	0.55	1.2	0.00	0.64
Non-cardiac angiography	1.28	0.07	0.00	1.1
Cardiac angiography	0.87	17	0.00	3.2
Cardiac PTCA	0.57	0.37	0.00	0.53
Cerebral	0.09	0.11	0.00	0.09
Vascular angiography (non-cardiac)	0.77	0.03	0.00	0.65
Other interventional	0.69	0.10	0.00	0.56
Pelvimetry	0.08	0.20	0.00	0.09
Other medical[a]	13	0.00	0.00	11
Total medical	100.00	100.00	100.00	100.00

Examinations	*Contribution (%)*			
	Level I	*Level II*	*Levels III–IV*	*World*
Intraoral dental	60	47	98	59
Panoramic dental	40	53	2	41
Dental CT	0.00	0.00	0.00	0.00
Total dental	100.00	100.00	100.00	100.00

[a] As there was only one return giving an effective dose for "other medical" examinations, a value of 1.6 mSv has been used, which is an average across all examinations when the data for "other medical" are included. This represents an estimate of the typical effective dose for "other diagnostic" examinations.

Table B52. Trends in the annual frequency of diagnostic medical radiological examinations expressed as number per 1,000 population

Level	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*	*1997–2007*
I	820	810	890	920	1 332
II	26	140	120	154	332
III	23	75	67	17	20
IV	27		8.8	29	20

Table B53. Trends in the annual frequency of diagnostic dental radiological examinations expressed as number per 1,000 population

Level	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*	*1997–2007*
I	320	390	350	310	275
II		0.8	2.5	14	16
III		0.8	1.7	0.3	2.6
IV				0.1	2.6

Table B54. Trends in average effective dose from diagnostic medical radiological examinations for countries in health-care level I

Examination	*Average effective dose per examination (mSv)*			
	1970–1979	*1980–1990*	*1991–1996*	*1997–2007*
Chest radiography	0.25	0.14	0.14	0.07
Chest photofluoroscopy	0.52	0.52	0.65	0.78
Chest fluoroscopy	0.72	0.98	1.1	2.1
Limbs and joints	0.02	0.06	0.06	0.05
Pelvis and hip	2.2	1.7	1.8	1.1
Head	2.1	1.2	0.83	0.08
Abdomen	1.9	1.1	0.53	0.82
Upper GI	8.9	7.2	3.6	3.4
Lower GI	9.8	4.1	6.4	7.4
Cholecystography	1.9	1.5	2.3	2.0
Urography	3	3.1	3.7	2.6
Mammography	1.8	1	0.51	0.26
CT	1.3	4.4	8.8	7.4
PTCA			22	11.9

Table B55. Estimated doses to the world population from medical and dental radiological examinations 1997–2007

Health-care level	*Population (millions)*	*Per caput effective dose (mSv)*		*Collective effective dose (man Sv)*	
		Medical	*Dental*	*Medical*	*Dental*
I	1 540	1.91	0.006 4	2 900 000	9 900
II	3 153	0.32	0.000 4	1 000 000	1 300
III	1 009	0.03	0.000 051	33 000	51
IV	744	0.03	0.000 051	24 000	38
World	6 446	0.62	0.002	4 000 000	11 000

APPENDIX C:
LEVELS AND TRENDS OF EXPOSURE IN NUCLEAR MEDICINE

I. INTRODUCTION

C1. A radiopharmaceutical is a compound whose molecular structure causes it to concentrate primarily in a specific region of the body and which also contains a radioactive species that allows: *(a)* external imaging of the body (diagnosis) to evaluate the structure and/or function of the region, or *(b)* delivery of a large radiation dose (therapy) to the region to control a specific disease. Most medical imaging or therapy procedures rely on external sources of ionizing or non-ionizing radiation to achieve their aims; nuclear medicine studies employ the unique approach of introducing a radiolabelled substance into the body of the subject, with devices external to the body being able to detect, and in some cases quantify, the activity in different regions of the subject. This thus permits not only the study of the configuration of internal structures, but the evaluation of internal physiological processes. In the case of therapy, the concentration of the material in the target tissue of interest allows the delivery of lethal doses of radiation to the undesirable tissues, with the aim of maintaining lower concentrations in other body tissues so as to minimize unwanted deleterious effects.

C2. In most nuclear medicine imaging procedures, the goal for the physician is diagnosis of disease or improper organ function via study of the distribution of radioactivity inside specific structures within the body. Many imaging procedures evaluate organ structure, size and shape, or may evaluate the presence of cancerous or otherwise deleterious lesions. Dynamic studies are also widely used to provide information on organ or system function through the measurement of the rate of accumulation and subsequent removal of the radiopharmaceutical by an organ of interest. Two examples of dynamic imaging include the study of dynamic cardiac function and of renal clearance of radiolabelled substances [M27].

C3. Nuclear medicine practice depends firstly on the availability of radioactive substances (radionuclides). Radionuclides are generally produced from [W18]:

- Nuclear reactors;
- Particle accelerators; or
- Radionuclide generator systems (devices that contain a longer-lived "parent" radionuclide that continuously produces a shorter-lived "progeny" that can be readily separated from the system for delivery to patients).

The reliable delivery of high-quality radionuclides directly to nuclear medicine centres, or more commonly, to radiopharmacies that produce radiopharmaceuticals and deliver them to nuclear medicine centres, is essential to the routine practice of nuclear medicine. Many hospitals and clinics are very busy, and depend on an uninterrupted supply of high-quality radiopharmaceuticals to function. The amount of a radiopharmaceutical product administered, in terms of mass, is generally quite small, as the specific activity (amount of activity per unit mass, e.g. Bq/g) is kept high. This allows the compound to act as a tracer within the system without perturbing the normal system kinetics or introducing toxicity concerns.

C4. The creation and dissemination of the labelled drug products (radiopharmaceuticals or radiotracers) is the next essential step to successful nuclear medicine practice.

- The large majority of radiopharmaceutical products are labelled with ^{99m}Tc, which has a half-life of approximately 6 hours and is supported in a generator system by its parent ^{99}Mo ($T_{1/2}$ = 66 h).
- Another large general class of radiopharmaceuticals is that of the radioiodinated compounds—tracers labelled with ^{131}I, ^{123}I, ^{125}I and possibly other isotopes of iodine.
- The other significant class of radiolabelled products are those designed for use with positron emission tomography (PET) systems. The principal radionuclides are ^{18}F, ^{11}C, ^{15}O and ^{13}N. The ^{18}F and ^{11}C labels are bound to a number of tracers of interest for the study of myocardial or cerebral function, cancer detection and other processes. The isotope ^{15}O as labelled O_2 or H_2O is used in a number of applications; ^{13}N as NH_3 is used for myocardial imaging.

C5. The equipment for imaging nuclear medicine studies is quite specialized and highly technical. These imaging systems and their associated electronic and computer components have evolved over the past five decades or so. The gamma camera is the main device used for imaging radionuclides. The main detecting medium is a large sodium iodide (NaI (Tl)) crystal, usually in a circular or square configuration. Radiation absorbed by the detector crystal is converted into light, which is detected by a large array of photomultiplier tubes (PMTs). Electronic circuits analyse the PMT signals to ensure that the energy of the pulses is within a preset tolerance for the nuclide's principal decay energy, to determine the position of the gamma ray interaction and to record acceptable events in a two-dimensional projection field. This information is then displayed and possibly analysed further using computer software provided with the imaging system. Regions of interest may be drawn over different portions of the image and the numbers of counts in different regions determined at various times. Nuclear medicine cameras employ a range of different types of collimator for nuclides of different energies and for particular types of study. Typically, cameras employ low-, medium- and high-energy collimators for large-area viewing, and pinhole or other specialized collimators may be used for particular studies. The majority of commercial cameras today contain more than one head (i.e. imaging system comprised of a NaI (Tl) crystal, PMTs and electronic circuitry). Dual-headed systems are the most common (these permit simultaneous acquisition of data on two sides of the subject, typically anterior and posterior, as well as rapid acquisition of tomographic data in single-photon-emission computed tomography (SPECT)), but some triple-headed systems have also been developed.

C6. Some simpler imaging systems are also routinely used, e.g. small NaI (Tl) crystals for studies of thyroid uptake and function. Simple gamma probes may be used to assist surgeons in identifying and resecting lymph nodes that take up ^{99m}Tc-labelled colloids. Some other studies using in vitro analysis of patient tissue or fluid samples may also be performed; for example, vitamin B12 absorption from the gastrointestinal tract may be evaluated by measuring the fraction of orally administered vitamin B12 labelled with radioactive cobalt (^{57}Co and/or ^{58}Co) that is excreted in urine. Other non-imaging uses of radiopharmaceuticals involve the in vitro studies of thyroid function [P8] and labelled blood cells [S5], and radioimmunoassay [Y13].

C7. The nuclear medicine camera may be used in a number of different data acquisition modes:

- A static image may be obtained by simply placing the camera near the region of the patient to be imaged and leaving it in place during data acquisition. The camera may be placed, for example, over the abdomen, near the chest (for cardiac imaging) or over the head (for cerebral imaging). In addition, the camera may be used to obtain images of the whole body of the subject for bone imaging, quantitative studies and other purposes. This requires the use of special collimators or large subject-to-camera distances. Multiple static images of parts of the body may also be pieced together to create whole-body images.
- Dynamic imaging studies may be performed in which the gamma camera is positioned over the organ to be imaged and images are acquired in a time series possibly before, and certainly after, the injection of the radiopharmaceutical. For example, in a renogram, which is used to assess kidney function, a radiopharmaceutical that is preferentially taken up by the kidney is administered to the patient, usually intravenously. The movement of the radiopharmaceutical through the body, its accumulation in the kidney and its subsequent excretion are imaged. Kidney function is assessed on the basis of the time it takes for the radiopharmaceutical to reach peak concentration and how long it takes for this activity to be cleared from the body. Many dynamic studies of cardiac function are also routinely performed.
- Tomographic data may be taken (SPECT) in a procedure whereby the camera is rotated around the subject and data are gathered from many different angles, with the collected data subsequently analysed to develop three-dimensional images of the radionuclide distribution in the patient. Static or dynamic gamma camera images provide a two-dimensional projection image of the activity within the body. A dual-headed camera provides two projection images, typically 180° apart from each other, although the camera heads can be manipulated to provide other configurations. With correction for scatter and attenuation, these two-dimensional projections can yield quantitative information about the radionuclide content of an identified region. If a three-dimensional representation is obtained using tomography, one may obtain images and quantitative estimates of activity constructed from millions of "voxels" (volume elements, corresponding to the "pixels", or picture elements, that constitute a two-dimensional electronic image). This allows a more detailed evaluation of the radionuclide distribution within the body. The procedures for correcting all of the many projection images taken around the body for attenuation, scatter and other effects are quite involved. Most camera systems provide some standard software for performing these evaluations; the science of these analyses, however, continues to be an area of active investigation and constant improvement.

C8. Properties of many radionuclides commonly used for in vivo imaging are shown in table C1. Many different radionuclides have been employed for imaging, but the most popular for most studies (except for PET) is ^{99m}Tc. This radionuclide has a short half-life (6 hours). It emits a gamma ray at 140 keV with about 89% abundance, which is ideally suited for typical gamma cameras. In addition, as noted above, it is readily available from commercially available molybdenum–technetium generator systems. Table C2 provides a summary of many important radiopharmaceuticals used in nuclear medicine [K15]. The radiopharmaceuticals in use change periodically, of course, as new agents are added or others fall out of use. Particularly in radiation therapy with internal emitters, new radionuclides and agents are continually being proposed and tested. In addition, studies that are popular in some parts of the world are not popular, or approved for use, in others, so practice varies widely.

C9. Improved spatial resolution in tomographic nuclear medicine studies can be achieved with PET. Radionuclides that emit a positron provide the unique advantage that after the positron interacts with an electron in the environment and both are annihilated, two photons of energy 0.511 MeV are emitted simultaneously at a 180º orientation to each other. A PET imaging device exploits this fact and detects pairs of photons in spatially opposed detectors, thereby permitting identification of the location at which the positron annihilation occurred. Table C3 lists some common PET radionuclides and studies [L19].

C10. PET offers another advantage in that small quantities of radiopharmaceutical can be used to measure metabolic function rates, receptor densities, blood flow and changes in function. The main disadvantage of PET scanning is that positron-emitting radionuclides (e.g. ^{11}C, ^{13}N, ^{15}O and ^{18}F) have relatively short half-lives. As a consequence, PET scanners need to be located within short travelling times of the facility that produces the radiopharmaceuticals.

C11. Some advantages of PET studies are that:

- The sensitivity and resolution of PET scanners are better than those of SPECT systems. The attenuation correction algorithms are more accurate.
- Many unique radiopharmaceuticals have been developed to image particular biological or physiological processes, such as general cardiac uptake, tumour imaging and neuroreceptor imaging.
- The use of short-half-life radionuclides may result in lower patient doses.

C12. In PET scanning, a number of radiopharmaceuticals are used for various diagnostic studies. One example is ^{18}F-labelled fluorodeoxyglucose (^{18}F FDG), which is a labelled sugar compound administered to the patient. FDG is thus a marker for sugar metabolism and is used for a number of useful studies.

- In cardiology, PET measures both blood flow (perfusion) and metabolic rate within the heart. PET imaging can identify areas of decreased blood flow as well as muscle damage in the heart. This information is particularly important in patients who have had a myocardial infarction and who are being considered for a revascularization procedure.
- PET studies may be used in neurological studies to diagnose Alzheimer’s disease, Parkinson’s disease, epilepsy and other neurological conditions.
- Cancer cells tend to have a higher metabolic rate than normal cells. As a consequence, ^{18}F FDG accumulates preferentially in cancer cells, which appear as an area of higher activity on a PET scan.

C13. PET is considered to be particularly effective for imaging a number of common cancers, such as lung cancer, colorectal cancer, lymphoma, melanoma and breast cancer. The nuclear medicine physician is able to identify whether cancer is present or if it has spread. PET is particularly useful in assessing response to treatment and to confirm whether a patient is cancer-free after treatment. PET is also used for cancer staging and for assessing the effectiveness of different kinds of therapy (e.g. chemotherapy).

C14. PET imaging studies have been of high interest to the nuclear medicine community for many years. Interest grew steadily, as did the general use of radiopharmaceuticals. In 1953, Gordon Brownell and H.H. Sweet built a positron detector based on the detection of annihilation photons by means of coincidence counting. Clinical use has been increasing in the last decade owing to increases in the availability of equipment and health-care reimbursement for PET procedures. Patient doses for PET studies are on the high end for diagnostic nuclear medicine procedures, as will be shown in detail below, and the 511 keV photon from the annihilation radiation contributes to staff radiation doses.

C15. Combined SPECT–CT and PET–CT scanners are in widespread use in many countries. In these devices, images from the two modalities may be obtained from a patient without the patient moving between scans. This enables images obtained from the two imaging approaches to be easily co-registered and combined to provide a three-dimensional activity map that is tied directly to the subject’s anatomical map.

II. ANALYSIS OF PRACTICE

C16. A wide variety of radiopharmaceuticals are administered diagnostically to patients to study tissue physiology and organ function. The practice of diagnostic nuclear medicine varies significantly between countries; broad estimates of worldwide practice have been made from the available national survey data using a global model, although the uncertainties in this approach are likely to be significant. There was particularly poor reporting from level III and level IV countries in this period, and some discrepancies in reporting caused difficulties in the data analysis. For example, many countries reported individual results for cardiac examinations using either ^{99m}Tc or ^{201}Tl. These examinations have markedly different values for the average dose per procedure (8.0 and 41 mSv, respectively). However, other countries that probably used both nuclides simply reported a “total” number of cardiac studies, without differentiating between ^{99m}Tc and ^{201}Tl. Only the data from the countries that reported these examinations separately were used to develop average numbers of procedures and values for dose per procedure. Also, none of the countries of levels II, III and IV reported values for dose per procedure. The values reported by level I countries were considered to be reliable, and the population-weighted average values were assumed to apply to the other levels and were used in the dosimetric analysis. The worldwide total number of procedures for 1997–2007 is estimated to be about 32.7 million annually, corresponding to an annual frequency of 5.1 per 1,000 population. Estimates of the worldwide total number of procedures for 1985–1990 and 1991–1996 were 24 and 32.5 million, respectively, corresponding to frequencies of 4.5 and 5.6 per 1,000 population. The present global total of procedures is distributed among the health-care levels of the model as follows: 89% in countries of level I (at a mean rate of 19 per 1,000 population); 10% in countries of level II (1.1 per 1,000 population); and <1% collectively in countries of health-care levels III and IV (<0.05 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 C4). The overall decrease in the average value for level I countries is likely to be due to under-reporting during this survey period. Several cases are seen of clear increases in the numbers of studies in individual countries, and some countries (e.g. the United States and Canada) that previously reported high values did not report during this survey.

C17. The estimated doses to the world population from diagnostic nuclear medicine procedures are summarized in table C5. The global annual collective effective dose for 1997–2007 is estimated to be about 202,000 man Sv, which equates with an average per caput dose of 0.031 mSv. These estimates are comparable to the figures for 1991–1996 (150,000 man Sv and 0.03 mSv) and 1985–1990 (160,000 man Sv and 0.03 mSv). The distribution of collective dose among the health-care levels of the global model is currently as follows: 92% in countries of level I (giving a mean per caput dose of 0.12 mSv), 8% in countries of level II (corresponding to <0.01 mSv per caput) and <1% in countries of level III (0.000 05 mSv per caput). Globally, practice is dominated by bone scans, cardiovascular studies and thyroid studies, with the last being particularly important in countries of health-care levels III and IV.

C18. Overall, the use of diagnostic practices with radiopharmaceuticals remains small in comparison with the use of X-rays. The annual numbers of nuclear medicine procedures and their associated collective doses are only 0.9% and 5.1%, respectively, of the corresponding values for medical X-rays. However, the mean dose per (diagnostic) procedure is larger for nuclear medicine (6.0 mSv) than for medical X-rays (1.3 mSv).

C19. 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 C6). Global annual numbers of radiopharmaceutical therapeutic treatments have been broadly estimated from the limited national survey data available using a global model, and the results are summarized in table C7. The uncertainties in these data are likely to be significant. The worldwide total number of treatments for 1997–2007 is estimated to be about 0.87 million annually, corresponding to an average annual frequency of 0.14 treatment per 1,000 population. Estimates of the total number of treatments annually for 1991–1996 and 1985–1990 were 0.4 million and 0.2 million, respectively, and for the same two periods the average annual frequency of treatments per 1,000 population was 0.065 and 0.04, respectively. However, this is surely an underestimate, because no level II, III or IV countries reported a frequency for therapy studies, when surely many occurred. The present global total of treatments is distributed among the health-care levels of the model as follows: 83% in countries of level I (at a mean rate of 0.47 per 1,000 population), 16% in countries of level II (0.043 per 1,000 population), 0.9% in countries of level III/IV (0.004 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 is similar in number of treatments to brachytherapy (total of 0.43 million).

III. DOSES FOR SPECIFIC NUCLEAR MEDICINE PROCEDURES

A. Diagnostic uses

C20. A nationwide survey of nuclear medicine practice in Japan in 2002 had the following findings [K16]:

- A total of 1,697 gamma cameras were installed in 1,160 facilities; 50% of these were dual-headed cameras.
- The estimated total annual number of examinations performed was 1.60 million, similar to that of an earlier survey in 1997.
- The annual frequency of SPECT studies increased to 40%, from 30% in the earlier survey.
- The most commonly performed procedure was bone scintigraphy (35%), followed by myocardial perfusion (24%) and brain perfusion (12%) studies. The annual frequency of all of these types of study has increased steadily over the past 20 years.
- Tumour imaging studies, however, fell from third to fourth place in terms of annual procedure frequency.
- The most commonly used radiopharmaceuticals were ^{99m}Tc HMDP for bone studies, ^{201}Tl chloride for myocardial studies, ^{67}Ga citrate for tumour imaging and ^{123}I IMP for brain studies.

- A total of 29,376 PET studies were performed in 2002. The use of ^{18}F FDG increased by a factor of 3.7 over previously reported results.
- There were 1,647 and 3,347 ^{131}I therapies for thyroid cancer and hyperthyroidism, respectively.
- A total of 31.35 million in vitro radioassays were reported; the number of in vitro radioassays has been decreasing continuously since 1992.

C21. A nationwide survey of nuclear medicine practice in the United Kingdom in 2003–2004 [H25] had the following findings:

- A total of 380 gamma cameras were installed in 240 facilities; an average of approximately 1,580 procedures are performed annually on these cameras.
- The total number of procedures performed annually increased by 36% over the last ten years. An estimated 670,000 procedures were performed, approximately 11 procedures per 1,000 population, which is up from 6.8 per 1,000 in 1982 and 7.6 per 1,000 in 1989.
- Planar imaging constitutes 73% of all nuclear medicine studies; SPECT and PET constitute 16% and 2% of all studies, respectively.
- Non-imaging diagnostic procedures represent 7% of all nuclear medicine studies, and therapy procedures account for the remaining 2% of studies.
- The most frequently performed procedures are bone scans, which constitute 29% of all procedures, followed by lung perfusion scans (14%) and myocardial perfusion studies (14%).
- The most frequently performed therapeutic scan is the use of ^{131}I for thyrotoxicosis, which accounts for 75% of all therapy procedures.
- The annual collective effective dose in the United Kingdom from diagnostic nuclear medicine is around 1,600 man Sv (corresponding to an annual per caput effective dose of about 0.03 mSv). Bone scans are the largest contributor to collective dose.
- Planar imaging comprises 61% of the total collective effective dose due to diagnostic nuclear medicine studies in the United Kingdom; SPECT, PET and non-imaging studies account for 33%, 6% and 0.3%, respectively.

C22. Effective doses for many typical radiopharmaceutical procedures for adults are shown in table C8. Most of these data are taken directly from the dose estimates given in ICRP Publication 80 [I25]. Doses for ^{201}Tl chloride and ^{99m}Tc Neurolite were taken from NUREG/CR-6345 [S27]. The doses for ^{153}Sm and ^{99m}Tc Apcitide and Depreotide came from the Radiation Internal Dose Information Center in Oak Ridge, Tennessee, United States [R5]. The survey form used for submitting data for this report asked the countries to report mean patient effective doses per examination. These doses will depend on the amount of activity administered and the assumed values of effective dose per unit activity administered. Data supplied by the respondents were taken as reported, without checking which source may have been used to estimate these doses.

C23. At the time of writing, a significant change is under way in the frequency of use of PET procedures, as well as in the use of combined PET–CT and SPECT–CT imaging systems. One study of four university hospitals in Germany [B4] revealed an average effective dose per PET–CT procedure of 25 mSv, with the majority coming from the CT scans. Ideas for reducing patient dose per procedure have been discussed by a number of authors [B4, C6, C19, T16, W3]. A study based in the United States [F7] concluded that data for CT-based attenuation corrections can be obtained with very-low-dose CT scans, and that for CT scans of diagnostic quality, the dose reduction ideas proposed by Donnelly et al. [D7] and Huda et al. [H6] can be helpful.

B. Therapeutic uses

C24. Therapeutic procedures using radiopharmaceuticals are considerably less frequent than diagnostic procedures. Many therapeutic procedures are for the treatment of thyroid disease using ^{131}I, which is particularly useful in the treatment of differentiated thyroid carcinoma and hyperthyroidism.

C25. Routine therapeutic applications of radiopharmaceuticals also include the use of a number of radiolabelled biological agents against various forms of cancer. Two monoclonal antibody products were recently approved in the United States (^{131}I Tositumomab and ^{90}Y Ibritumomab tiuxetan) for the treatment of non-Hodgkin's lymphoma (The use of ^{90}Y Ibritumomab tiuxetan is also approved in the European Union.). A number of other compounds and nuclides are of current interest in radioimmunotherapy [G16] (tables C9 and C10).

C26. The general concept of "molecular targeting" has been used for both imaging and diagnosis in nuclear medicine therapy. It may be defined as "the specific concentration of a diagnostic tracer or therapeutic agent by virtue of its interaction with a molecular species that is distinctly present or absent in a disease state" [B23]. Specific molecular targets have been attacked with antisense molecules, aptamers, antibodies and antibody fragments. Other cellular physiological activities, including metabolism, hypoxia, proliferation, apoptosis, angiogenesis, response to infection and multiple drug resistance, have also been studied by means of molecular targeting [B23].

C27. A number of radionuclides are used in the palliation of bone pain [L20]. The characteristics and treatment modes are shown in tables C11 and C12.

C28. Another form of radiopharmaceutical therapy involves administration of compounds directly into intracavitary spaces to treat diffuse tumours or arthritis and synovitis.

Direct injection of sodium or chromic phosphate labelled with ^{32}P or ^{198}Au colloids or of ^{131}I- or ^{90}Y-labelled antibodies is made into confined anatomical spaces such as the pleural space or the peritoneal cavity. Treatment of arthritis and synovitis has also been performed using ^{90}Y ferric hydroxide macroaggregate (FHMA), ^{165}Dy FHMA or ^{169}Er colloid into joint spaces.

C29. Polycythemia vera is a relatively rare disease that is characterized by overproduction of red and white blood cells by the bone marrow. ^{32}P phosphate given intravenously will localize in bone, and the radiation dose delivered results in mild bone marrow suppression and management of this disease.

C30. ^{131}I-labelled oil contrast and ^{90}Y glass or resin microspheres have been used to perform intra-arterial therapy for highly vascularized tumours that may not be amenable to surgery or chemotherapy. These radiolabelled compounds are injected and lodge in the arterioles and capillaries of the tumour, providing a highly localized radiation dose.

C31. There are significant advantages in combining PET and CT images for radiation treatment planning [T18]. This technology provides the ability to acquire accurately aligned anatomical and functional images for subjects in a single imaging session. This aids in accurate identification of pathology and accurate localization of abnormal foci. This technology is currently undergoing rapid growth. Some PET–CT design features in 2004 are shown in table C13. The radionuclides and techniques employed here are not used directly in the therapeutic procedures, but are used to diagnose and stage disease.

IV. DOSES FOR SPECIFIC POPULATIONS

A. Paediatric patients

C32. When paediatric patients undergo nuclear medicine procedures, it is accepted practice that lower activities of radionuclide are administered. In general, administered activities of radionuclide are adjusted to body surface area or body weight. If the second approach is adopted, then the effective dose to paediatric patients will be comparable to that of an adult. Effective doses to paediatric patients from diagnostic nuclear medicine procedures are given in table C14 [H16, I25, I34, S27]. The references are the same as those for the adult procedures described above.

B. Foetal dosimetry

C33. Doses to the embryo and foetus arise from the uptake of radionuclides by the mother and the transfer of radionuclides across the placenta, and depend on the types and distribution of radionuclides in foetal tissue. Radiation doses to the embryo and foetus resulting from intakes of radionuclides by the mother also depend on a number of other factors:

- Their transfer through maternal blood and placenta after deposition in the tissues of the mother;
- Their distribution and retention in foetal tissues;
- Growth of the embryo/foetus;
- Irradiation from deposits in the placenta and maternal tissue;
- Direct transfer to the embryo and foetus from maternal blood.

C34. The processes involved in transfer from maternal to foetal blood through the placenta include simple diffusion, facilitated transport and active transport, movement through pores and channels, and pinocytosis [I37]. A radioisotopes follows the same pathways of uptake to maternal blood as the stable element. If data on a particular element are unavailable, then radionuclides will have similar pathways to elements that are chemically similar. For many elements, the rate of transfer depends on the chemical affinity for the different transport systems in various tissues and the placenta [I37].

C35. A comprehensive treatment of radiation doses for radiopharmaceuticals has been given in a document of the American National Standards Institute/Health Physics Society [S23]; the values are shown in table C15.

C36. An area of particular concern in foetal dosimetry is the dose to the foetal thyroid, principally from administration of radioiodines. Radiation doses to the foetal thyroid at various stages of gestation were estimated by Watson [W19] and are shown in table C16.

C. The breast-feeding infant

C37. Another population of concern in nuclear medicine is that of infants who ingest radioactive material excreted in the breast milk of lactating women who undergo nuclear medicine examinations. Several review articles on the subject have been produced, with varying recommendations about cessation times for breastfeeding after administration of various radiopharmaceuticals. Data on such exposures to the population are sparse, as reporting of these events is irregular [M46, M47, R25, S4].

V. SURVEY

C38. The nuclear medicine questionnaires are given in Form 3 of the UNSCEAR Global Survey of Medical Radiation Usage and Exposures.

C39. Tables C17 and C18 summarize the current status of diagnostic nuclear medicine equipment in each country, according to health-care level, obtained from the latest UNSCEAR survey. The number of examinations, number of examinations per million population and effective dose for various diagnostic nuclear medicine procedures are given in tables C19 (a–b), C20 (a-b) and C21 (a–b).

C40. The results of the UNSCEAR survey of practice in therapeutic nuclear medicine are given in tables C22, C23 and C24. The number of procedures, the number of procedures per million population, and the mean and variance on effective dose are recorded in these tables.

C41. Numbers of diagnostic examinations per 1,000 population, effective dose per examination and annual collective dose for diagnostic nuclear medicine examinations are given in table C25.

VI. SUMMARY

C42. A survey of practice in nuclear medicine has been undertaken. Responses from various countries have been received. These data have been supplemented by information on nuclear medicine procedures and treatments obtained from a review of the published literature.

C43. A global model, as used in earlier UNSCEAR reports, has been used. In this model, countries are stratified into four health-care levels, depending on the number of physicians per 1,000 members of the population. As with previous UNSCEAR surveys of global exposure, there are considerable uncertainties on the results estimated using this global model.

C44. The uncertainty arises from a number of sources, but primarily in extrapolating from the limited survey data obtained. For example, the small sample size in the UNSCEAR survey could mean that the annual frequency data are distorted. There is also an uncertainty on the population estimates for the global population.

C45. According to this global model, the annual frequency of diagnostic nuclear medicine examinations per 1,000 population in health-care level I countries has increased from 11 in 1970–1979 to 19 in the present survey. Comparative values for health-care level II countries also exhibit an increase, from 0.9 per 1,000 in 1970–1979 to 1.1 per 1,000 in 1997–2007.

C46. By comparison, for therapeutic nuclear medicine procedures, according to this global model, the annual frequency of nuclear medicine treatments in health-care level I countries has increased from 0.17 per 1,000 population in 1991–1996 to 0.47 per 1,000 population in this survey. Comparative values for health-care level II countries exhibit an even greater increase, from 0.036 per 1,000 population in 1991–1996 to 0.043 per 1,000 population in 1997–2007. In the period covered by this UNSCEAR report, the estimated dose to the world population due to diagnostic nuclear medicine procedures is estimated to be 202,000 man Sv. This represents an increase in collective dose of 52,000 man Sv, a rise of just over a third. This rise in collective dose occurs because of two factors. Firstly, the average effective dose per procedure has increased from 4.6 mSv to 6.0 mSv. Secondly, there has been an increase in the annual number of diagnostic nuclear medicine examinations to the world population.

Table C1. Properties of some radionuclides used for in vivo imaging

Radionuclide	*Half-life*	*Principal emissions*	*Examples of uses*
^{11}C	20 min	Positrons + 511 keV photons	Cerebral perfusion studies
^{13}N	10 min	Positrons + 511 keV photons	Myocardial perfusion studies
^{15}O	2 min	Positrons + 511 keV photons	Oxygen or water flow studies
^{18}F	110 min	Positrons + 511 keV photons	Glucose metabolism
^{67}Ga	78 h	92 keV, 182 keV photons	Detection of soft tissue malignancies, infection
^{99m}Tc	6 h	140 keV photons	Many
^{111}In	2.8 d	173 keV, 247 keV photons	Blood element imaging
^{123}I	13 h	160 keV photons	Thyroid imaging
^{125}I	60 d	25–35 keV X-rays and photons	Blood volume determination
^{131}I	8 d	365 keV photons	Thyroid imaging, therapy of cancer and hyperthyroidism
^{133}Xe	5.3 d	81 keV photons	Lung ventilation studies
^{201}Tl	73 h	80 keV X-rays	Myocardial perfusion studies

Table C2. Radiopharmaceuticals used in nuclear medicine [K15]

Radionuclide	*Form*	*Use*	*Typical administered activity (adult subjects) (MBq)*	*Route*
^{11}C	Carbon monoxide	Cardiac, blood volume	2 200–3 700	Inhalation
^{11}C	Flumazenil injection	Brain, benzodiazepine receptor	740–1 110	IV
^{11}C	Methionine injection	Neoplastic brain disease	370–740	IV
^{11}C	Raclopride injection	Dopamine receptor	370–555	IV
^{11}C	Sodium acetate	Cardiac	444–1 480	IV
^{14}C	Urea	Helicobacter pylori diagnosis	0.037	PO
^{51}Cr	Sodium chromate	Red blood cells	0.37–2.96	IV
^{57}Co	Cyanoalbain capsules	Pernicious anaemia	0.019	PO
^{18}F	Fludeoxyglucose injection	Glucose utilization	370–555	IV
^{18}F	Fluorodopa	Dopamine neuronal	148–220	IV
^{18}F	Sodium fluoride injection	Bone imaging	370	IV
^{67}Ga	Gallium citrate	Hodgkin’s lymphoma	296–370	IV
^{67}Ga	Gallium citrate	Acute inflammatory lesions	185	IV
^{111}In	Capromab pendetide injection	Metastases	185	IV
^{111}In	Indium chloride solution	Radiolabelling		
^{111}In	Indium oxide solution	Labelling autologous leucocytes	18.5	IV
^{111}In	Pentetate injection	Cisternography	18.5	Intrathecal
^{111}In	Pentetreotide	Neuroendocrine tumours	111	IV
^{111}In	Pentetreotide	Neuroendocrine tumours (SPECT)	220	IV
^{111}In	Ibritumomab tiuxetan	Biodistribution	185	IV
^{123}I	Iobenguane injection	Pheochromocytoma	5.18/kg (child)	IV
^{123}I	Sodium iodide	Thyroid imaging	14.8–22	PO
^{123}I	Sodium iodide	Thyroid metastases	74	PO
^{125}I	Albumin injection	Plasma volume	0.19–0.37	IV
^{125}I	Iothalamate sodium injection	Glomerular filtration rate	1.11	IV
^{131}I	Iobenguane injection	Pheochromocytoma	18.5/1.7 m^2	IV
^{131}I	Sodium iodide	Thyroid function	0.19–0.37	PO
^{131}I	Sodium iodide	Thyroid imaging	1.9–3.7	PO
^{131}I	Sodium iodide	Thyroid imaging (substernal)	3.7	PO
^{131}I	Sodium iodide	Thyroid metastases	74	PO
^{131}I	Sodium iodide	Hyperthyroidism	185–1 221	PO
^{131}I	Sodium iodide	Carcinoma	5 550–7 400	PO
^{131}I	Iodohippurate sodium	Recoverable renal function	2.775–7.4	IV
^{131}I	Tositumomab	Treatment of non-Hodgkin’s lymphoma	<0.75 Gy	IV
^{13}N	Ammonia injection	Myocardial perfusion	370–740	IV
^{15}O	Water injection	Cardiac perfusion	1.11–3.7	IV
^{32}P	Chromic phosphate	Peritoneal and pleural effusions	370–740	Intraperitoneal
^{32}P	Sodium phosphate	Polycythemia	37–296	IV
^{82}Rb	Rubidium chloride	Myocardial perfusion	1.11–2.22	IV
^{153}Sm	Lexidronam	Bone palliation	37/kg	IV
^{89}Sr	Strontium chloride	Bone palliation	148	IV
^{99m}Tc	Albumin injection	Heart blood pool	740	IV
^{99m}Tc	Albumin aggregated	Lung perfusion	111	IV
^{99m}Tc	Bicisate	Stroke	740	IV
^{99m}Tc	Disofenin	Hepatobiliary	185	IV
^{99m}Tc	Exametazime	Cerebral perfusion	370–740	IV

Radionuclide	*Form*	*Use*	*Typical administered activity (adult subjects) (MBq)*	*Route*
^{99m}Tc	Gluceptate	Brain	740	IV
^{99m}Tc	Gluceptate	Renal perfusion	370	IV
^{99m}Tc	Mebrofenin	Hepatobiliary	185	IV
^{99m}Tc	Medronate	Bone	740–1 110	IV
^{99m}Tc	Mertiatide	Kidney imaging	185	IV
^{99m}Tc	Mertiatide	Renogram, renal transplant	37–111	IV
^{99m}Tc	Mertiatide	Renogram	37–111	IV
^{99m}Tc	Oxidronate	Bone	740–1 110	IV
^{99m}Tc	Pentetate injection	Glomerular filtration rate (quantitative)	111	IV
^{99m}Tc	Pentetate injection	Renogram	111	IV
^{99m}Tc	Pentetate injection	Renal perfusion	370	IV
^{99m}Tc	Pyrophosphate	Infarct-avid	555	IV
^{99m}Tc	Red blood cells	Gastrointestinal bleeding	555	IV
^{99m}Tc	Sestamibi	Myocardial perfusion	296–1 480	IV
^{99m}Tc	Sodium pertechnetate	Brain	740	IV
^{99m}Tc	Sodium pertechnetate	Thyroid imaging	370	IV
^{99m}Tc	Sodium pertechnetate	Ventriculogram	740	IV
^{99m}Tc	Sodium pertechnetate	Cystography	37	Urethral
^{99m}Tc	Sodium pertechnetate	Dacrocystography	3.7	Eye drops
^{99m}Tc	Sodium pertechnetate	Meckel’s diverticulum	185	IV
^{99m}Tc	Succimer	Renal scan, renal function	185	IV
^{99m}Tc	Succimer	Renal scan, cortical anatomy	185	IV
^{99m}Tc	Sulphur colloid	Liver–spleen	185	IV
^{99m}Tc	Sulphur colloid	Lymphoscintigraphy, breast	14.8–22	Interstitial
^{99m}Tc	Sulphur colloid	Lymphoscintigraphy, melanoma	18.5–29.6	Intradermal
^{99m}Tc	Sulphur colloid	Gastric emptying	37	PO
^{99m}Tc	Sulphur colloid	Gastrointestinal bleeding	370	IV
^{99m}Tc	Sulphur colloid	Lung aspiration	185	PO
^{99m}Tc	Sulphur colloid	Gastroesophageal reflux	7.4	PO
^{99m}Tc	Tetrofosomin	Myocardial perfusion	296–1 480	IV
^{201}Tl	Thallium chloride	Myocardial perfusion	111–148	IV
^{133}Xe	Xenon	Lung ventilation	370–740	Inhalation
^{90}Y	Ibritumomab tiuxetan	Treatment of non-Hodgkin’s lymphoma	11.1–14.8/kg	IV

Table C3. Radiopharmaceuticals used for clinical PET studies (adapted from reference [L19])

Radionuclide and compound	*Types of study performed*
^{15}O	
Carbon dioxide	Cerebral blood flow
Oxygen	Quantification of myocardial oxygen consumption and oxygen extraction fraction, measurement of tumour necrosis
Water	Quantification of myocardial oxygen consumption and oxygen extraction fraction, tracer for myocardial blood perfusion
^{13}N	
Ammonia	Myocardial blood flow
^{11}C	
Acetate	Oxidative metabolism
Carfentanil	Opiate receptors in the brain

Radionuclide and compound	*Types of study performed*
Cocaine	Identification and characterization of drug binding sites in the brain
Deprenyl	Distribution of monoamine oxidase (MAO) type B, the isoenzyme that catabolizes dopamine
Leucine	Amino acid uptake and protein synthesis, providing an indicator of tumour viability
Methionine	Amino acid uptake and protein synthesis, providing an indicator of tumour viability
N-methylspiperone	Neurochemical effects of various substances on dopaminergic function
Raclopride	Function of dopaminergic synapses
^{18}F	
Haloperidol	Binding sites of haloperidol, a widely used antipsychotic and anxiety-reducing drug
Fluorine ion	Clinical bone scanning
Fluorodeoxyglucose (FDG)	Neurology, cardiology and oncology to study glucose metabolism
Fluorodopa	Metabolism, neurotransmission and cell processes
Fluoroethylspiperone	Metabolism, neurotransmission and cell processes
Fluorouracil	Delivery of chemotherapeutic agents in the treatment of cancer
^{82}Rb	
^{82}Rb	Myocardial perfusion

Table C4. Trends in annual number of diagnostic nuclear medicine procedures per 1,000 population [U3]
Data from the UNSCEAR Global Surveys of Medical Radiation Usage and Exposures

Country/area	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*	*1997–2007*
Health-care level I					
Argentina			11.5	11.1	
Australia	3.8	8.9	8.3	12.0	19.0
Austria	18.0				41.9
Belarus				0.5	0.4
Belgium			36.8		52.8
Bulgaria		13.0		3.3	
Canada			12.6	64.6	
Cayman Islands				0	
China - Taiwan				6.6	
Croatia				2.4	8.6
Cuba[a]	(0.8)				
Cyprus				6.6	
Czechoslovakia[b]	13.6	18.3	22.9		
Czech Republic				28.3	12.6
Denmark	14.0	14.2	13.4	15.2	
Ecuador[a]	(0.5)		(0.8)	0.8	
Estonia				8.0	2.0
Finland	12.6	17.7		10.0	7.7
France		9.0	6.9		14.0
Germany[c]	31.1	39.7	39.8	34.1	46.7
Greece					16.7
Hungary				15.3	17.9
Iceland					14.1
Ireland				6.1	
Italy	6.0		7.3	11.0	
Japan			8.3	11.7	10.2
Kuwait			13.1	12.7	

Country/area	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*	*1997–2007*
Latvia					6.8
Lithuania				10.6	
Luxembourg			23.5	52.2	34.5
Netherlands			11.6	15.7	24.3
New Zealand	5.6	7.3	7.5	8.3	6.7
Norway	3.9		9.3		10.9
Panama				3.4	
Poland					3.0
Portugal				4.0	
Qatar				4.7	
Romania		3.0	3.5	3.0	2.8
Russian Federation[d]	(9)	(11)	(15)	12.6	
Slovakia[d]			(4.9)	9.4	
Slovenia				11.2	10.4
Spain					16.9
Sweden	9.8		12.6	13.6	10.8
The former Yugoslav Republic of Macedonia					4.0
Switzerland	44.9			9.5	11.7
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	22.1
Health-care level II					
Antigua and Barbuda				0	
Barbados			1.0		
Brazil			1.7	1.1	
China			0.6		
Costa Rica					1.73
Dominica				0	
El Salvador					0.61
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	0
Trinidad and Tobago					0.17
Tunisia			1.0	0.8	
Turkey			2.5	2.1	
Average	0.9	0.1	0.5	1.1	1.0

Country/area	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*	*1997–2007*
Health-care level III					
Egypt	0.07	0.21	0.48		
Ghana				0.05	
Indonesia					0.01
Jamaica[a]	(2.8)		(2.0)		
Morocco				0.62	
Myanmar	0.54	0.36	0.11		0.06
Sudan	0.12	0.28	0.28	0.09	
Thailand	0.25	0.18	0.26		
Zimbabwe					0.02
Average	0.25	0.25	0.30	0.28	0.02
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 C5. Estimated dose to the world population from diagnostic nuclear medicine procedures (1997–2007) [U3]

Health-care level	*Population (millions)*	*Annual per caput effective dose (mSv)*	*Annual collective effective dose (man Sv)*
I	1 540	0.12	186 000
II	3 153	0.005 1	16 000
III-IV	1 752	0.000 047	82
World	6 446	0.031	202 000

Table C6. Annual number of therapeutic treatments with radiopharmaceuticals per million population (1997–2007)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures [U3]

Country/area	*Thyroid malignancy*	*Hyperthyroidism*	*Polycythemia vera*	*Bone metastases*	*Synovitis*	*Other, e.g. ^{90}YCl*	*Total*
Health-care level I							
Austria	134	415	1.2	12.2	183.2	17.1	763
Croatia	81.8	203	0.0	1.4	0.7	0.0	287
Czech Republic	27.7	117	0.0	77.6	50.5		272
Estonia	117	252	3.6	36.5	3.6	1.5	414
Finland	106	242	70.9	10.7	8.8	1.5	440
Greece	103			16.8			120
Hungary	45.1	260		11.5	12.0		329
Iceland	91.8	252		3.4			347
Japan	17.3	17.3					34.5
Luxembourg	102			4.4	2.2		108
Malta	100	60.0	25.0				185
Norway	59.3	138	0.9	5.0	1.9	3.9	209
Poland	41.5	272		15.6	5.2	1.3	336
Slovenia	105	559		1.5	3.0	15.0	684
Spain	611	1 267	21.8	72.3	63.3	5.6	2 040
Sweden	11.7	259.2	32.8	38.4	1.6	1.1	345

Country/area	*Thyroid malignancy*	*Hyperthyroidism*	*Polycythemia vera*	*Bone metastases*	*Synovitis*	*Other, e.g. ^{90}YCl*	*Total*
Switzerland		201.0			37.9	70.1	309
The former Yugoslav Republic of Macedonia	130	34.4					164
United Kingdom	19.3	193.3	11.9	9.1	6.7	3.4	244
Average	106	279	16.8	21.1	27.2	10.9	401
Health-care level II							
Costa Rica	23.1	34.7					57.8
El Salvador	19.7	13.2					32.9
Average	21.4	24.0					45.4
Health-care levels III and IV							
Indonesia	0.5	0.7		0.06			1.3
Myanmar	1.6	18.6					20.2
Zimbabwe	1.7	0.8			0.0	0.0	2.5
Average	1.3	6.7		0.06	0.0	0.0	8.0

Table C7. Estimated annual number of therapeutic treatments with radiopharmaceuticals in the world (1997–2007) [U3]

Health-care level	*Population (millions)*	*Annual number of treatments*	
		Millions	*Per 1 000 population*
I	1 540	0.73	0.47
II	3 153	0.14	0.043
III–IV	1 752	0.007 5	0.004 3
World	6 446	0.87	0.14

Table C8. Effective dose (adult subjects) from typical nuclear medicine procedures [H29, I25, I34, S27]

Procedure	*mSv/MBq*	*MBq*	*mSv*
^{14}C urea (normal)	3.10×10^{-2}	0.037	1.15×10^{-3}
^{14}C urea (Heliobacter positive)	8.10×10^{-2}	0.037	3.00×10^{-3}
^{57}Co cyanocobalamin (IV, no carrier)	4.40×10^{0}	0.037	1.63×10^{-1}
^{57}Co cyanocobalamin (IV, with carrier)	4.60×10^{-1}	0.037	1.7×10^{-2}
^{57}Co cyanocobalamin (oral, no flushing)	3.1×10^{0}	0.037	1.15×10^{-1}
^{57}Co-7 cyanocobalamin (oral, with flushing)	2.1×10^{0}	0.037	7.77×10^{-2}
^{51}Cr sodium chromate RBCs	1.7×10^{-1}	5.6	9.5×10^{-1}
^{18}F FDG	1.90×10^{-2}	370	7.0×10^{0}
^{67}Ga citrate	1.00×10^{-1}	185	1.85×10^{1}
^{123}I hippuran	1.20×10^{-2}	14.8	1.78×10^{-1}
^{123}I MIBG	1.30×10^{-2}	14.8	1.92×10^{-1}
^{123}I sodium iodide (0% uptake)	1.10×10^{-2}	14.8	1.63×10^{-1}
^{123}I sodium iodide (35% uptake)	2.20×10^{-1}	14.8	3.26×10^{0}
^{125}I albumin	2.20×10^{-1}	0.74	1.63×10^{-1}
^{131}I hippuran	5.20×10^{-2}	0.74	3.85×10^{-2}
^{131}I MIBG	1.40×10^{-1}	0.74	1.0×10^{-1}
^{131}I sodium iodide (0% uptake)	6.10×10^{-2}	3 700	n.a.
^{131}I sodium iodide (35% uptake)	2.40×10^{2}	3 700	n.a.
^{111}In pentetreotide, also known as Octreoscan	5.40×10^{-2}	222	1.20×10^{1}
^{111}In white blood cells	3.6×10^{-1}	18.5	6.66×10^{0}
^{81m}Kr krypton gas	2.70×10^{-5}	370	9.99×10^{-3}

Procedure	*mSv/MBq*	*MBq*	*mSv*
^{15}O water	9.30×10^{-4}	370	3.44×10^{-1}
^{32}P phosphate	2.40×10^{0}	148	3.55×10^{2}
^{153}Sm lexidronam, also known as Quadramet	1.97×10^{-1}	2 590	n.a.
^{89}Sr chloride, also known as Metastron	3.10×10^{0}	148	n.a.
^{99m}Tc apcitide, also known as AcuTect	9.30×10^{-3}	740	6.88×10^{0}
^{99m}Tc depreotide, also known as NeoTect	2.30×10^{-2}	740	1.70×10^{1}
^{99m}Tc disofenin, also known as HIDA (iminodiacetic acid)	1.70×10^{-2}	185	3.15×10^{0}
^{99m}Tc DMSA (dimercaptosuccinic acid), also known as Succimer	8.80×10^{-3}	185	1.63×10^{0}
^{99m}Tc exametazime, also known as Ceretec and HMPAO	9.30×10^{-3}	740	6.88×10^{0}
^{99m}Tc macroaggregated albumin (MAA)	1.10×10^{-2}	148	1.63×10^{0}
^{99m}Tc medronate, also known as Tc-99m Methyenedi-phosphonate (MDP)	5.70×10^{-3}	740	4.22×10^{0}
^{99m}Tc mertiatide, also known as MAG3 (normal renal function)	7.00×10^{-3}	740	5.18×10^{0}
^{99m}Tc mertiatide, also known as MAG3 (abnormal renal function)	6.10×10^{-3}	740	4.51×10^{0}
^{99m}Tc mertiatide, also known as MAG3 (acute unilateral renal blockage)	1.00×10^{-2}	740	7.40×10^{0}
^{99m}Tc Neurolite, also known as ECD and Bicisate	1.10×10^{-2}	740	8.14×10^{0}
^{99m}Tc pentetate, also known as Tc-99m DTPA	4.90×10^{-3}	370	1.81×10^{0}
^{99m}Tc pyrophosphate	5.70×10^{-3}	555	3.16×10^{0}
^{99m}Tc red blood cells	7.00×10^{-3}	740	5.18×10^{0}
^{99m}Tc sestamibi, also known as Cardiolite (rest)	9.00×10^{-3}	740	6.66×10^{0}
^{99m}Tc sestamibi, also known as Cardiolite (stress)	7.90×10^{-3}	740	5.85×10^{0}
^{99m}Tc sodium pertechnetate	1.30×10^{-2}	370	4.81×10^{0}
^{99m}Tc sulphur colloid	9.40×10^{-3}	296	2.78×10^{0}
^{99m}Tc Technegas	1.50×10^{-2}	740	1.11×10^{1}
^{99m}Tc tetrofosmin, also known as Myoview (rest)	7.60×10^{-3}	740	5.62×10^{0}
^{99m}Tc tetrofosmin, also known as Myoview (stress)	7.00×10^{-3}	740	5.18×10^{0}
^{201}Tl thallous chloride (with contaminants)	1.60×10^{-1}	74	1.18×10^{1}
^{133}Xe xenon gas (rebreathing for 5 minutes)	8.00×10^{-4}	555	4.44×10^{-1}

Note: n.a. = not applicable.

Table C9. Radionuclides of current interest in radioimmunotherapy [G16]

Isotope	*$t_{1/2}$ (h)*	*Emission (for therapy)*	*Maximum energy (keV)*	*Maximum particle range (mm)*
^{131}I	193	β	610	2.0
^{90}Y	64	β	2 280	12.0
^{177}Lu	161	β	496	1.5
^{67}Cu	62	β	577	1.8
^{186}Re	91	β	1 080	5.0
^{188}Re	17	β	2 120	11.0
^{212}Bi	1	α	8 780	0.09
^{213}Bi	0.77	α	$>$6 000	$<$0.1
^{211}At	7.2	α	7 450	0.08

Table C10. Recent clinical studies of radioimmunotherapy in haematological tumours [G16]

Tumour type	*Target antigen*	*Antibody*	*Radiolabels*
Non-Hodgkin's lymphoma	CD20	B1	^{131}I
	CD20	Y2B8	^{90}Y
	CD22	hLL2	^{131}I, ^{90}Y
	HLA-DR	Lym-1	^{131}I, ^{67}Cu
Hodgkin's disease	Ferritin	Rabbit	^{131}I, ^{90}Y
Myelocytic leukemia	CD33	HuM195	^{131}I, ^{213}Bi
	NCA95	BW250/183	^{188}Re

Table C11. Physical characteristics of therapeutic radionuclides for bone pain palliation [L20]

Radionuclide	*Half-life*	*Maximum energy (MeV)*	*Mean energy (MeV)*	*Maximum range*	*γ emission (keV)*
^{32}P	14.3 d	1.7 (ß)	0.695 (ß)	8.5 mm	None
^{89}Sr	50.5 d	1.4 (ß)	0.583 (ß)	7 mm	None
^{186}Re	3.7 d	1.07 (ß)	0.362 (ß)	5 mm	137
^{188}Re	16.9 h	2.1 (ß)	0.764 (ß)	10 mm	155
^{153}Sm	1.9 d	0.81 (ß)	0.229 (ß)	4 mm	103
^{117m}Sn	13.6 d	0.13 and 0.16 conversion electrons		$<1\ \mu$m	159
^{223}Ra	11.4 d	5.78 (α) (average)		$<10\ \mu$m	154

Table C12. Administered activity, typical response time and duration, and re-treatment interval for bone-seeking radionuclides [L20]

Radiopharmaceutical	*Usual administered activity*	*Typical response time (days)*	*Typical response duration (weeks)*	*Re-treatment interval (months)*
^{32}P	444 MBq (fractionated)	14	10	>3
$^{89}SrCl_2$	148 MBq	14–28	12–26	>3
^{186}Re-HEDP	1.3 GBq	2–7	8–10	>2
^{188}Re-HEDP	1.3–4.4 GBq	2–7	8	n.e.
^{153}Sm-EDTMP	37 MBq/kg	2–7	8	>2
^{117m}Sn-DTPA	2–10 MBq/kg	5–19	12–16	>2
$^{223}RaCl_2$	50–200 kBq/kg	<10	n.e.	n.e.

Note: n.e. = not established.

Table C13. CT and PET parameters in PET–CT designs (2004) [L20]

CT parameters		*PET parameters*	
Detectors	Ceramic	Scintillator	BGO, GSO, LSO
Slices	1, 2, 4, 8, 16	Detector size	4 × 4 mm, 6 × 6 mm
Rotation speed	0.4–2.0 s	Axial FOV	15–18 cm
Tube current	80–280 mA	Septa	2-D/3-D, 3-D only
Heat capacity	3.5–6.5 MHU	Attenuation	Rod, point, CT only
Transaxial FOV	45–50 cm	Transaxial FOV	55–60 cm
Time/100 cm	13–90 s	Time/bed	1–5 min
Slice width	0.6–10 mm	Resolution	4–6 mm
Patient port	70 cm	Patient port	60–70 cm

Note: BGO = bismuth germanate; GSO = gadolinium oxyorthosilicate; LSO = lutetium oxyorthosilicate; FOV = field of view; MHU = mega Hounsfield units.

Table C14. Radiation dose (paediatric subjects) from typical nuclear medicine procedures [H16, I34, I35, S27]

Procedure	*15-year-old (mSv/MBq)*	*10-year-old (mSv/MBq)*	*5-year-old (mSv/MBq)*	*1-year-old (mSv/MBq)*
^{18}F FDG	0.025	0.036	0.050	0.095
^{67}Ga citrate	0.130	0.200	0.330	0.640
^{123}I sodium iodide (0% uptake)	0.016	0.024	0.037	0.037
^{123}I sodium iodide (5% uptake)	0.053	0.080	0.150	0.290
^{123}I sodium iodide (15% uptake)	0.110	0.170	0.350	0.650
^{123}I sodium iodide (25% uptake)	0.170	0.260	0.540	1.000
^{123}I sodium iodide (35% uptake)	0.230	0.350	0.740	1.400
^{123}I sodium iodide (45% uptake)	0.290	0.440	0.940	1.800
^{123}I sodium iodide (55% uptake)	0.350	0.530	1.100	2.100
^{111}In pentatreotide, also known as Octreoscan	0.071	0.100	0.160	0.280
^{111}In white blood cells	0.836	1.240	1.910	3.380
^{99m}Tc disofenin, also known as HIDA (iminodiacetic acid)	0.021	0.029	0.045	0.100
^{99m}Tc DMSA (dimercaptosuccinic acid), also known as Succimer	0.011	0.015	0.021	0.037
^{99m}Tc exametazime, also known as Ceretec and HMPAO	0.011	0.017	0.027	0.049
^{99m}Tc macroaggregated albumin (MAA)	0.016	0.023	0.034	0.063
^{99m}Tc medronate, also known as Tc-99m methylene diphosphonate (MDP)	0.007	0.011	0.014	0.027
^{99m}Tc mertiatide, also known as MAG3	0.009	0.012	0.012	0.022
^{99m}Tc Bicisate, also known as ECD and Neurolite	0.014	0.021	0.032	0.060
^{99m}Tc pentetate, also known as Tc-99m DTPA	0.006	0.008	0.009	0.016
^{99m}Tc pyrophosphate	0.007	0.011	0.014	0.027
^{99m}Tc red blood cells	0.009	0.014	0.021	0.039
^{99m}Tc sestamibi, also known as Cardiolite (rest)	0.012	0.018	0.028	0.053
^{99m}Tc sestamibi, also known as Cardiolite (stress)	0.010	0.016	0.023	0.045
^{99m}Tc sodium pertechnetate	0.017	0.026	0.042	0.079
^{99m}Tc sulphur colloid	0.012	0.018	0.028	0.050
^{99m}Tc tetrofosmin, also known as Myoview (rest)	0.010	0.013	0.022	0.043
^{99m}Tc tetrofosmin, also known as Myoview (stress)	0.008	0.012	0.018	0.035
^{201}Tl thallous chloride	0.293	1.160	1.500	2.280

Table C15. Estimated foetal dose from various nuclear medicine procedures [S23]
(shading indicates maternal and foetal self-dose contributions)

Radiopharmaceutical	*Activity administered (MBq)*	*Dose to foetus at different ages*			
		Early (mGy)	*3 months (mGy)*	*6 months (mGy)*	*9 months (mGy)*
^{57}Co vitamin B12					
Normal, flushing	0.04	4.0×10^{-2}	2.7×10^{-2}	3.4×10^{-2}	3.5×10^{-2}
Normal, no flushing	0.04	6.0×10^{-2}	4.0×10^{-2}	4.8×10^{-2}	5.2×10^{-2}
Pernicious anaemia, flushing	0.04	8.4×10^{-3}	6.8×10^{-3}	6.8×10^{-3}	6.0×10^{-3}
Pernicious anaemia, no flushing	0.04	1.1×10^{-2}	8.4×10^{-3}	8.8×10^{-3}	8.0×10^{-3}
^{58}Co vitamin B12					
Normal, flushing	0.03	7.5×10^{-2}	5.7×10^{-2}	6.3×10^{-2}	6.3×10^{-2}
Normal, no flushing	0.03	1.1×10^{-1}	8.4×10^{-2}	9.3×10^{-2}	9.3×10^{-2}
Pernicious anaemia, flushing	0.03	2.5×10^{-2}	2.2×10^{-2}	1.9×10^{-2}	1.4×10^{-2}
Pernicious anaemia, no flushing	0.03	2.9×10^{-2}	2.6×10^{-2}	2.3×10^{-2}	1.8×10^{-2}

Radiopharmaceutical	*Activity administered (MBq)*	*Dose to foetus at different ages*			
		Early (mGy)	*3 months (mGy)*	*6 months (mGy)*	*9 months (mGy)*
^{18}F FDG	370	8.1×10^{0}	8.1×10^{0}	6.3×10^{0}	6.3×10^{0}
^{67}Ga citrate	190	1.8×10^{1}	3.8×10^{1}	3.4×10^{1}	2.5×10^{1}
^{197}Hg chlormerodrin	4	4.4×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.8×10^{-2}
^{123}I hippuran	75	2.3×10^{0}	1.8×10^{0}	6.3×10^{-1}	5.9×10^{-1}
^{123}I IMP	200	3.8×10^{0}	2.2×10^{0}	1.4×10^{0}	1.2×10^{0}
^{123}I MIBG					
Phaeochromocytoma	350	6.3×10^{0}	4.2×10^{0}	2.4×10^{0}	2.2×10^{0}
Cecholamine tumour	80	1.4×10^{0}	9.6×10^{-1}	5.4×10^{-1}	5.0×10^{-1}
^{123}I sodium iodide					
Thyroid uptake study	30	6.0×10^{-1}	4.2×10^{-1}	3.3×10^{-1}	2.9×10^{-1}
Thyroid imaging	15	3.0×10^{-1}	2.1×10^{-1}	1.7×10^{-1}	1.4×10^{-2}
^{125}I HSA	2	5.0×10^{-1}	1.6×10^{-1}	7.6×10^{-2}	5.2×10^{-2}
^{125}I NaI	1	1.8×10^{-2}	9.5×10^{-3}	3.5×10^{-3}	2.3×10^{-3}
^{131}I hippuran					
Renal function	1.3	8.3×10^{-2}	6.5×10^{-2}	2.5×10^{-2}	2.3×10^{-2}
Renal imaging	1.3	8.3×10^{-2}	6.5×10^{-2}	2.5×10^{-2}	2.3×10^{-2}
^{131}I HSA	0.5	2.6×10^{-1}	9.0×10^{-2}	8.0×10^{-2}	6.5×10^{-2}
^{131}I MAA	55	3.7×10^{0}	2.3×10^{0}	2.2×10^{0}	2.3×10^{0}
^{131}I MIBG	20	2.2×10^{0}	1.1×10^{0}	7.6×10^{-1}	7.0×10^{-1}
^{131}I NaI (diagnostic)					
Thyroid uptake	0.55	4.0×10^{-2}	3.7×10^{-2}	1.3×10^{-1}	1.5×10^{-1}
Scintiscanning	4	2.9×10^{-1}	2.7×10^{-1}	9.2×10^{-1}	1.1×10^{0}
Localization of extra-thyroid metastases	40	2.9×10^{0}	2.7×10^{0}	9.2×10^{0}	1.1×10^{1}
^{131}I NaI (therapeutic)					
Hyperthyroidism	350	2.5×10^{1}	2.3×10^{1}	8.1×10^{1}	9.5×10^{1}
Ablation of normal thyroid tissue	1 900	1.4×10^{2}	1.3×10^{2}	4.4×10^{2}	5.1×10^{2}
^{131}I rose bengal	0.04	8.8×10^{-3}	8.8×10^{-3}	6.4×10^{-3}	3.6×10^{-3}
^{111}In DTPA	20	1.3×10^{0}	9.6×10^{-1}	4.0×10^{-1}	3.6×10^{-1}
^{111}In pentetreotide					
Planar imaging	110	9.0×10^{0}	6.6×10^{0}	3.8×10^{0}	3.4×10^{0}
SPECT imaging	230	1.9×10^{1}	1.4×10^{1}	8.0×10^{0}	7.0×10^{0}
^{111}In platelets	10	1.7×10^{0}	1×10^{0}	9.9×10^{-1}	8.9×10^{-1}
^{111}In white blood cells	20	2.6×10^{0}	1.9×10^{0}	1.9×10^{0}	1.9×10^{0}
^{81m}Kr gas	600	1.1×10^{-4}	1.0×10^{-4}	1.6×10^{-4}	2.0×10^{-4}
^{99m}Tc disofenin	350	6.0×10^{0}	5.2×10^{0}	4.2×10^{0}	2.3×10^{0}
^{99m}Tc DMSA	220	1.1×10^{0}	1.0×10^{0}	8.8×10^{-1}	7.5×10^{-1}
^{99m}Tc DTPA					
Kidney imaging and glomular filtration	750	9.0×10^{0}	6.5×10^{0}	3.1×10^{0}	3.5×10^{0}
Brain imaging and renal perfusion	750	9.0×10^{0}	6.5×10^{0}	3.1×10^{0}	3.5×10^{0}
First pass	350	4.2×10^{0}	3.0×10^{0}	1.4×10^{0}	1.6×10^{0}
Gastric reflux	10	1.2×10^{-1}	8.7×10^{-2}	4.1×10^{-2}	4.7×10^{-2}
Hypertension	800	9.6×10^{0}	7.0×10^{0}	3.3×10^{0}	3.8×10^{0}
Residual urine determination	350	4.2×10^{0}	3.0×10^{0}	1.4×10^{0}	1.6×10^{0}
^{99m}Tc DTPA aerosol	40	2.3×10^{-1}	1.7×10^{-1}	9.2×10^{-2}	1.2×10^{-1}

Radiopharmaceutical	*Activity administered (MBq)*	*Dose to foetus at different ages*			
		Early (mGy)	*3 months (mGy)*	*6 months (mGy)*	*9 months (mGy)*
^{99m}Tc glucoheptonate					
Renal imaging	750	9.0×10^{0}	8.2×10^{0}	4.0×10^{0}	3.4×10^{0}
Brain imaging	750	9.0×10^{0}	8.2×10^{0}	4.0×10^{0}	3.4×10^{0}
^{99m}Tc HDP	750	3.9×10^{0}	4.10×10^{0}	2.3×10^{0}	1.9×10^{0}
^{99m}Tc HMPAO	750	6.5×10^{0}	5.0×10^{0}	3.6×10^{0}	2.7×10^{0}
^{99m}Tc HSA	200	1.0×10^{0}	6.0×10^{-1}	5.2×10^{-1}	4.4×10^{-1}
^{99m}Tc MAA					
Hepatic artery perfusion	150	4.2×10^{-1}	6.0×10^{-1}	7.5×10^{-1}	6.0×10^{-1}
Lung imaging	200	5.6×10^{-1}	8.0×10^{-1}	1.0×10^{0}	8.0×10^{-1}
Isotopic venography	220	6.2×10^{-1}	8.8×10^{-1}	1.1×10^{0}	8.0×10^{-1}
LeVeen shunt patency	110	3.1×10^{-1}	4.4×10^{-1}	5.5×10^{-1}	4.4×10^{-1}
^{99m}Tc MAG3	750	1.4×10^{1}	1.0×10^{1}	4.1×10^{0}	3.9×10^{0}
^{99m}Tc MDP	750	4.6×10^{0}	4.0×10^{0}	2.0×10^{0}	1.8×10^{0}
^{99m}Tc MIBI, rest	1 100	1.7×10^{1}	1.3×10^{1}	9.2×10^{0}	5.9×10^{0}
^{99m}Tc MIBI, stress	1 100	1.3×10^{1}	1.0×10^{1}	7.6×10^{0}	4.8×10^{0}
^{99m}Tc pertechnetate					
Brain imaging	1 100	1.2×10^{1}	2.4×10^{1}	1.5×10^{1}	1.0×10^{1}
Thyroid imaging	400	4.4×10^{0}	8.8×10^{0}	5.6×10^{0}	3.7×10^{0}
Salivary gland imaging	200	2.2×10^{0}	4.4×10^{0}	2.8×10^{0}	1.9×10^{0}
Placental localization	110	1.1×10^{0}	2.4×10^{0}	1.5×10^{0}	1.0×10^{0}
Blood pool imaging	1 100	1.1×10^{1}	2.4×10^{1}	1.4×10^{1}	1.0×10^{1}
Cardiovascular shunt detection	550	6.0×10^{0}	1.2×10^{1}	7.7×10^{0}	5.1×10^{0}
First pass	550	6.0×10^{0}	1.2×10^{1}	7.7×10^{0}	5.1×10^{0}
^{99m}Tc PYP					
Skeletal imaging	550	3.3×10^{0}	3.6×10^{0}	2.0×10^{0}	1.6×10^{0}
Cardiac imaging	700	4.2×10^{0}	4.6×10^{0}	2.5×10^{0}	2.0×10^{0}
^{99m}Tc red blood cell in vitro labelling	930	6.3×10^{0}	4.4×10^{0}	3.2×10^{0}	2.6×10^{0}
^{99m}Tc red blood cell in vivo labelling					
Rest	550	3.5×10^{0}	2.4×10^{0}	1.8×10^{0}	1.5×10^{0}
Exercise	930	6.0×10^{0}	4.0×10^{0}	3.1×10^{0}	2.5×10^{0}
Lower GI bleeding	930	6.0×10^{0}	4.0×10^{0}	3.1×10^{0}	2.5×10^{0}
^{99m}Tc sulphur colloid, normal					
Liver–spleen imaging	300	5.4×10^{-1}	6.3×10^{-1}	9.6×10^{-1}	1.1×10^{0}
Bone marrow imaging	450	8.1×10^{-1}	9.5×10^{-1}	1.4×10^{0}	1.7×10^{0}
Pulmonary aspiration	20	3.6×10^{-2}	4.2×10^{-2}	6.4×10^{-2}	7.4×10^{-2}
LeVeen shunt patency	110	2.0×10^{-1}	2.3×10^{-1}	3.5×10^{-1}	4.1×10^{-1}
^{99m}Tc white blood cells	200	7.6×10^{-1}	5.6×10^{-1}	5.8×10^{-1}	5.6×10^{-1}
^{201}Tl chloride					
Planar imaging	150	1.5×10^{1}	8.7×10^{0}	7.0×10^{0}	4.0×10^{0}
SPECT imaging	110	1.1×10^{1}	6.4×10^{0}	5.2×10^{0}	3.0×10^{0}
Myocardial perfusion	55	5.3×10^{0}	3.2×10^{0}	2.6×10^{0}	1.5×10^{0}
Thyroid imaging	80	7.8×10^{0}	4.6×10^{0}	3.8×10^{0}	2.2×10^{0}
^{133}Xe, injection					
Muscle blood flow	20	9.8×10^{-5}	2.0×10^{-5}	2.8×10^{-5}	3.2×10^{-5}
Pulmonary function with imaging	1 100	5.4×10^{-3}	1.1×10^{-3}	1.5×10^{-3}	1.8×10^{-3}

Table C16. Absorbed dose to the foetal thyroid per unit activity administered to the mother (mGy/MBq) [W19]

Gestational age (months)	^{123}I	^{124}I	^{125}I	^{131}I
3	2.7	24	290	230
4	2.6	27	240	260
5	6.4	76	280	580
6	6.4	100	210	550
7	4.1	96	160	390
8	4.0	110	150	350
9	2.9	99	120	270

Table C17. Number of items of nuclear medicine equipment and of sites, physicians and examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Number of items of equipment*					*Number of sites, physicians and examinations*			
	Planar gamma camera	*SPECT gamma camera*	*PET or PET–CT scanner*	*Rectilinear scanner*	*Static gamma detector*	*Sites*	*Physicians*	*Diagnostic examinations*	*Therapeutic treatments*
Health-care level I									
Albania		1			1	2			
Argentina	212	145	1	118					
Australia			4				145	504 000	
Austria	70	53	23			90	170	343 000	6 250
Belarus	13	9				1 500	48	3 838	
Belgium			18				153	570 900	
Croatia	13	15	2		6	9	67	38 102	1 274
Czech Republic	51	61	3			19	159		
Estonia	2	1	1			3	5	2 708	567
Finland	14	42	4		5		45	45 693	2 026
France		550	10			220			
Germany			60				904	3 831 000	
Greece	20	120	1	6	20	155	210	183 239	1 315
Hungary			3				106	143 500	3 285
Iceland	1	4			2	4	<10	4 133	102
Japan	1 570	1 252	56			1 265		1 560 000	4 400
Korea, Rep.	79	205	66						
Latvia	1	3				4		14 714	
Lithuania	4			11					
Luxembourg	3	5	1			5	7	17 246	49
Malta	0	2	0	0	0	2	1	2 305	74
Netherlands	180		4				60	247 000	5 000
New Zealand	1	20	2			14	8	26 895	
Norway	15	36	2	0	4	25	44	50 438	971
Poland	60	22	2	24	50		150	114 000	12 950
Romania	51					25		71 650	
Russian Federation							2 106		
Slovakia	22	14	4	0	20	11			
Slovenia	14	3	1			7	30	22 830	1 360

Country	*Number of items of equipment*					*Number of sites, physicians and examinations*			
	Planar gamma camera	*SPECT gamma camera*	*PET or PET–CT scanner*	*Rectilinear scanner*	*Static gamma detector*	*Sites*	*Physicians*	*Diagnostic examinations*	*Therapeutic treatments*
Spain	89	181	21	2		176	356	810 000	90 000
Sweden	70	30	10	0	30		200	110 000	3 496
Switzerland	80	20	16			67	57	97 827	2 306
The former Yugoslav Republic of Macedonia	2	2				2	15	7 937	334
United Kingdom							1 200	650 000	14 500
Venezuela (Bolivarian Republic of)	21		4						
Health-care level II									
Brazil	95	342	9				314		
Chile						30			
China	100	230	13	170	840			725 088	74 880
Costa Rica	1	6			1	4	5	7 500	250
El Salvador	1	2				3	5	3 977	214
Iraq	7						10		
Trinidad and Tobago	1	4				2		1 130	
Health-care level III									
Indonesia		17			15	17	28	3 522	310
Myanmar	3	2			4	5	9	2 796	956
Zimbabwe	2	2				3	1	206	30
Health-care level IV									
Maldives	0	0	0	0	0	0	0	0	0

Table C18. Number of items of nuclear medicine equipment and of physicians per million population

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Number of items of equipment*					
	Planar gamma camera	*SPECT gamma camera*	*PET or PET–CT scanner*	*Rectilinear scanner*	*Static gamma detector*	*Number of physicians*
Health-care level I						
Albania		0.31			0.31	
Argentina	5.88	4.02	0.03	3.28		
Australia			0.20			7.11
Austria	8.55	6.47	2.81			21
Belarus	1.26	0.87	0.00			4.7
Belgium			1.75			15
Croatia	2.93	3.38	0.45		1.35	15
Czech Republic	4.96	5.93	0.29			15
Estonia	1.46	0.73	0.73			3.7
Finland	2.67	8.00	0.76		0.95	8.6
France		8.91	0.16			
Germany			0.73			11
Greece	1.82	10.9	0.09	0.55	1.82	19
Hungary			0.30			11
Iceland	3.40	13.61			6.80	
Japan	12.32	9.82	0.44			

Country	*Number of items of equipment*					
	Planar gamma camera	*SPECT gamma camera*	*PET or PET–CT scanner*	*Rectilinear scanner*	*Static gamma detector*	*Number of physicians*
Korea, Rep.	1.68	4.36	1.40			
Latvia	0.44	1.31				
Lithuania	1.15			3.15		
Luxembourg	6.64	11.1	2.21			15
Malta	0.00	5.00	0.00	0.00	0.00	2.5
Netherlands	11.5		0.26			3.8
New Zealand	0.27	5.35	0.54			2.1
Norway	3.23	7.76	0.43	0.00	0.86	9.5
Poland	1.56	0.57	0.05	0.62	1.30	3.9
Romania	2.29					
Russian Federation						14
Slovakia	4.04	2.57	0.74	0.00	3.68	
Slovenia	6.99	1.50	0.50			15
Spain	2.02	4.10	0.48	0.05		8.1
Sweden	7.90	3.39	1.13		3.39	23
Switzerland	10.7	2.68	2.14			7.6
The former Yugoslav Republic of Macedonia	0.98	0.98				7.4
United Kingdom						20
Venezuela (Bolivarian Rep. of)	0.78		0.15			
Health-care level II						
Brazil	0.51	1.83	0.05			1.7
Chile						
China	0.080	0.18	0.01	0.14	0.67	
Costa Rica	0.23	1.39			0.23	1.2
El Salvador	0.15	0.31				0.77
Iraq	0.26					0.37
Trinidad and Tobago	0.79	3.17				
Health-care level III						
Indonesia		0.069			0.061	0.11
Myanmar	0.063	0.042			0.084	0.19
Zimbabwe	0.17	0.17				0.08
Health-care level IV						
Maldives	0	0	0	0	0	0

Table C19a. Annual number of various nuclear medicine examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Bone (^{99m}Tc)*	*Cardiovascular*			*Lung perfusion (^{99m}Tc)*	*Lung ventilation*				*Thyroid scan*		
			^{99m}Tc	*^{201}Tl*	*Total*		*^{99m}Tc*	*^{81m}Rb*	*^{133}Xe*	*Total*	*^{99m}Tc*	*^{131}I/^{123}I*	*Total*
I	Australia	196 200	38 900	38 000	76 900	26 800	26 600			26 600	26 200		26 200
	Austria	52 000		40 000	40 000	14 000	10 000			10 000	200 000		200 000
	Belarus	2 485	38		38	27	4			4	4		4
	Belgium	251 874	99 619		99 619	29 377	20 752			20 752	100 631		100 631
	Croatia	11 992			4 191	1 687	128			128	12 238		12 238
	Czech Republic	49 685	2 822		2 822	29 143	4 740			4 740	7 223		7 223
	Estonia	850	400		400	120	80			80	550		550
	Finland	17 190	5 209	979	6 188	4 389	2 847			2 847	152	103	255
	France	423 000			212 000					127 000			101 000
	Germany	954 000			499 000					294 000			1 435 000
	Greece	73 000		55 000	55 000	7 400	1 900			1 900	30 000		30 000
	Hungary	57 000	18 500		18 500	10 500	2 700			2 700	58 000		58 000
	Iceland	2 631	84		84	81	51			51		290	290
	Japan	471 000	396 000		396 000	33 000	33 000			33 000	87 000		87 000
	Latvia	4 251	1 832		1 832	1 344	1 344			1 344	4 603		4 603
	Luxembourg	5 575	2 518		2 518	414	403			403	4 893		4 893
	Malta	830	481		481	261	46			46	252		252
	Netherlands	122 000			125 000	34 000				14 000			35 000
	New Zealand	13 945	4 579		4 579	1 094	958			958	1 675		1 675
	Norway	17 375	11 148		11 148	2 758	1 757			1 757	5 930		5 930
	Poland	24 740	12 540		12 540	4 200	700			700	30 883	18 137	49 020
	Romania	10 607	1 555		1 555	347				0	21 350	22 432	43 782
	Slovenia	9 225	2 750	450	3 200	1 300				0	3 500	250	3 750
	Spain	341 376	101 976		101 976	66 664	54 933			54 933	89 432		89 432
	Sweden	28 650	10 039	2 851	12 890	8 808	5 464		144	5 608	8 386	5 037	13 423
	Switzerland	39 500	16 700	5 500	22 200	4 800	1 280		1 200	2 480	3 860	1 740	5 600
	The former Yugoslav Republic of Macedonia	1 530	830		830	370	255			255	2 793		2 793
II	Costa Rica	2 544	384		384	144	144			144			2 900
	El Salvador	523	64		64	52	51			51		2 901	2 901
	Trinidad and Tobago	660	120		120	50							

Health-care level	Country	Bone (^{99m}Tc)	Cardiovascular			Lung perfusion (^{99m}Tc)	Lung ventilation				Thyroid scan		
			^{99m}Tc	^{201}Tl	Total		^{99m}Tc	^{81m}Rb	^{133}Xe	Total	^{99m}Tc	^{131}I/^{123}I	Total
III	Indonesia	374	240		240	17	17			17	2 010		2 010
	Myanmar	490	160		160					0	1 528		1 528
	Zimbabwe	150			0	10				0	15		15

Table C19b. Annual number of various nuclear medicine examinations

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	Country	Renal	Gastroenterology	Brain	Liver	PET	PET–CT combined	Other gastric emptying	Other ^{67}Ga scan	Total
I	Australia	20 400	3 200	2 900	9 200					
	Austria	11 000		5 000		10 000	1 000			
	Belarus	1 271	13							
	Belgium	12 349		14 151				9 297	6 016	
	Croatia	6 437	911	4 34		84	0			
	Czech Republic	16 820	11 214	5 862		2 265				
	Estonia	550	30	60		31	37			
	Finland	5 690	423	1 633		1 930				
	Germany	295 000	67 000	57 000		230 000				
	Greece	14 500	1 200				239			
	Hungary	15 000	7 800	5 200		1 300	2 500			
	Iceland	336	232	428		0	0			
	Japan	65 000	5 600	199 000		12 000				
	Latvia	2 148								
	Luxembourg	346	136	252			1 039			
	Malta	307	87	41						
	Netherlands	16 000	5 800	5 200		21 000			2 500	
	New Zealand	2 558	229	57						
	Norway	5 116	166	2 352		318	3 518			
	Poland	16 600	1 000	2 600			2 600			
	Romania	6 750	266						114	
	Slovenia	2 900	160	350		40				
	Spain	40 929	14 327	21 579		1 817	14 546			

Health-care level	*Country*	*Renal*	*Gastroenterology*	*Brain*	*Liver*	*PET*	*PET–CT combined*	*Other gastric emptying*	*Other ^{67}Ga scan*	*Total*
I	Sweden	13 781	2 041	7 831	846	1 545		439	50	
	Switzerland	4 220		470		7 970				
	The former Yugoslav Republic of Macedonia	2 085	267							
	United Kingdom									650 000
II	Costa Rica	1 000		240	144					
	El Salvador	178	180	27						
	Trinidad and Tobago	170	50							
III	Indonesia	821	52	8						
	Myanmar	521	41	58						
	Zimbabwe	25	6	0		0	0			

Table C20a. Number of various diagnostic nuclear medicine examinations per million population

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Bone (^{99m}Tc)*	*Cardiovascular*			*Lung perfusion (^{99m}Tc)*	*Lung ventilation*				*Thyroid scan*		
			^{99m}Tc	*^{201}Tl*	*Total*		*^{99m}Tc*	*^{81m}Rb*	*^{133}Xe*	*Total*	*^{99m}Tc*	*^{131}I/^{123}I*	*Total*
I	Australia	9 615	1 906	1 862	3 768	1 313	1 304			1 304	1 284		1 284
	Austria	6 349		4 884	4 884	1 709	1 221			1 221	24 420		24 420
	Belarus	241	3.7		3.7	2.6	0.4			0.4	0.4		0.4
	Belgium	24 454	9 672		9 672	2 852	2 015			2 015	9 770		9 770
	Croatia	2 703			945	380	28.8			28.8	2 758		2 758
	Czech Republic	4 828	274		274	2 832	461			461	702		702
	Estonia	620	292		292	87.6	58.4			58.4	402		402
	Finland	3 274	992	186	1 179	836	542			542	29	20	49
	France	6 656			3 436					2 058			1 637
	Germany	11 627			6 082					3 583			17 489
	Greece	6 636		5 000	5 000	673	173			173	2 727		2 727
	Hungary	57 11	1 854		1 854	1 052	271			270	5 811		5 811
	Iceland	8 949	286		286	276	174			174		986.4	986
	Japan	3 696	3 108		3 108	259	259			259	683		683
	Latvia	18 52	798		798	586	586			586	2 006		2 006
	Luxembourg	12 334	5 571		5 571	916	892			892	10 825		10 825

Health-care level	Country	Bone (^{99m}Tc)	Cardiovascular ^{99m}Tc	Cardiovascular ^{201}Tl	Cardiovascular Total	Lung perfusion (^{99m}Tc)	Lung ventilation ^{99m}Tc	Lung ventilation ^{81m}Rb	Lung ventilation ^{133}Xe	Lung ventilation Total	Thyroid scan ^{99m}Tc	Thyroid scan ^{131}I/^{123}I	Thyroid scan Total
I	Malta	2 075	1 202		1 202	652	115.0			115	630		630
	Netherlands	7 802			7 993	2 174				895			2 238
	New Zealand	3 732	1 225		1 225	293	256			256	448		448
	Norway	3 745	2 403		2 403	594	379			378	1 278		1 278
	Poland	642	325		325	109	18.2			18.2	801	471	1 272
	Romania	476	69.7		69.7	15.6				0.0	957	1 006	1 963
	Slovenia	4 606	1 373	225	1 598	649				0.0	1 747	125	1 872
	Spain	7 739	2 312		2 312	1 511	1 245			1 245	2 028		2 028
	Sweden	3 233	1 133	322	1 455	994	617		16.3	633	946	568	1 515
	Switzerland	5 294	2 238	737	2 976	643	172		160.8	332	517	233	750
	The former Yugoslav Republic of Macedonia	753	408		408	182	125			125	1 374		1 374
II	Costa Rica	588	88.8		88.8	33.3	33.3			33.3			670
	El Salvador	80	9.8		9.8	8.0	7.8			7.8		446	446
	Trinidad and Tobago	523	95.1		95.1	39.6							
III	Indonesia	1.5	1.0		1.0	0.1	0.1			0.1	8.2		8.2
	Myanmar	10.3	3.4		3.4					0.0	32.2		32.2
	Zimbabwe	12.5			0.0	0.8				0.0	1.3		1.3

Table C20b. Number of various diagnostic nuclear medicine examinations per million population

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	Country	Renal	Gastroenterology	Brain	Liver	PET	PET–CT combined	Other gastric emptying	Other ^{67}Ga scan	Total
I	Australia	1 000	157	142	451					
	Austria	1 343		611		1 221	122			
	Belarus	123	1.3							
	Belgium	1 199		1 374				903	584	
	Croatia	1 451	205	97.8		18.9				
	Czech Republic	1 635	1 090	570		220				
	Estonia	402	21.9	43.8		22.6	27.0			
	Finland	1 084	81	311		368				
	Germany	3 595	817	695		2 803				

Health-care level	*Country*	*Renal*	*Gastroenterology*	*Brain*	*Liver*	*PET*	*PET–CT combined*	*Other gastric emptying*	*Other ^{67}Ga scan*	*Total*
I	Greece	1 318	109				21.7			
	Hungary	1 503	781	521		130	250			
	Iceland	1 143	789	1 456		0	0			
	Japan	510	43.9	1 562		94.2				
	Latvia	936								
	Luxembourg	765	301	558			2 299			
	Malta	768	218	103						
	Netherlands	1 023	371	333		1 343			160	
	New Zealand	685	61.3	15.3						
	Norway	1 103	35.8	507		68.5	758			
	Poland	431	25.9	67.5			67.5			
	Romania	303	11.9						5.1	
	Slovenia	1 448	79.9	174.7		20.0				
	Spain	928	325	489		41.2	330			
	Sweden	1 555	230	884	95	174.4		50	6	
	Switzerland	566		63		1 068				
	The former Yugoslav Republic of Macedonia	1 026	131							
	United Kingdom									10 924
II	Costa Rica	231		55.5	33.3					
	El Salvador	27.4	27.7	4.2						
	Trinidad and Tobago	135	39.6							
III	Indonesia	3.3	0.2							
	Myanmar	11.0	0.9	1.2						
	Zimbabwe	2.1	0.5							

Table C21a. Mean patient effective dose (mSv) for various nuclear medicine diagnostic examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Bone (^{99m}Tc)*	*Cardiovascular*			*Lung perfusion (^{99m}Tc)*	*Lung ventilation*				*Thyroid scan*		
		^{99m}Tc	*^{201}Tl*	*Total*		*^{99m}Tc*	*^{81m}Rb*	*^{133}Xe*	*Total*	*^{99m}Tc*	*^{131}I/^{123}I*	*Total*
Health-care level I												
Australia	5.6	14.1	21.3		2.3	0.7				2.8		
Austria	4.0		23		1.2	2.4				1.0		
Belarus	9	5			38					18		
Belgium	4.1	8.4			2.1					1.8		
Croatia	4.7			7.9	1.8					0.84		
Czech Republic	4	9.9			2.3				0.6	1.8		
Estonia	4.8	7.5			1.2	1.2				1.1		
Finland	3.6	7.5	22.8		1.4	0.6				1.6		
Germany	3.5			7.4	1.2				1.2			0.7
Japan	5.1		46.1		4	4				3.5		
Malta	4.0	5.1			1.2	1.3				2.6		
Netherlands	3.1			6.8	1.1				0.1			3.2
Norway	3.9	4.7			2.1	2.9				2		
Poland		4.9										
Romania	7.2	8.6			1.8					2.4	32.4	
Spain	5.1	9.9			2.4	2.9				2.8		
Sweden	2.9	8.5	15		1.2	1.5				1.3	8	
Switzerland	4.2	5.8	20		2.1	0.28		0.068		1.7	25	
Health-care level III												
Myanmar	3	5.3								0.36		

Table C21b. Mean patient effective dose (mSv) for various nuclear medicine diagnostic examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Renal*	*Gastro-enterology*	*Brain*	*Liver*	*PET*	*PET-CT combined*	*Other gastric emptying*	*Other ^{67}Ga scan*	*Total*
I	Australia	2	2.4	7.5	4.1					
	Austria	0.9		6.5		10.8	10.8			
	Belarus	0.02	1.4							
	Belgium	1.4		7.5				1	14.5	
	Croatia	1.1	4.6	3.5		6.3				
	Czech Republic	1.2	0.9	4.2		6.9				
	Estonia	2.2	7	4.4		6	6			
	Germany	1.5	4.5	5.6		5.6				2.7
	Japan	2.5	5.7	6.8		6.4				
	Malta	1.0	3.4	6						
	Netherlands	0.6		5.7		7.4			6.8	
	Norway	1	0.1	2		6.4				
	Romania	3.8	2.6	4.9					2	
	Spain	1.8	1	5.8			7.4			
	Switzerland	0.4		6.4		6.0				
III	Myanmar	0.6	1.1	2.5						

Table C22. Number of various therapeutic nuclear medicine examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Thyroid malignancy*	*Hyper-thyroidism*	*Polycythemia vera*	*Bone metastases*	*Synovitis*	*Other, e.g. ^{90}YCl*	*Total*
I	Austria	1 100	3 400	10	100	1 500	140	6 250
	Croatia	363	902	0	6	3	0	1 274
	Czech Republic	285	1 200	0	799	520		2 804
	Estonia	160	345	5	50	5	2	567
	Finland	556	1 273	372	56	46	8	2 311
	Greece	1 130			185			1 315
	Hungary	450	2 600		115	120		3 285
	Iceland	27	74		1			102
	Japan	2 200	2 200					4 400
	Luxembourg	46			2	1		49
	Malta	40	24	10				74
	Netherlands							6 000
	Norway	275	642	4	23	9	18	971
	Poland	1 600	10 500		600	200	50	12 950
	Slovenia	210	1 120		3	6	30	1 369
	Spain	26 951	55 863	960	3 191	2 790	245	90 000
	Sweden	104	2 297	291	340	14	10	3 056
	Switzerland		1 500			283	523	2 306
	The former Yugoslav Republic of Macedonia	264	70					334
	United Kingdom	1 150	11 500	710	540	400	200	14 500
II	Costa Rica	100	150					250
	El Salvador	128	86					214
III	Indonesia	132	163		15			310
	Myanmar	77	879					956
	Zimbabwe	20	10	0	0	0	0	30

Table C23. Number of various therapeutic nuclear medicine examinations per million population
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Thyroid malignancy*	*Hyper-thyroidism*	*Polycythemia vera*	*Bone metastases*	*Synovitis*	*Other, e.g. ^{90}YCl*	*Total*
I	Austria	134	415	1.2	12.2	183	17.1	763
	Croatia	81.8	203	0.0	1.4	0.7		287
	Czech Republic	27.7	117	0.0	77.6	50.5		272
	Estonia	117	252	3.6	36.5	3.6	1.5	414
	Finland	106	242	70.9	10.7	8.8	1.5	440
	Greece	103			16.8			120
	Hungary	45.1	261		11.5	12.0		329
	Iceland	91.8	252		3.4			347
	Japan	17.3	17.3					34.5
	Luxembourg	102			4.4	2.2		108
	Malta	100	60.0	25.0				185
	Netherlands							384
	Norway	59.3	138	0.9	5.0	1.9	3.9	209
	Poland	41.5	272		15.6	5.2	1.3	336
	Slovenia	105	559		1.5	3.0	15.0	683
	Spain	611	1 266	21.8	72.3	63.3	5.6	2 040
	Sweden	11.7	259	32.8	38.4	1.6	1.1	345
	Switzerland		201			37.9	70.1	309
	The former Yugoslav Republic of Macedonia	130	34.4					164
	United Kingdom	19.3	193	11.9	9.1	6.7	3.4	244
II	Costa Rica	23.1	34.7					57.8
	El Salvador	19.7	13.2					32.9
III	Indonesia	0.5	0.7		0.1			1.3
	Myanmar	1.6	18.6					20.2
	Zimbabwe	1.7	0.8	0.0		0.0	0.0	2.5

Table C24. Reported mean patient dose (mSv) for various nuclear medicine therapeutic examinations
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Thyroid malignancy*	*Hyperthyroidism*	*Polycythemia vera*	*Bone metastases*	*Synovitis*	*Other, e.g. ^{90}YCl*
I	Austria				380		
	Estonia			400	435		
	Spain	9 356	7 511		615	130	2 220
III	Myanmar	390 000	98 000				

Table C25. Frequency, population-weighted average effective dose and collective dose for nuclear medicine diagnostic examinations (1997–2007)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

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*
Bone ^{99m}Tc	6.17×10^{0}	3.08×10^{-1}	3.33×10^{-3}	1.6×10^{0}	4.74	4.74	4.74	4.74	29 263	1 461	15.8	30 741
Cardiovascular ^{99m}Tc	2.19×10^{0}	4.70×10^{-2}	1.37×10^{-3}	5.5×10^{-1}	7.97	7.97	7.97	8.0	17 476	375	10.9	17 861
Cardiovascular ^{201}Tl	2.26×10^{0}			5.4×10^{-1}	40.7	40.7	40.7	40.7	91 892	0.0	0.0	91 892
Lung perfusion ^{99m}Tc	7.61×10^{-1}	2.04×10^{-2}	1.05×10^{-4}	1.9×10^{-1}	3.52	3.52	3.52	3.52	2 681	71.7	0.4	2 753
Lung ventilation ^{99m}Tc	5.12×10^{-1}	1.80×10^{-2}	6.93×10^{-5}	1.3×10^{-1}	2.66	2.66	2.66	2.66	1 363	47.9	0.2	1 411
Lung ventilation ^{81m}Rb								0.0	0.0	0.0	0.0	0.0
Lung ventilation ^{133}Xe	8.23×10^{-2}			2.0×10^{-2}	0.07	0.07	0.07	0.07	5.6	0.0	0.0	5.6
Thyroid scan ^{99m}Tc	1.97×10^{0}		1.17×10^{-2}	4.8×10^{-1}	3.75	3.75	3.75	3.8	7 374	0.0	43.7	7 418
Thyroid scan ^{131}I/^{123}I	5.67×10^{-1}	4.46×10^{-1}		3.5×10^{-1}	30.5	30.5	30.5	30.5	17 304	13 632	0.0	30 937
Renal	1.27×10^{0}	1.12×10^{-1}	4.48×10^{-3}	3.6×10^{-1}	1.89	1.89	1.89	1.89	2 403	210	8.5	2 622
Gastroenterology	2.87×10^{-1}	2.96×10^{-2}	3.25×10^{-4}	8.3×10^{-2}	3.97	3.97	3.97	3.97	1 140	118	1.3	1 259
Brain	8.19×10^{-1}	2.47×10^{-2}	2.17×10^{-4}	2.1×10^{-1}	6.09	6.09	6.09	6.09	4 984	150	1.3	5 135
Liver	3.43×10^{-1}	3.33×10^{-2}		9.9×10^{-2}	4.10	4.10	4.10	4.10	1 407	136	0.0	1 544
PET	8.74×10^{-1}			2.1×10^{-1}	6.42	6.42	6.42	6.42	5 612	0.0	0.0	5 612
PET–CT combined	2.07×10^{-1}			5.0×10^{-2}	7.88	7.88	7.88	7.9	1 632	0.0	0.0	1 633
Other gastric emptying	5.08×10^{-1}			1.2×10^{-1}	1.00	1.00	1.00	1.0	508	0.0	0.0	508
Other ^{67}Ga scan	1.52×10^{-1}			3.6×10^{-2}	7.26	7.26	7.26	7.3	1 104	0.0	0.0	1 104
Thyroid malignancy	1.09×10^{-1}	2.11×10^{-2}	3.45×10^{-3}	3.7×10^{-2}								
Hyperthyroidism	2.85×10^{-1}	2.18×10^{-2}	3.45×10^{-3}	8.0×10^{-2}								
Polycythemia vera	1.61×10^{-2}	1.68×10^{-2}		3.9×10^{-3}								
PET												
Bone metastases	2.88×10^{-2}			6.9×10^{-3}								
Synovitis	2.88×10^{-2}			6.9×10^{-3}								
Other, e.g. ^{90}YCl	6.65×10^{-3}			1.6×10^{-3}								
Total diagnostic	1.9×10^{1}	1.09×10^{0}	2.15×10^{-2}	5.07×10^{0}					186 000	16 000	82	202 437
Average effective dose per caput from diagnostic nuclear medicine examinations (mSv)									0.121	0.005 1	0.000 047	0.031 4

APPENDIX D: LEVELS AND TRENDS IN THE USE OF RADIATION THERAPY

I. INTRODUCTION

D1. Radiation therapy, often referred to as "radiotherapy", is the collection of treatment options available in the medical specialty known as clinical radiation oncology. Nowadays radiation therapy is used for the treatment of many types of cancer [C18, P14, U3, U4]. The goal of radiation therapy is to achieve cytotoxic levels of irradiation to a well-defined target volume (the volume of tissue that must be treated to assure that the tumour receives the prescribed dose) of the patient, while as far as possible avoiding the exposure of surrounding healthy tissues. Treatments generally involve multiple exposures (fractions) spaced over a period of time for maximum therapeutic effect. Radiation therapy is an important treatment modality for malignant disease, and is most often delivered in combination with surgery or chemotherapy, or both [C18, M28, S10, S11, W22]. The utilization of radiation treatment in oncology varies significantly among the different sites of disease and also between countries. In the United States, for example, 37% of women diagnosed with early stage breast cancer in 2002 received radiation treatment [N7]. In contrast, the radiation therapy utilization rate for breast cancer patients in the Russian Federation in 1995 was 2% [U3]. Less commonly, radiation is also used in the treatment of benign disease [O7]. In 2000, external beam radiation therapy utilization varied considerably among countries. In level I countries, Hungary and the Czech Republic reported 3.5 or more patients treated per 1,000 population, while the United States and the United Kingdom reported approximately 2.0 to 2.5 patients per 1,000 population, and Ecuador, Kuwait and the United Arab Emirates reported fewer than 0.3 patient per 1,000 population. In level II countries, 0.7 patient per 1,000 population received radiation therapy, and in level III countries, only 0.5 patient per 1,000 population received treatment [U3]. The clinical goal in radiation therapy is either the eradication of cancer (curative treatment) or the relief of symptoms associated with the disease (palliative treatment) [C18]. In level I and II countries, the majority of treatments are considered curative. In level III and IV countries, where tumours are less likely to be diagnosed early and where equipment and techniques are generally less advanced than in level I and II countries, a larger proportion of treatments are palliative.

D2. Radiation therapy is delivered by one of two methods: teletherapy, in which a beam of radiation is directed to the target tissue from outside the body; or brachytherapy, in which radioactive sources are placed in a body cavity or placed directly in the tissue. For some tumours, such as cancers of the uterine cervix and the prostate, teletherapy and brachytherapy often are used sequentially or even concomitantly, as is described in more detail below. Unsealed sources of radiation are sometimes used for treatment of metastatic or widespread disease. Such therapy with unsealed sources (radiopharmaceuticals) or with monoclonal antibodies (radioimmunotherapy) is discussed in appendix C. Beams of radiation for therapeutic purposes are produced by machines that fall into four general types: X-ray machines are quite commonly used for therapy, and produce beams of radiation generated between about 50 and 300 kVp. Cobalt teletherapy units contain large sources of radioactive ^{60}Co, with a mechanism that moves the source from a shielded location to a position that permits the gamma rays to pass through an opening of adjustable size, called a collimator. In one type of cobalt unit, multiple sources are arranged in a spherical shield, into which a patient's head is positioned for treatment. Caesium-137 sources have been used in the past, but these have largely been replaced by more modern machines. Megavoltage X-rays can be produced by electron linear accelerators, which are now commonly used throughout the developed world and are becoming more widely used in developing countries. A small number of radiation therapy centres operate cyclotrons or synchrotrons that accelerate beams of protons or heavier charged particles that are used for treatment. At present, 31 centres operate such machines, most of them in Europe, Japan and the United States. Another six are under construction and at least eight more have been proposed [F14, P23].

D3. Radiation therapy involves the use of intense radiation beams and high-activity sources. Treatments are often complex, requiring the delivery of conformally shaped beams from multiple directions, or the use of sophisticated beam modifiers. Properly trained staff are required, and they must follow carefully developed procedures. The equipment must be properly maintained. Failure to adhere to recommended quality assurance procedures and the use of inadequately prepared staff can contribute to a significant potential for accidents. Such events have resulted in serious consequences for the health of both patients and staff; such incidents are discussed further in section VII of this appendix.

II. TECHNIQUES

D4. The objectives of radiation protection in radiation therapy are to minimize the radiation dose to the patient outside the target volume, and to maintain the doses to staff and members of the public as low as reasonably achievable [P14]. Radiation therapy is becoming increasingly sophisticated in the pursuit of these objectives. Achieving the first objective requires that the extent of the tumour be established precisely and that nearby sensitive structures be identified. This requires the use of state-of-the-art diagnostic techniques to distinguish tissues involved with tumours from healthy tissues. The use of CT and MRI for radiation therapy treatment planning is becoming more common. Treatment planning involves the use of a computer to calculate the radiation dose distribution within the body. With advances in computing and the availability of inexpensive fast computer processors, it has become practical to plan radiation therapy treatments in three dimensions (3-D), thereby more closely matching or "conforming" the treated volume to the tumour. Optimized treatments may require multiple beam angles, different beam weights, complex field shapes, wedge filters or other modifiers, or the use of intensity-modulated techniques. The second goal is addressed through improvements in the design and operation of equipment and facilities to provide greater protection for staff and members of the public.

D5. External beam radiation therapy (also called teletherapy) can be delivered with several classes of treatment machines. These can be grouped as: *(a)* kilovoltage X-ray generators, *(b)* radionuclide teletherapy units, *(c)* megavoltage X-ray machines such as linear accelerators, and *(d)* proton and heavy particle accelerators.

D6. Kilovoltage X-ray machines can be of three main types: (1) Contact therapy machines, though rare today, produce X-rays at energies of 25 to 40 kVp. (2) Superficial therapy machines produce X-rays in the range 40–120 kVp, with a typical source–skin distance (SSD) of 30 cm or less, and are used to treat small epithelial lesions. The beam quality of superficial X-ray therapy is usually specified in terms of its half-value layer and lies in the range 0.5–8 mm aluminium [H17, I21]. Lesions of the skin and of the oral, vaginal or rectal mucosa are sometimes treated with this technique [L23]. (3) Orthovoltage therapy machines generate X-ray beams in the range 150–300 kVp. Orthovoltage units have been used to treat skin lesions and bone metastases. The beam size is limited by either an applicator or a diaphragm. SSDs in the range 30–60 cm are used. Orthovoltage therapy units have half-value layers in the range 0.2–5 mm copper [I21].

D7. Many centres worldwide use radiation therapy units containing a high-activity source of radioactive cobalt (^{60}Co). The isotope ^{60}Co decays with a half-life of 5.26 years to ^{60}Ni, producing two gamma rays of 1.17 MeV and 1.33 MeV. Consequently, the radiation from this source is referred to as megavoltage radiation. The activity of the source must be high enough to allow an SSD of 80–100 cm. This means that isocentric treatments are possible. As the source size is relatively large, there is a wide penumbra associated with these radiation sources [H17]. Satellite collimators, or "penumbra trimmers", were introduced to reduce the width of the penumbra, but in comparison with linear accelerator beams, the penumbra of a cobalt beam is still large [H17, J10].

D8. Megavoltage radiation therapy may also be delivered using medical accelerators, usually electron linear accelerators (linacs). These machines use radiofrequency radiation to accelerate electrons to energies of between 4 and 25 MeV. The accelerated narrow electron beam can be passed through a scattering foil to produce a broad uniform electron beam that is directed towards the patient and is defined by a cone or applicator that typically extends to within 5 cm of the patient surface. Electrons lose energy at the rate of about 2 MeV/cm in tissue and are useful for treating superficial tissues quite uniformly while sparing deeper-seated structures. When using sterile intraoperative techniques, electrons can be used to treat a tumour or the tumour bed once it has been exposed through surgery.

D9. Alternatively, the accelerated electron beam can be steered into a metal target, producing bremsstrahlung and characteristic X-rays whose energies fall in a spectrum with a maximum energy equal to the energy of the accelerated electrons. Similar to kilovoltage X-rays, accelerator-produced megavoltage photon beams are commonly described by a potential corresponding to the maximum electron energy, e.g. 4 MV to 25 MV. A collimator consisting of several parts limits and shapes the X-ray beam. A primary collimator is placed near the target and limits the beam to some maximum size, generally 56 cm diameter at the normal treatment distance. A secondary collimator consists of two pairs of heavy moveable jaws that can shape the beam to any rectangle up to the maximum size. Some accelerators are equipped with multileaf collimators (MLCs) that can produce an irregular-shaped beam. The MLC either replaces one pair of collimator jaws or is mounted below the jaws. High-energy photon beams are more penetrating than superficial or orthovoltage X-rays and have a skin-sparing effect. Consequently, these beams are very useful for treating deep-seated tumours, as well as shallower structures such as the breast, for which beams can be directed tangentially.

D10. Worldwide in 1991–1996, approximately equal numbers of radiation therapy patients were treated using X-ray machines, radionuclide units and linear accelerators (table B1 in appendix B) [U3]. Insufficient data were received in 1997–2007 to estimate numbers of patients treated with each type of treatment device. However, the relative availability of linear accelerators worldwide was about 1.6 machines per million population. X-ray machines and cobalt units were each found at a frequency of 0.4 per million population. In level I countries, however, the availability of treatment equipment was considerably greater, and linear accelerators were reported at a frequency of 5.4 per million population (table D1). The total number of treatment machines also varied from one health-care level to another (table D2). The numbers of patients treated in different countries varied in relation to the availability of treatment equipment. In level I countries, the number of courses of treatment given was 2.4 per 1,000 population, while smaller numbers were reported by level II and III countries (table D3).

D11. The characteristics of a radiation beam are often described through the use of isodose curves. These curves represent a map of the radiation dose distribution, in which each curve corresponds to the locus of points at which the dose is a selected value, such as 20 Gy, or a relative value, such as 70% of the dose at a reference point. Patient dose distributions are generally displayed by superimposing isodose curves on a CT image or other representation of the patient. Several examples of isodose distributions are shown in figures D-I, D-II, D-III and D-IV.

Figure D-I. Representative isodose distributions: A 3-dimensional conformal treatment plan for the prostate, showing significant dose to the rectum

Isodose levels (in Gy) are shown by solid lines, while structures are contoured in dashed lines. Red dashed line – prostate; purple dashed line – prostate PTV (see paragraphs D28-D31); pink dashed line – rectum

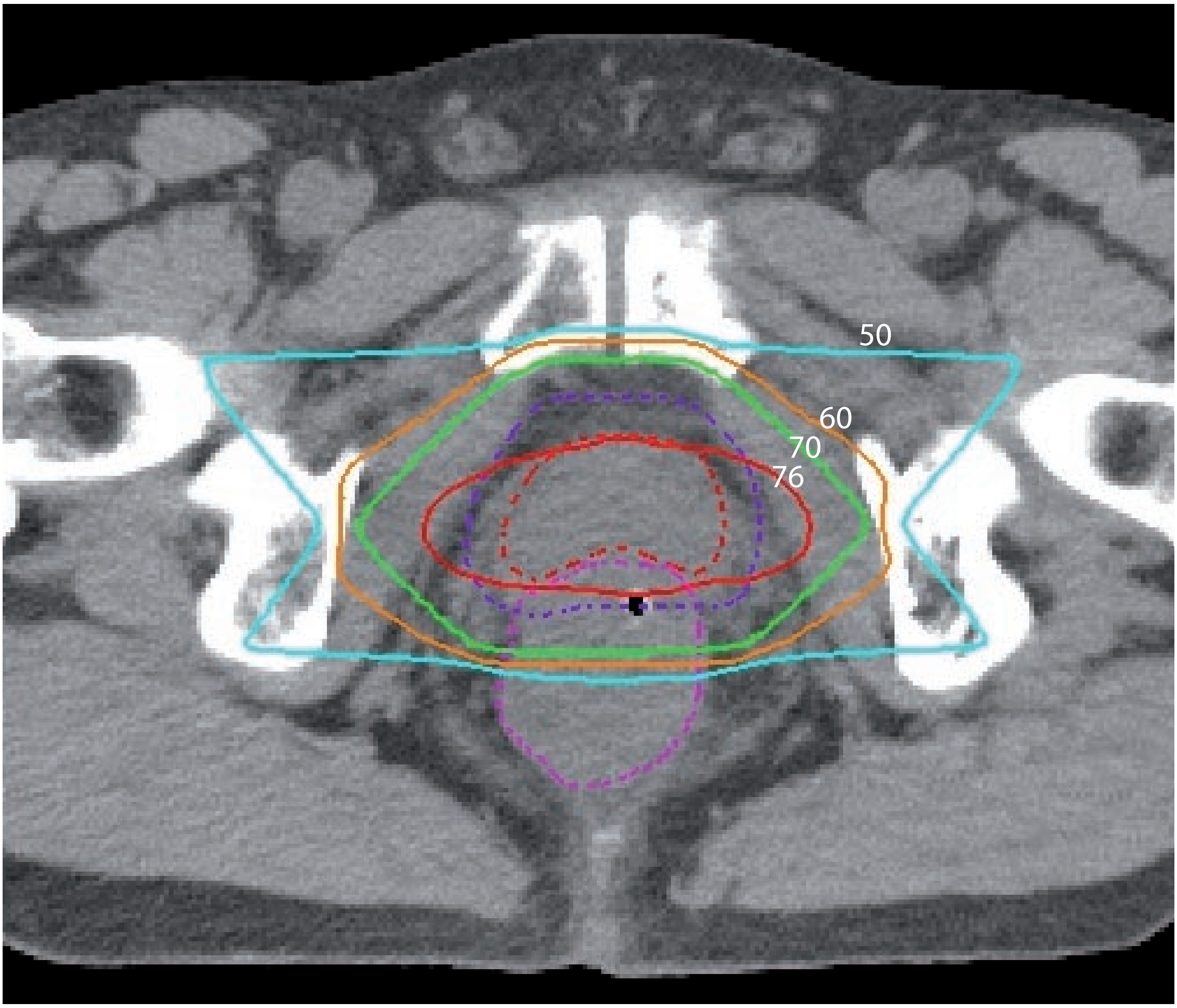


Figure D-II. Representative isodose distributions: Intensity-modulated radiation therapy plan for a prostate tumour, showing superior conformation of the 50 Gy isodose line to the planning target volume

Isodose levels (in gray) are shown by solid lines, while structures are contoured in dashed lines. Blue dashed line – prostate; dark red dashed line – prostate PTV (see paragraphs D28-D31); yellow dashed line – bladder; pink dashed line – rectum

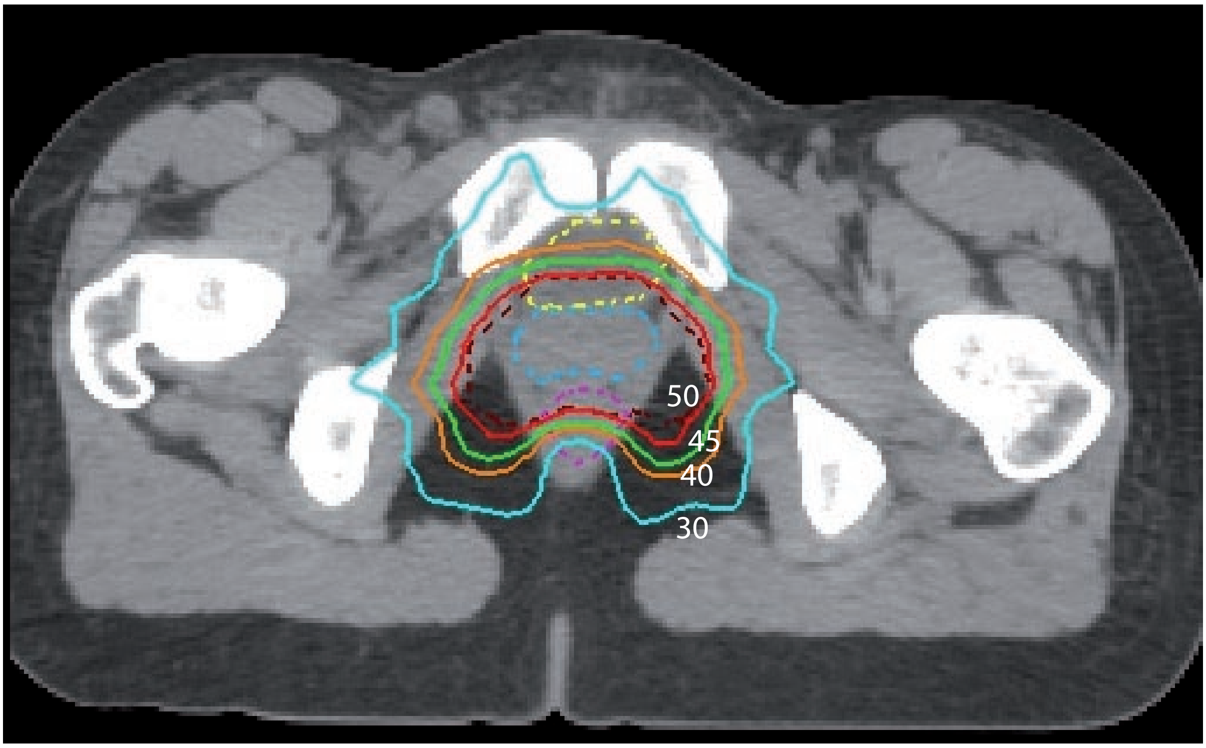


Figure D-III. Representative isodose distributions: Treatment plan showing the use of stereotactic body radiation therapy for a lung tumour

Isodose levels (in gray) are shown by solid lines, while structures are contoured in dashed lines. Red dashed line – lung tumour CTV (see paragraphs D28-D31); purple dashed line – PTV; yellow dashed line – spinal cord

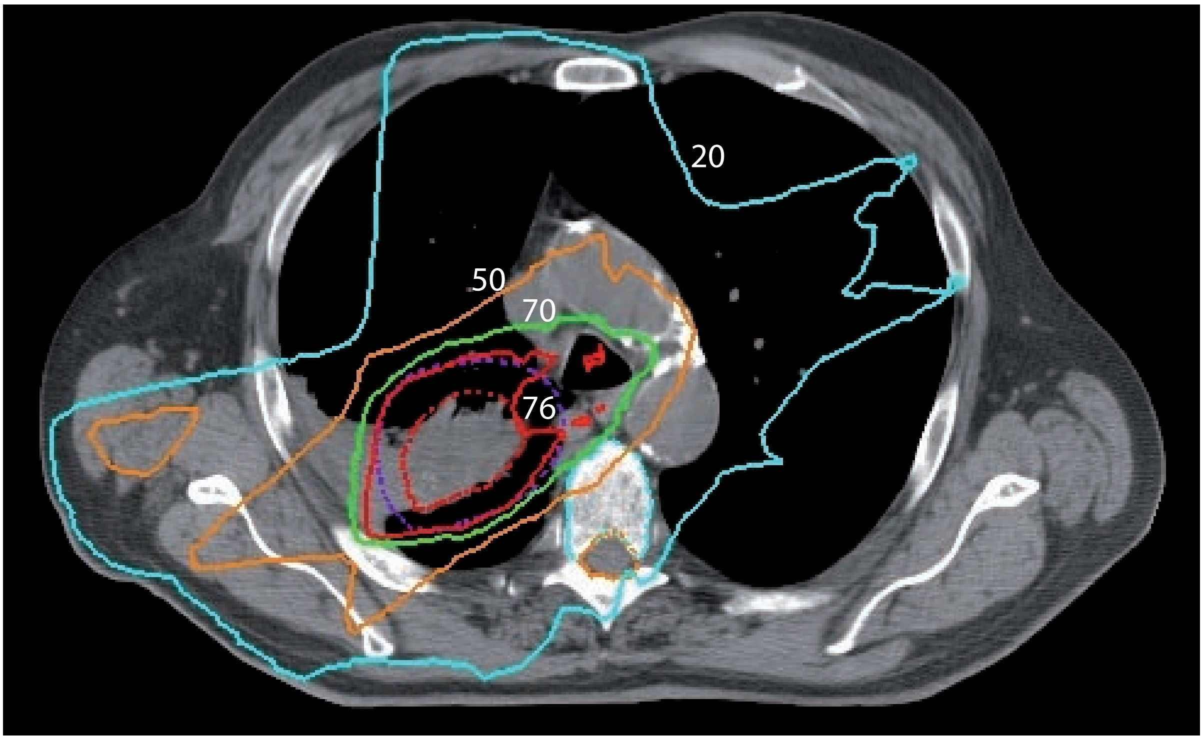
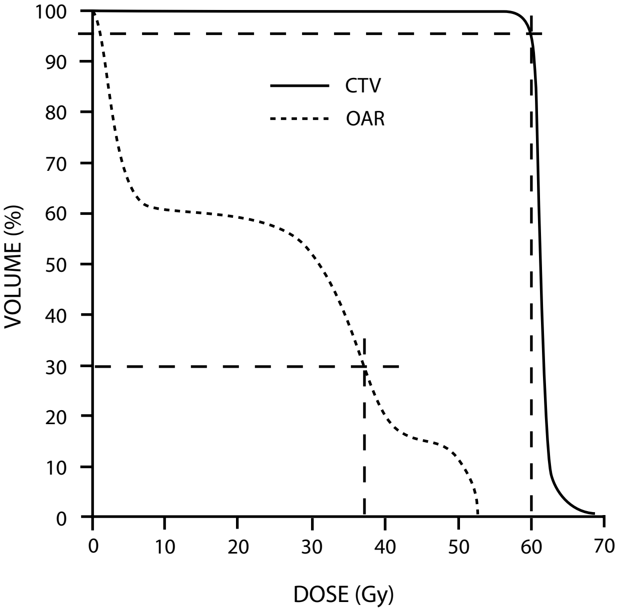


Figure D-IV. Representative isodose distributions: Dose–volume histograms for a clinical target volume (CTV) and an organ at risk (OAR)



D12. The fluence distribution of a teletherapy beam can be adjusted by several means. A simple method of modulating the beam is through the use of a metal wedge filter, which differentially attenuates the beam, producing a sloping intensity profile. The angle through which the isodose curves are tilted is termed the wedge angle. Modern treatment machines use programmable wedges, meaning that one jaw is moved across the field while the beam is on, to differentially modulate the beam and produce wedge-shaped dose distributions.

D13. MLCs can be used to shape the field to the projection of the target volume and to protect normal tissue. This obviates the need for heavy metal alloy shielding blocks and can result in reduced set-up time for treatment. MLCs also can be programmed to modulate the intensity of the treatment beam to create highly conformal dose distributions. This procedure is known as intensity-modulated radiation therapy (IMRT) [B26]. IMRT can be delivered in several ways: *(a)* in step-and-shoot IMRT, at each of several gantry angles the MLC is programmed to several different shapes. A selected number of monitor units is delivered through each MLC setting, creating a non-uniform intensity distribution. When combined with the non-uniform intensity distributions produced at the other gantry angles, a dose distribution is produced that conforms to the target volume; *(b)* in sliding window IMRT, a non-uniform intensity distribution is created by moving pairs of leaves across the field while the beam is on. The width of the field created by each pair of leaves is changed, resulting in an increased or decreased dose at each location. Again, this is done for each of several gantry angles; *(c)* serial tomotherapy is delivered through the use of a “binary MLC” [C3]. This device, first marketed in the 1990s as the Peacock system, uses a 40-cm-wide by 2-cm-long field, which can be blocked by an MLC consisting of 40 pairs of leaves of 1 cm width. Regions 1 cm wide by 2 cm long can be effectively switched on and off, as the gantry is rotated continuously, delivering an IMRT treatment to a 2-cm-thick transverse section of the patient. Following each gantry arc, the patient support couch must be moved precisely 2 cm and the process repeated as necessary to treat the entire length of the target volume; *(d)* helical tomotherapy is a similar process, but rather than delivering an IMRT treatment to a single transverse slice of the patient, the patient couch is moved continuously as the gantry rotates, in exactly the same manner that helical CT is performed. A dedicated treatment machine has been developed for this type of treatment [M5]; *(e)* intensity-modulated arc therapy (IMAT) is delivered by adjusting the MLC to a specific shape, then rotating the accelerator gantry through a range of angles with the beam on. The arc is then repeated, but with the MLC set to a different shape, to increase the dose only to selected regions of the target volume. This process may be repeated several times [Y9].

D14. Radiation therapy is generally delivered to specific, well-defined volumes of tissue, although large-field techniques are also used: whole-body photon beam irradiation in conjunction with bone marrow transplantation for the treatment of leukaemia, hemibody irradiation for the palliation of painful bone metastases, mantle irradiation in the treatment of lymphomas, and irradiation of the entire central nervous system in the treatment of medulloblastoma [S28, W22]. Total-skin electron therapy is used for the treatment of widespread skin diseases such as cutaneous T-cell lymphoma, or Kaposi’s sarcoma [B27].

D15. Stereotactic radiosurgery (SRS) refers to the use of narrow, well-defined beams of ionizing radiation for the precise ablation of a well-defined intracranial or extracranial target volume at the focus of a stereotactic guiding device, without significant damage to adjacent (healthy) tissues. SRS is typically given through a single fraction of radiation, with the intention of obliterating the target [C4, F13, G5].

D16. A related treatment called stereotactic radiation therapy (SRT) refers to the use of stereotactic techniques for multifraction radiation therapy. When delivered to extracranial targets, this technique is often referred to as stereotactic body radiation therapy (SBRT) [K9]. An example of an SBRT treatment to a lung tumour is shown in figure D-III. Since the introduction of the technique in 1951, clinical studies have been undertaken with high-energy photons from linear accelerators [F13, G12, K3, K9] and ^{60}Co sources, with protons and with heavy particles.

D17. Brachytherapy involves the placement of an encapsulated source or a group of such sources on or in the patient by application to a surface, within a cavity or directly into the tissue to deliver gamma or beta radiation at a distance of up to a few centimetres [D22]. Radium-226 sources, on the basis of which many brachytherapy techniques were developed, have a number of undesirable characteristics, including the risk of contamination through leakage or breaking, and have been replaced almost completely by a variety of artificial radionuclides, principally ^{137}Cs, ^{192}Ir and specially designed small ^{60}Co sources [T4].

D18. A novel electronic brachytherapy source has been described recently [R16]. The device consists of a miniature X-ray tube having outer dimensions of approximately 3 mm by 3 mm. The tube operates at either 40 or 50 kVp and is designed to emit X-rays essentially isotropically. Preliminary data indicate that the device can be used quite successfully to simulate an ^{192}Ir brachytherapy source [R27]. Dose rates of as much as 1 Gy/min at 1 cm can be delivered.

D19. When brachytherapy is practical, it offers several advantages over other types of radiation therapy: the radiation source can be placed within or adjacent to the target tissue; the radiation usually does not have to traverse healthy tissue to reach the target tissue; and in the case of low-dose-rate (LDR) brachytherapy, the low dose rate and continuous irradiation offer radiobiological advantages.

D20. Permanent interstitial brachytherapy implants are generally used for deep-seated tumours and today are principally used for treatment of the prostate [S29]. The most commonly used sources are ^{125}I and ^{103}Pd, either as individual miniature sources (seeds) or loaded in dissolvable sutures. Temporary interstitial implants also are used for superficial and easily accessible tumours such as those of the breast, head and neck, and base of the tongue.

D21. The intracavitary implant technique consists of the placement of an applicator containing radioactive sources into a natural body cavity to irradiate an adjacent tumour. It 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 [S30]. Ophthalmic applicators are used for treating malignant melanoma of the uvea and other malignant and benign tumours of the eye [H26]; medium-sized and large tumours are usually treated with ^{103}Pd or ^{125}I plaques, and small tumours with beta ray applicators incorporating ^{106}Ru or ^{90}Sr.

D22. A number of multicentre studies were completed to investigate the efficacy of endovascular brachytherapy treatment for the inhibition of restenosis after angioplasty [W21]. These have shown that, while brachytherapy is successful in delaying restenosis, newer drug-eluting stents provide equivalent results. Initial concerns about increases in the rate of stent thrombosis leading to increases in the risk of death and myocardial infarction following the use of drug-eluting stents have recently been retracted. In a revised statement, the United States Food and Drug Administration reported that the small increased risk of stent thrombosis with drug-eluting stents was not associated with an increased risk of death or myocardial infarction compared bare metal stents [F8]. Consequently, intravascular brachytherapy has been abandoned at most centres.

D23. Brachytherapy can be used alone but is more 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 entire target volume, including the parametrial and pelvic lymph nodes. Intracavitary brachytherapy is used to deliver an additional dose to the primary tumour volume, thus sparing normal tissues and organs at risk from doses above tolerance levels. 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. Prostate tumours are often treated with external beam therapy followed by a brachytherapy boost, although it is also common to use brachytherapy alone (monotherapy).

D24. Conventional LDR brachytherapy using ^{137}Cs sources involves dose rates at the prescribed point or surface in the range 0.4–2.0 Gy/h, with most treatments given over a period of several days in one fraction, or more often two; higher-activity ^{137}Cs sources can provide medium dose rates (MDR) of up to 12 Gy/h. High-dose-rate (HDR) brachytherapy utilizes ^{192}Ir sources to provide even higher dose rates, generally 2–5 Gy/min, with treatment times reduced to minutes or less and the treatment generally delivered through several fractions [P10, T11]. Sources having a nominal activity of 3,700 GBq (10 Ci) are generally used, and are driven through coupling tubes into the implanted applicator by a machine called a remote afterloader [S29]. The source is programmed to stop (“dwell”) at selected locations within the applicator, most often in a pattern that simulates the source placement used in conventional LDR brachytherapy. In some countries, sources of ^{60}Co are increasingly being used for HDR brachytherapy; worldwide in 2006, the use of 103 such devices was reported, with most in the Russian Federation and China. Pulsed-dose-rate (PDR) brachytherapy has recently become popular and allows pulses of HDR radiation to be delivered over a time period comparable to that used for LDR brachytherapy. This method uses a high-activity source (typically 370 GBq or 1 Ci) and a remote afterloading machine to deliver the radiation in fractions of a few minutes; these are repeated at intervals of 1 or 1.5 h. Remote afterloading offers significant radiation protection benefits, in that the source is returned to the shielded storage container periodically to allow other persons to be present, for example to give the patinet medical attention. The source can be retracted at any time in the event of an emergency. From a radiological protection point of view, remote afterloading is essential, for HDR, PDR and MDR techniques. Other developments in radiation therapy are discussed in section VI.A in relation to trends in the practice.

III. SUMMARY FROM THE UNSCEAR 2000 REPORT

D25. Radiation therapy involves the delivery to patients of high absorbed doses to target volumes for the treatment of malignant or benign conditions. Resources for radiation therapy were distributed unevenly around the world, with significant variations in radiation therapy practice both among and often within individual countries. Many cancer patients had little or no access to radiation therapy services. Global annual numbers of complete treatments by the two main modalities, teletherapy and brachytherapy, were estimated from the scarce national survey data available, supplemented using a global model, although the uncertainties in this approach are likely to be significant. The world annual total number of treatments for 1991–1996 was estimated to be about 5.1 million, with teletherapy accounting for over 90% of the treatments. The corresponding average annual frequency of 0.9 treatment per 1,000 population was similar to the level quoted for 1985–1990 [U6] on the basis of an estimated total number of 4.0 million treatments.

IV. DOSIMETRIC APPROACHES

D26. Successful treatment of cancer with radiation is dependent upon the accurate and consistent delivery of high doses of radiation to specified volumes of the patient, while minimizing the irradiation of healthy tissues. 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 the ICRU [I9, I10, I13, I14, I15], the IAEA [I12, I42, I43, I44, I45] and others [A12, B28, B29], as well as various codes of practice (e.g. [A2, I45, K10, M29, N18, N21, R17]). Special treatment and dosimetry techniques are required for pregnant patients to minimize potential risks to the foetus from exposure in utero [A3, M20, M21, S31]. Approximately 4,000 pregnant patients required treatment for malignancy in the United States in 1995. The radiofrequency radiation from radiation therapy treatment machines can cause permanently implanted cardiac pacemakers to malfunction, and special techniques have been recommended for the planning and administration of treatment to such patients [L21, M30]. Quality assurance measures and dosimetry intercomparisons are widely recommended to ensure continuing performance to accepted standards [D14, D21, I7, K17, K18, N12, N19, W9].

D27. The delivery of clinical radiation therapy requires assessment of the extent of the disease (staging); identification of the appropriate treatment modality; specification of a prescription defining the treatment volume (encompassing the tumour volume and tissues at risk for microscopic spread), intended tumour doses, consideration of critical normal tissues, number of treatment fractions, dose per fraction, frequency of treatment and overall treatment period; preparation of a treatment plan to provide an optimal dose distribution; and delivery of treatment and follow-up. Radiological imaging, frequently involving CT but also including radiography, MRI and PET when appropriate, is widely used throughout this process; applications include the assessment of extent of disease, preparation of the treatment plan, verifying the location of brachytherapy sources and confirming correct patient set-up for external beam therapy. Because radiation therapy practice is largely empirical, significant variations are apparent in the dose/time schedules used in the treatment of specific clinical problems [D11, D19, G17, N19, P5, U17]. However, the publication of results of clinical trials, both from single-institution practice and from cooperative cancer study groups, has helped to bring a certain degree of conformity to treatment practice among cancer centres. [I16, K19, M23, S32, V11].

D28. The ICRU has promoted a uniform approach to the specification and reporting of dose distributions. ICRU Reports 50 and 62 [I9, I31] have updated Report 29 [I10] and introduce several clinical volumes: gross tumour volume (GTV); clinical target volume (CTV); planning target volume (PTV); organ at risk (OAR); planning organ-at-risk volume (PRV); treated volume (TV); and irradiated volume (IV) [I9, I10, I31]. The failure to accurately define the tumour, its spread into adjacent tissue and its movement relative to landmarks during a course of treatment can result in inadequate dose being delivered to part or all of the tumour. The consequence of such inadequate treatment can be a recurrence of the tumour. Consequently, the systematic identification of the volumes described above can aid in achieving the goal of designing and delivering a successful treatment.

D29. The GTV defines the extent of a demonstrable tumour. This is determined from clinical examination, surgical resection or findings from imaging.

D30. The CTV extends beyond the GTV by a certain margin to take into account the possible microscopic spread of the tumour [S9]. The CTV also can be defined to include local lymph nodes, and sometimes encompasses several GTVs. For gynaecological brachytherapy, MRI is most useful to demonstrate the anatomy, although its use is largely limited to a few centres in level I countries. A recent publication suggests that the tumour identified at the time of diagnosis be termed the intermediate-risk CTV and be prescribed a moderate dose, say 15 Gy, following 45 Gy of external beam radiation. The volume at risk visible on MRI at the time of brachytherapy plus a margin is considered the high-risk CTV and is prescribed a higher dose, typically 35 Gy, following external beam radiation [P3].

D31. With very few exceptions (such as possibly tumours of the brain), there will inevitably be movement of the CTV relative to external landmarks during a course of treatment involving a number of fractions. To accommodate this interfraction motion, as well as the uncertainty in reproducing the patient position from one fraction to the next, the ICRU specifies an additional margin to the CTV to create the PTV. The PTV is equivalent to the previous concept of target volume [I10, S9]. Dose planning, specification and reporting are based upon the PTV, although reporting of doses to the CTV is appropriate under some circumstances [S9].

D32. Healthy tissues that are sensitive to radiation are defined as organs at risk (OAR) and are spared as much as possible during radiation therapy. To accommodate any movement of an OAR during a course of therapy and to take into account the uncertainty of delineating an OAR, a margin can be drawn around the OAR to produce a planning organ-at-risk volume (PRV), which is analogous to the PTV drawn around a CTV.

D33. The doses to healthy tissues from radiation therapy can be estimated from isodose distributions such as those shown in figures D-I, D-II, D-III and D-IV. For example, figure D-I indicates that the dose to the rectum from this prostate treatment plan varies from below 50 Gy to more than 76 Gy. However, it is clear that the distribution shown in figure D-I represents the dose only in a single transverse plane. To understand the dose to the entire rectal volume (or that of another organ), multiple transverse planes must be examined. Alternatively, a dose–volume histogram (DVH) can be valuable to indicate the dose to an organ. A DVH is a graph of the fractional volume of an organ or structure receiving a selected dose or greater. Figure D-IV shows typical DVHs for a target organ (CTV) and an OAR. The figure shows that about 95% of the CTV is receiving at least 60 Gy, while 30% of the OAR is receiving about 37 Gy or more.

D34. Brachytherapy treatments for carcinoma of the uterine cervix have evolved little from the early Stockholm and Paris techniques developed in the 1920s and 1930s [H23, P10, R11]. For example, the Manchester system was evolved from the Paris technique and is still used in a number of centres. Similar treatment applicators are used. In the Manchester system, doses are specified at point A and point B. Point A is defined as being 2 cm lateral to the centre of the uterine canal and 2 cm from the mucous membrane of the lateral fornix in the plane of the uterus. Point B is 5 cm from the midline of the uterus.

D35. In the past several years, significant efforts have been made to develop protocols for image-guided brachytherapy [N19, P3]. The ICRU terminology for defining target volumes has been adapted for brachytherapy, with modifications that make it possible to distinguish between the masses of tumour present before and after surgery. Such protocols allow the treatment to be tailored to the patient’s precise condition, rather than relying on simplistic prescriptions based on surrogate non-anatomical reference markers such as point A.

D36. In many treatment centres today, radiation therapy considers the location and shape of the CTV in three dimensions, and the treatment planning process attempts to conform the dose distribution to the PTV and to avoid PRVs. Such 3-D conformal radiation therapy (3-D CRT) uses custom-designed beam blocking or MLCs to shape the field to the projection of the PTV, and allows the display of patient anatomy and dose distributions using 3-D techniques. Modern treatment planning systems also perform dose calculations that consider the effects of tissue densities in three dimensions.

D37. The 3-D CRT technique is capable of shaping dose distributions only to relatively simple convex shapes (figure D-I). In a number of common treatment situations, the PTV exhibits concavities or invaginations produced by the presence or pressure of another structure. A common example is the prostate, which frequently partially wraps around the rectum. Tumours of the posterior nasopharynx can wrap partly around the spinal cord. It is possible with IMRT to generate dose distributions that conform to complex and convoluted PTVs, with the primary goal of minimizing the dose to nearby PRVs, to allow the delivery of high doses to the PTV [B26]. The IMRT technique can achieve uniform dose delivery to the PTV, but generally uniformity of dose is considered of secondary importance to the sparing of organs at risk. Figure D-II provides an example of the use of IMRT.

D38. A principal objective of radiation therapy dosimetry is to measure or predict the absorbed dose in various tissues [H17, I15]. Radiation therapy dosimetry is typically conducted in two stages.

D39. Firstly, the radiation beam from the treatment unit must be fully characterized in a manner that allows a treatment planning computer to reproduce the dose distribution under a range of clinical circumstances. This is done through measurements made in a uniform tissue-simulating medium. Water is most often used, as it is very nearly tissue-equivalent and is easily obtained. It has the further important advantage of allowing an ionization chamber or another radiation detector to be moved to positions within and near the radiation beam to determine the dose distribution. These depth-dose data describe the variation of dose with depth, field size and shape, and distance from the source.

D40. In addition to the depth-dose measurements, it is important to know how radiation output at a reference point changes with various important parameters, including the field size and shape and the distance from the source, and the attenuation of field-shaping and field-modulating devices. It is impractical to measure all conceivable variations, so a sufficient number of representative measurements must be made to allow accurate estimations for clinical treatment situations [H17, I15]. For example, wedge factors are measured to deduce the impact of the wedge on patient field sizes and depth doses.

D41. In many situations, ionization chambers or similar detectors used in water phantoms are inadequate to describe the dose distribution in regions of steep dose gradient, as is found near brachytherapy sources or in very small fields such as are used for SRS. Radiochromic film can be used for quantitative planar dosimetry to map dose distributions under these circumstances as well as for proton beam therapy, and beta ray ophthalmic plaque therapy [N6, V12, Z7]. Radiochromic film offers advantages over radiographic film: it does not require processing, and as it has no high-atomic-number components, it shows very little energy dependence.

D42. The data obtained to characterize the beam are either stored in the treatment planning system or are used to create a mathematical model to simulate dose distributions. Data characterizing the patient are also entered, and the dose distribution is calculated taking into account the beam arrangement, the location of the tumour and the anatomy of the patient.

D43. Radiation therapy equipment is calibrated to determine the relationship between the dose delivered at a reference point and time (in the case of isotope units) and the signal from a monitor chamber (in a linear accelerator). Various protocols exist that explicitly describe each stage of the calibration process [A2, I45]. A quality assurance programme is necessary to ensure that the treatment unit performs consistently from one treatment fraction to the next and from one patient to the next. Recommendations for quality assurance programmes have been published [F15, K17].

D44. In vivo dosimetry is conducted to monitor the actual dose received by the patient during treatment to check the accuracy of delivery and as a means of determining the dose to critical organs, such as the lens of the eye and the spinal cord [E7, M15]. TLDs [D18, K20, K21] and several types of solid-state detector [A9, B30, C7, S8, V7, W23] are used. In vivo dosimetry is particularly useful during 3-D conformal radiation therapy [L24].

D45. Quality assurance of IMRT treatments requires the measurement of dose and dose distribution in a phantom to ensure that the patient will be treated correctly [B26]. This is most often done by simulating a simple water or water-equivalent phantom (generally rectangular or cylindrical) with the treatment planning computer and imposing on it the fluence distributions determined for patient treatment [L15, L22, T14, W24]. The shape of the hybrid phantom, as it is often called, will distort the dose distribution from that intended for the patient, but it allows the placement of ion chambers and film or other detectors to compare the calculated distribution with measurements. Agreement in the hybrid phantom provides assurance that the intended dose and dose distribution will be delivered to the patient [L1].

D46. Independent quality audits of radiation therapy facilities are conducted to help provide assurance that patient treatments are delivered consistently from one facility to another. Several groups, including the IAEA, the European Society for Therapeutic Radiology and Oncology (ESTRO) Quality Assurance Programme (EQUAL) and the Radiological Physics Center (RPC), among others, perform periodic audits of megavoltage treatment machine calibration using mailed TLDs [F5, H8, I20, I29, K32]. These programmes identify, at relatively low cost, errors in treatment machine calibration, often resulting from misinterpretation of a calibration protocol, incorrect use of the dosimetry equipment or the failure of a component of the treatment machine itself. Audits also have been conducted of complex treatment procedures through the use of anthropomorphic phantoms [I35, I40, M42]. These audits permit evaluation of the entire radiation therapy process, from imaging, through treatment planning and quality assurance, to treatment delivery. The experience of the RPC indicates that, in an evaluation of IMRT, roughly one third of the institutions surveyed failed to deliver the intended dose distribution to within 7% and 4 mm distance to agreement [I35].

V. ANALYSIS OF PRACTICE

A. Frequency of treatments

D47. Differences in the resources available for radiation therapy lead to wide variations in national practice, with many smaller countries or less developed countries having no treatment facilities, or only a few. Even in countries with treatment facilities, the type of equipment available varies considerably, and this affects the numbers of patients treated as well as the types of treatment given. The number of treatment centres available to residents, by country, is shown in table D4. The data demonstrate an average in level I countries of 3.4 radiation therapy centres per million population. The number of centres also varies within level I. Monaco has only one radiation therapy centre, but with its small population, the relative value is over 30 per million residents. Excluding Monaco, the United States and Japan have the highest values, with 9.2 and 5.7 centres per million population, respectively. In level II countries, the average falls to 0.56 centre per million population, with a range of from 0.1 (for example for Algeria, Pakistan and Uganda) to more than 6 (for example for Barbados and the Bahamas, both countries with small populations). In level III countries, there were fewer than 0.2 centre per million population, while in level IV, there were fewer than 0.1 centre per million. Annual numbers of treatments reported by different countries from 2000 to 2006 are summarized in tables D5(a–c) and D6(a–b) for teletherapy procedures and in table D7 for brachytherapy procedures.

D48. Patterns of practice vary significantly from country to country, even within a single health-care level. For comparison, countries in health-care level I reported 5.41 linear accelerators per million population (table D4). The number dropped to 0.34 per million population for level II countries, to 0.06 per million for level III countries and to 0.53 per million for Botswana, the only level IV country reporting these data. These numbers show a significant increase for level II and III countries over data from 1991–1996. In contrast, the number of cobalt units reported by health-care level was 0.78 per million population for level I, 0.43 per million for level II, 0.19 per million for level III and 0.05 per million for level IV. These numbers have increased for all levels except level I. Within level I, the number of accelerators varied from less than 0.1 per million population in countries such as the Republic of Korea and Ukraine to 9 per million in Denmark and 16 per million in the United States. Annual frequencies of teletherapy treatments differed by a factor of over 6 within the sample of 18 countries in health-care level I, where the average was 2.4 courses of treatment per 1,000 population (see tables D3, D5 (a–c) and D6 (a–b)). Disregarding countries reporting zero practice, similarly large variations existed in level II countries, where the average was 0.4 course per 1,000 population. Insufficient data were available from level III and IV countries.

D49. Brachytherapy practice was difficult to ascertain for several reasons. Firstly, limited data were obtained through the UNSCEAR surveys. Secondly, the surveys did not distinguish clearly between remote and manual afterloading procedures. Consequently, the analyses discussed here are based on limited data from a small number of countries. Additional data were obtained from a survey of brachytherapy use in European installations [G7].

D50. The average annual frequency of brachytherapy treatments in level I countries (0.12 treatment per 1,000 population) is about 1/18 of that for teletherapy. In level II, practice in brachytherapy is lower by a factor of about 2 compared with level I.

D51. Regardless of the differences between the individual countries, some broad patterns of practice in radiation therapy 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 level II. Brachytherapy practice is universally dominated by treatments of gynaecological tumours. Some interesting variations among countries are evident from tables D5 (a–c) and D6 (a–b). Luxembourg reports that a large fraction of teletherapy treatments are used for breast cancer, while more than 50% of teletherapy treatments in El Salvador are for gynaecological disease. Japan reports a high annual treatment frequency for head and neck cancer as well as for digestive tumours other than colorectal. Both Hungary and Norway use teletherapy frequently for palliative treatments, but the Czech Republic reports that 40% of teletherapy is used for benign disease. Temporal trends in the annual frequency of examinations are discussed elsewhere.

B. Exposed populations

D52. The distributions reported by different countries of the age and sex of patients undergoing teletherapy treatments for selected diseases in 1997–2007 are presented in table D8. 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. As might be expected, since radiation therapy is primarily employed in the treatment of cancer, therapeutic exposures are largely conducted on older patients (>40 years old), with the skew in ages being even more pronounced than for the populations of patients undergoing diagnostic examinations with X-rays or radiopharmaceuticals. 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].

D53. For certain teletherapy and brachytherapy procedures, for example the treatment of breast and gynaecological tumours in females and of prostate tumours in males, there are obvious links to patient sex. However, there are some surprising exceptions in the reported data. For example, Hungary reported that, of the patients treated with external beam therapy for head and neck cancer, 84% were female. For other treatments, there is a general bias towards males in the populations of patients. In a few cases, the bias towards females appears extreme; for example, several countries report the use of brachytherapy almost exclusively in females, evidently for gynaecological disease.

C. Doses from treatments

D54. The doses received by patients from radiation therapy are summarized in tables D9 (a–c) and D10 (a–c) in terms of the prescribed doses to target volumes for complete courses of treatment, as discussed previously. The average doses for each type of treatment and health-care level are weighted by 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 radiation therapy for leukaemia, testis tumours, benign disease and some paediatric tumours. Other variations in the reported data are apparent, although these might have resulted from misinterpretation of the data requested by the survey forms.

D55. In teletherapy with photon beams, the doses to tissues at large distances from the target volume arise from several sources: (1) radiation scattered in the patient; (2) leakage through the treatment head of the machine; (3) scatter from the collimator and its accessories; and (4) radiation scattered from the floor, walls or ceiling [N20, V4]. The first and fourth contributions depend on field size, distance and photon energy, and can be measured and applied generally. The second and third contributions are machine-specific and in principle require 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 [K22, S34]. When evaluating the deleterious effects of out-of-field doses, the gonads are generally considered the limiting organ, although organs such as the thyroid and the breasts of young women must also be considered. When the distance between the organ being considered (for example the gonads) and the primary beam is large (around 40 cm, for example, in the treatment of breast cancer), gonad dose is primarily determined by the leakage radiation. Collimator scatter can be influenced by the presence of accessories, in particular wedge filters, which increase the out-of-field dose significantly [F16]. Specific data have also been reported in relation to the peripheral dose during therapy using a linear accelerator equipped with multileaf collimation [S34]. 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 and the patient's age and medical condition [M16].

D56. Measurements in a patient population have demonstrated a broad range of gonad doses from photon teletherapy treatments for some specific treatment sites [V4]. 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 between men and women in the distance to the gonads. 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. These data are also relevant for estimating the dose to a foetus carried by a pregnant woman.

D57. The risk to patients of a second malignancy as a result of out-of-field radiation has been estimated [S31]. With IMRT, these risk estimates are increased. An IMRT treatment requires that the MLC be adjusted to create small field segments for much of the treatment, while different regions of the target volume are irradiated to different doses. This makes IMRT delivery considerably less efficient than 3-D conformal therapy. It is not unusual for the number of monitor units used for IMRT to be from four to ten times as great as for 3-D conformal therapy. As a result, the leakage radiation emitted by the accelerator head during IMRT is proportionally greater [K22].

D58. 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 [V4].

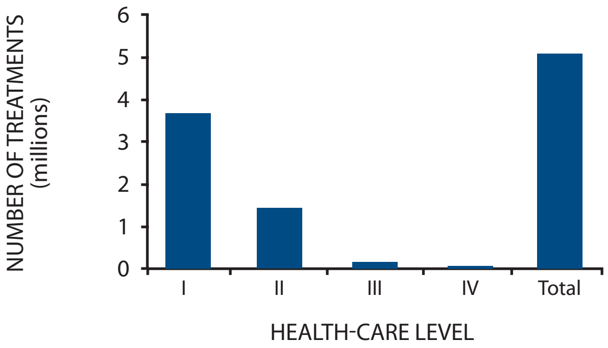
D59. The skin-sparing advantage and clinical efficacy of high-energy photon beams can be compromised by electron contamination arising from the treatment head of the machine and the intervening air volume, and comprehensive dosimetric assessment requires taking into consideration the effect of this component on the depth-dose distribution [H18, S35, Z8]. Electrons and photons with energies of above 8 MeV can produce neutrons through interactions with various materials in the target, the flattening filter and the collimation system of the linear accelerator, as well as in the patient [K7]. 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 is 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 [V4]. High-energy X-ray beams will also undergo photonuclear reactions in tissue to produce protons and alpha particles [S36], 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

D60. The data in table D3 for the period 1997–2007 provide estimates of the annual total numbers of teletherapy and brachytherapy patients per 1,000 population within each health-care level. The frequencies of teletherapy in levels II and III may have been overestimated as it appears that some of the national data used refer to numbers of treatments rather than cancer patients, although these sources of uncertainty are reduced when considering global practice. Data broken down by disease category and by patient age were provided by too few countries for 1997–2007 to permit an in-depth evaluation. Consequently, the mean values shown in table D8 for the individual types of treatment within each health-care level were averaged over different populations because of the lack of comprehensive information for all countries listed and so do not represent a self-consistent set of data. Analyses are presented separately for both teletherapy and brachytherapy. The estimates of world practice have been calculated using the global model of population described above. 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.

D61. According to the model developed, the global annual frequencies assessed for radiation therapy treatments during 1997–2007 are dominated by the national practices in health-care level I countries, which provide contributions of about 73% and 42% to the total numbers of teletherapy and brachytherapy treatments, respectively, in the world (table D2**.** The most important uses of teletherapy are for treatments of breast, lung, genitourinary and gynaecological tumours, while practice in brachytherapy is principally concerned with the treatment of gynaecological and genitourinary tumours, although some differences are apparent between the mean frequencies for the different health-care levels. The global average annual frequency assessed for brachytherapy treatments (0.07 per 1,000 population) is about one-tenth that for teletherapy treatments (0.7 per 1,000 population) (see table D3). Figure D-V shows the estimated annual number of all radiotherapy (both teletherapy and brachytherapy) treatments (in millions) for the four health-care levels.

Figure D-V. Estimated total annual number of radiotherapy treatments (both teletherapy and brachytherapy)



D62. While radiation therapy is most often used for treatment of malignant diseases, a significant number of patients are treated with radiation for benign conditions. The use of radiation to treat conditions such as bursitis and acne, while common in the 1950s, has essentially disappeared today. However, as shown in tables D5 and D6, the use of radiation for treatment of benign conditions, such as arteriovenous malformations, trigeminal neuralgias and acoustic neuromas, today is quite common in some countries [C4].

VI. TRENDS IN RADIATION THERAPY

A. Teletherapy

D63. Over the last 50 years, there have been continuing advances in engineering, the planning and delivery of treatment, and clinical radiation therapy practice, all with the aim of improving performance [B31]. In developed countries, at least, there has been growing use of high-energy linear accelerators for the effective treatment of deep-seated tumours. 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 [D23]. Units with ^{60}Co sources remain important for developing countries in view of their lower initial and maintenance costs and their simpler dosimetry in comparison with linear accelerators.

D64. Chemotherapy has been used in combination with radiation therapy for many years. The delivery of certain chemotherapeutic agents in close temporal proximity to radiation therapy can enhance the effectiveness of the radiation against cancer cells. The synergistic effects of combined therapy will continue to be pursued as new drugs are developed.

D65. Developments in diagnostic imaging, such as CT and MRI, have benefited the assessment of disease and also the planning and delivery of therapy [C8, R18]. Treatment plans are calculated using sophisticated computer algorithms to provide 3-D dose distributions, including so-called beam's-eye views. Monte Carlo simulation techniques are beginning to be used in selected cases for comparison [M17, S37]. Computer control of the linear accelerator has facilitated the development of new treatment techniques. MLCs 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 [G20]. This type of therapy seeks to provide optimal shaping of the dose distribution in three dimensions so as to fit the target volume [D16, F17]. Developments include: tomotherapy, which uses slit beams provided by dynamic control of MLCs coupled with movement of the gantry during treatment [Y7]; IMAT, which combines spatial and temporal intensity modulation [Y9]; and adaptive radiation therapy, in which treatment plans for individual patients are automatically reoptimized 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 or tracking of the radiation beam with respiration is being evaluated in a number of centres [K8].

D66. Tumours of the lung, breast and liver can move as a result of normal respiration. Such intrafraction motion is difficult to estimate, much less accommodate in treatment planning without sophisticated imaging procedures. Four-dimensional computed tomography (4-DCT) is being evaluated at a number of centres to demonstrate the respiratory motion of some tumours. The 4-DCT technique requires the use of a fast multidetector helical CT scanner, and either gating of imaging with respiratory motion, or continuous imaging during free breathing, with subsequent binning of the images according to the stage of the respiratory cycle at the time of each scan. From 4-DCT images, an internal target volume can be drawn that contains the full range of motion of the CTV.

D67. The use of a novel 3-D gel dosimeter for evaluating IMRT dose distributions has been described recently [G19, I22, I38, I39]. The dosimeter, composed of acrylic monomers stabilized in a gelatin matrix, responds to irradiation by polymerizing. The distribution of polymer microparticles is proportional to the absorbed dose, and a map of the distribution can be obtained either by MRI or by optical CT scanning [I39].

D68. 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 [A5, S33, T10]. Some treatment machines are equipped with on-board X-ray imaging devices, and use is beginning to be made of these systems to image patients on the treatment table, so that adjustments to patient position can be made immediately before treatment [G18].

D69. A technique called volumetric modulated arc therapy (VMAT) has been described recently [T15]. This technique combines sliding-window MLC control simultaneously with gantry rotation to eliminate the requirement for couch movement. Commercialization of this technique began at the end of 2007.

D70. Patients undergoing radiation therapy should have available to them the necessary facilities and staff to provide safe and effective treatment. Many radiation therapy centres in level II, III and IV countries do not have sufficient numbers of linear accelerators, simulators or remote afterloading brachytherapy units, and the level of availability significantly compromises their ability to deliver radiation therapy [B6].

B. Brachytherapy

D71. 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 throughout the world by ^{137}Cs. The remote afterloading technique is standard practice in most countries for the treatment of carcinoma of the cervix and is increasingly being used for interstitial implants in relation to the bronchus, breast and prostate [S29]. HDR brachytherapy offers advantages over the manual LDR technique, for example in terms 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 [J6, J7, T11]. PDR brachytherapy has been developed in the hope of combining the advantages of the two techniques, while avoiding their disadvantages [B32, 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 an 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.

D72. Endovascular brachytherapy treatments to inhibit restenosis after angioplasty enjoyed a brief popularity during the 1990s and early 2000s, but they have now largely been replaced by the use of drug-eluting stents. Patients who are not candidates for these stents are occasionally treated with intravenous brachytherapy using catheters for the temporary implantation of radioactive seeds and wires (^{192}Ir or ^{90}Sr/^{90}Y) and also for the permanent implantation of radioactive stents (^{32}P) [C9, J8, T3].

C. Other modalities

D73. A continuing obstacle to definitive radiation therapy 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, M19]. The entire dose is delivered as a single fraction in a complex configuration, which makes dose control and measurement particularly critical [B24]. 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 radiation therapy, in which the afflicted bone is temporarily excised surgically so that it can undergo high-level irradiation in isolation before immediate reimplanting [W25]. 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. Modelling has been reported for therapeutic applications of iodine contrast agents in association with a CT scanner modified for rotation X-ray therapy [M7, S14] and for a silver metalloporphyrin for use in interstitial brachytherapy with ^{125}I seeds [Y8].

D74. There were at least 451 dedicated stereotactic devices in use worldwide in 2008, of which 247 were in the United States. Of the 451 devices worldwide, at least 247 were units containing multiple ^{60}Co sources called a Leksell Gammaknife (LGK). Data from the manufacturer indicate a total of 46 gamma knives in Japan and 16 in China; additional information is given in table D11 [E2]. Data from the 2000 UNSCEAR Global Survey of Medical Radiation Usage and Exposures indicated a total of 20 gamma knives in Japan and 36 in China. The reason for the difference in numbers in Japan is not known. The difference in numbers in China may reflect the use of a similar device sold by a Chinese manufacturer. The Leksell Society reported that 350,000 treatments had been delivered with the LGK worldwide up to the end of 2005 [L7]. 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 [G5]. 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 [M8, M9]. Data from the manufacturer indicate that there were 98 of these devices in use worldwide in 2006, of which 62 were in the United States and 17 were in Japan [A6]. At least 72 conventional linear accelerators were used for SRS in 2006; these were modified by adding a micro-MLC. 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 [B9, B25, D17, Y10].

D75. There are potential advantages in conducting radiation therapy with high-energy, heavy charged particles such as protons and heavier charged particles [W5]. Such beams of charged particles can provide superior localization of dose at depth within target volumes [L9, M10, N21]. Furthermore, 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 and electrons [B17]. During proton therapy, secondary neutrons and photons make small contributions to the patient dose [A10]. However, the dose received by non-target tissues is low, and is considered comparable to the neutron dose received during treatments with high-energy photon beams.

D76. Proton beams have been used therapeutically since 1955 and represent the treatment of choice for ocular melanoma [B17, I41]. Protons are currently also being used to treat deep-seated tumours, including those of the prostate, brain and lung. As of early 2007, there had been more than 53,000 patient treatments worldwide with protons and heavier ions. The largest numbers of patients have been treated in the United States. There are currently 31 facilities actively engaged in proton or ion therapy. Another 20 facilities are in various stages of planning and construction in several European countries, the United States, Africa and Asia [M10, N21, P23, S15, S16].

D77. Light ions (e.g. helium or carbon) are attractive owing to their favourable physical and radiobiological characteristics, such as high relative biological effectiveness, small oxygen effect and small cell-cycle dependence [K1, P23]. In 1996, only two heavy-ion facilities were operational in the world: HIMAC in Japan and GSI in Germany. A third facility opened in 2002 at the HIBMC facility in Japan. However, developments for the establishment of ion therapy centres in Europe have gained momentum and at present are in a very dynamic phase. In Heidelberg, Germany, a new facility has just initiated patient treatments. In Pavia, Italy, and in Wiener Neustadt, Austria, similar facilities are scheduled to become operational before 2009. The ENLIGHT cooperation, coordinated by ESTRO and supported by the European Commission, has been instrumental in networking all these projects and in creating for them a common platform for research and a concerted clinical approach between European radiation oncologists. More than 2,800 patients with various types of tumour located in various organs have been treated with a carbon beam at the HIMAC facility alone since 1994 [K2]. As of early 2007, more than 3,300 patients had been treated worldwide. In addition, about 1,100 patients were treated with negative pi mesons between 1974 and 1994, although with no active facilities since 1996, this is not a significant modality.

D78. 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 [G6]. Later, in the 1960s. studies in the United Kingdom 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 ten 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 conventional radiation therapy [D20, R6, R12]. Neutron brachytherapy using ^{252}Cf sources is being carried out at one medical centre in the United States [M11]. Boron neutron capture therapy is currently being evaluated at a few reactor facilities. This technique is predicated on the supposition that pharmaceuticals containing boron can be designed that will be deposited preferentially in a tumour. If a patient whose tumour contained an adequate concentration of boron were irradiated with a beam of neutrons from a reactor, the tumour would receive a significantly higher dose than the surrounding tissue. The technique is proposed for treatment of brain tumours, specifically glioblastoma multiforme. However, to date, the results have been disappointing owing to the lack of selectivity of the boron carriers [V3].

VII. ACCIDENTS IN RADIATION THERAPY

D79. The practice of radiation therapy involves the use of large doses of radiation, which if applied incorrectly can cause serious harm or death to the irradiated individual. The delivery of radiation doses that exceed the tolerance of normal tissues can result in unintended adverse effects, referred to as complications of treatment. It should be emphasized that such complications are distinct from radiation therapy accidents; the risk of complications is well known and understood, and most radiation therapy treatments are prescribed with the full knowledge of an attendant small risk of significant complications.

D80. While radiation therapy accidents are rare, a number of serious mistakes have resulted in unfortunate consequences for patients and members of the public. A summary of nearly 100 radiation therapy accidents has been published by the IAEA [I18] and a similar number have been reported by the ICRP [I27]. These accidents have been examined in detail and categorized to indicate their educational value to practitioners. Annex C to the present report, “Radiation exposures in accidents”, also discusses radiation therapy accidents in the context of other radiation accidents.

D81. The IAEA grouped the accidents into the following categories: radiation measurement systems; external beam therapy machine commissioning and calibration; external beam therapy treatment planning, patient set-up and treatment; decommissioning of teletherapy equipment; mechanical and electrical malfunctions; LDR brachytherapy sources and applicators; HDR brachytherapy; and unsealed sources.

D82. The accidents include events such as the failure to correctly interpret the treatment time setting during calibration, resulting in overdoses of 50% to patients. Other accidents have resulted in doses significantly below what was needed; when such accidents occur under circumstances from which recovery is not possible, they can result in progression of the patient’s tumour. Accidents caused by misinterpretation of the physician’s prescription are also reported.

D83. Accidents involving SRS have been reported, including errors caused by misinterpretation of the coordinates of the target volume [N22]. In one reported case, a patient was positioned in a CT scanner feet-first rather than the more common head-first position. This change was not recognized by the treatment staff, who mistakenly irradiated the wrong side of the patient’s head. Calibration errors have also been reported, including one in which a linear accelerator used for SRS was calibrated in error by 50% [J9]. According to news reports, 77 patients were treated before the error was discovered and received 50% greater doses than had been prescribed.

D84. The use of modern technology, including dynamic MLCs and programmable wedge distributions, has been involved in several accidents resulting in patient injury. In one case, 23 patients received doses that were 7% to 34% greater than prescribed. The error was due to a misinterpretation of treatment planning software in which the operators confused dynamic wedge treatments with the use of mechanical (metal) wedge filters. Information displayed by the software was in English rather than the operators’ native language, apparently contributing to the confusion. The result was that, on some occasions, the monitor unit setting for the accelerator was calculated as if a mechanical wedge filter was to be used, when in fact a programmable wedge distribution was created by moving one collimator jaw across the field to modulate the intensity [P2].

D85. Accidents involving IMRT have been reported, including several in which patients received lethal doses of radiation. In at least one case, a treatment plan was corrupted in the process of transferring it from the treatment-planning computer to the treatment machine. Reportedly, the treatment staff overlooked or ignored a warning message indicating that the treatment plan had not been transferred correctly. As a result, the treatment was delivered through open fields, rather than with the MLC modulating the beam intensity. The patient was believed to have received approximately seven times the intended dose [V15].

D86. Accidents involving brachytherapy also have been reported. One in which a patient received an extremely large dose, causing her death, was reported in November 1992 in Indiana, Pennsylvania. The accident involved a female patient scheduled for an HDR brachytherapy procedure using a 159 GBq ^{192}Ir source. The treatment was to be given in three fractions of 6 Gy each. Part-way through the first fraction, the source broke off the guidewire and remained inside one of the catheters that had been surgically implanted into the patient’s tumour. The patient was returned to a local nursing home without a radiological survey being performed. The catheter containing the source became dislodged four days later and was discarded in the biohazard waste. It was discovered soon afterwards when a waste truck passed through a radiation detector installed at an incinerator facility. The estimated dose at 1 cm in tissue was 16,000 Gy. Ninety-four additional individuals, including staff, visitors, family members and other nursing home residents were exposed, although the doses were not medically significant [M38].

D87. A website has been established by a group called the Radiation Oncology Safety Information System (ROSIS), to which individuals can post a description of radiation therapy errors or accidents, with the goal of providing education to others [R4]. The website lists over 700 such events, ranging from typographical errors in a verification system discovered at the time of the first treatment, to the failure to use a wedge filter for an entire course of treatment, resulting in a dose delivery error approaching a factor of 2.

VIII. SUMMARY

D88. Cancer is likely to be an increasingly important disease in populations with increasing lifespan, and this will probably cause radiation therapy practice to grow in most countries. WHO estimates that, worldwide, by the year 2015 the annual number of new cancer cases will have risen to about 15 million, from 9 million in 1995, with about two thirds of these cases occurring in developing countries [W8]. If half of these cases 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.

D89. In the period 1997–2007, the global use of radiation therapy increased to 5.1 million treatments, from 4.7 million treatments in 1991–1996. About 4.7 million patients were treated with external beam radiation therapy, while 0.4 million were treated with brachytherapy. The number of linear accelerator treatment units increased to about 10,000 worldwide, from about 5,000 in the previous period. A large increase was seen in level I countries. Level II countries appeared to show a decrease, but this is likely to be an artefact of the limited data received from the survey. At the same time, the number of brachytherapy treatments and the number of afterloading brachytherapy units appeared to have changed very little.

D90. Radiation therapy 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 of staff. 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 radiation therapy, 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 [D14, D21, K17].

Table D1. Global use of radiotherapy (1997–2007): normalized values
Data from United Nations Survey of Nations and IAEA/WHO Directory (DIRAC)

Quantity		*Number per million population at health-care level*				
		I	*II*	*III*	*IV*	*Globally*
Teletherapy						
Equipment	X-ray	1.3	0.2	—[a]	—[a]	0.4
	Radionuclide	0.8	0.4	0.2	0.0	0.4
	Linac	5.4	0.3	0.1	0.5	1.6
Annual number of patients		2 241.1	370.0	55.4	—[a]	729.7
Brachytherapy						
Afterloading units		1.4	0.2	0.07	0.02	0.5
Annual number of patients		115.7	61.9	—[a]	—[a]	67.2

[a] No data submitted.

Table D2. Global use of radiotherapy (1997–2007): total values
Data from United Nations Survey of Nations and IAEA/WHO Directory (DIRAC)

Quantity		*Total number (millions) at health-care level*				
		I	*II*	*III*	*IV*	*Globally*
Teletherapy						
Equipment	X-ray	0.002	0.000 6	—[a]	—[a]	0.002
	Radionuclide	0.001	0.001	0.000 19	0.000 04	0.003
	Linac	0.008	0.001	0.000 06	—[a]	0.009
Annual number of patients		3.45	1.17	0.06	(0.03)[b]	4.7
Brachytherapy						
Afterloading units		0.002	0.001	0.000 1	0.000 0	0.003
Annual number of patients		0.18	0.20	(0.05)[b]	(0.01)[b]	0.43

[a] No data submitted.
[b] Assumed value in the absence of data.

Table D3. Estimated annual number of radiotherapy treatments[a] in the world (1997–2007)

Data from United Nations Survey of Nations and United Nations World Population Database

Health-care level	*Population (millions)*	*Annual number of teletherapy treatments*		*Annual number of brachytherapy treatments*[b]		*Annual number of all radiotherapy treatments*	
		Millions	*Per 1 000 population*	*Millions*	*Per 1 000 population*	*Millions*	*Per 1 000 population*
I	1 540	3.5	2.2	0.18	0.12	3.6	2.4
II	3 153	1.2	0.4	0.20	0.06	1.4	0.4
III	1 009	0.1	0.1	(<0.05)[c]	(<0.01)[c]	0.1	0.06
IV	744	(0.03)[c]	(<0.01)[c]	(<0.01)[c]	(<0.005)[c]	(0.03)[c]	(0.01)[c]
World	6 446	4.7	0.73	0.43	0.067	5.1	0.8

[a] Complete courses of treatment.
[b] Excluding treatments with radiopharmaceuticals.
[c] Assumed value in the absence of data.

Table D4. Number of radiotherapy centres and of items of radiotherapy equipment per million population (1997–2007)

Data from IAEA/WHO Directory (DIRAC), United Nations Survey of Nations, United Nations World Population Database and Radiological Physics Center

Country/area	*Radiotherapy centres*	*Teletherapy units*			*Brachytherapy afterloading units*
		X-ray	*Radionuclide*	*Linear accelerator*	
Health-care level I					
Albania	0.3		0.63		
Argentina	2.3		2.25	1.29	0.10
Armenia	0.7		1.00	0.33	0.33
Australia	1.6	0.96		5.40	1.30
Austria	1.6		0.36	4.66	1.83
Azerbaijan	0.2				
Belarus	1.3		2.17	0.52	0.72
Belgium	2.4	1.91	0.38	4.11	0.86
Bulgaria	1.7		1.57	0.26	0.13
Canada	1.0		1.06	3.19	0.82
China - Hong Kong SAR	1.2		0.28	2.91	0.14
China - Taiwan	0.4				
Croatia	1.5	0.88	1.54	1.54	1.76
Cuba	0.8		0.89	0.18	0.44
Cyprus	2.3		2.34	2.34	1.17
Czech Republic	3.7	2.26	1.57	2.06	2.75
Democratic People's Republic of Korea	0.0		0.04	0.04	
Denmark	1.1		0.18	8.82	0.74
Ecuador	0.6		0.52	0.37	0.30
Estonia	1.5		0.75	1.50	3.00
Finland	1.9	0.38		5.69	2.08
France	3.4		1.65	5.43	0.41
Georgia	0.9		0.91		
Germany	3.0	1.03	0.24	4.72	2.49
Greece	2.2	0.27	1.26	2.96	0.99
Hungary	1.2	2.09	0.90	2.29	2.29
Iceland	3.3	3.32		6.64	3.32
Ireland	1.9		0.93	2.09	0.23
Israel	2.0		1.15	3.61	0.43

Country/area	*Radiotherapy centres*	*Teletherapy units*			*Brachytherapy afterloading units*
		X-ray	*Radionuclide*	*Linear accelerator*	
Italy	2.6		1.56	4.48	0.46
Japan	5.7		0.33	5.81	2.70
Kazakhstan	1.2		1.95	0.13	0.84
Kuwait	0.7		0.70	0.35	
Kyrgyzstan	0.2		0.38	0.19	
Latvia	1.8	0.44	0.88	3.07	0.88
Lebanon	1.5		0.98	2.20	
Lithuania	1.5	4.13	5.31	0.59	2.06
Luxembourg	2.1			4.28	2.14
Malta	2.5	2.46	2.46	2.46	
Monaco	30.3				
Netherlands	1.3		0.06	4.39	2.74
New Zealand	1.4	1.68	0.24	4.55	0.48
Norway	1.9	2.55		7.02	1.06
Panama	0.9		0.60	1.20	
Poland	0.6	0.11	0.37	1.68	1.10
Portugal	1.5		0.66	2.45	0.85
Qatar	2.4				
Republic of Korea	1.1		0.12	1.43	0.64
Republic of Moldova	0.3		1.05		0.53
Romania	2.1	1.63	0.79	0.23	0.19
Russian Federation	0.9		1.43	0.26	0.47
Singapore	0.7		0.23	2.25	0.68
Slovakia	3.0	0.37	3.53	2.60	5.01
Slovenia	0.5	1.00	1.00	3.00	
South Africa	0.4		0.43	0.54	0.16
Spain	2.6	0.54	1.08	4.00	1.56
Sri Lanka	0.2		0.36		0.10
Sweden	2.1	5.04	0.11	6.58	2.41
Switzerland	3.5	6.41	0.27	6.28	4.41
The former Yugoslav Republic of Macedonia	0.5		0.49	0.98	1.47
Ukraine	1.0		1.93	0.04	0.13
United Arab Emirates	0.5		0.46	0.91	0.46
United Kingdom	1.0		0.35	3.11	0.31
United States	9.2		0.32	15.50	2.49
Uruguay	4.2		2.69	1.50	
Uzbekistan	0.5		0.55		
Venezuela (Bolivarian Rep. of)	1.7		0.51	0.58	0.14
Average[a]	3.4	1.26	0.78	5.41	1.37
Health-care level II					
Algeria	0.1		0.27	0.18	
Bahamas	6.0			3.02	
Barbados	6.8		6.80		3.40
Bolivia	0.6		0.52	0.10	
Bosnia and Herzegovina	0.3		0.25	0.51	0.25
Brazil	0.8	0.31	0.58	0.82	0.26
Chile	1.3		0.90	0.96	0.12
China	0.6	0.16	0.41	0.32	0.30

Country/area	*Radiotherapy centres*	*Teletherapy units*			*Brachytherapy afterloading units*
		X-ray	*Radionuclide*	*Linear accelerator*	
Colombia	0.8		0.84	0.37	0.02
Costa Rica	0.7	0.22	0.67	0.67	0.45
Dominican Republic	0.3		0.31	0.10	0.20
El Salvador	0.4		0.44	0.15	0.73
Iran	0.3		0.37	0.01	
Jordan	0.7		0.68	1.01	0.17
Libyan Arab Jamahiriya	1.1		0.97		0.32
Malaysia	1.2		0.26	0.49	0.04
Mauritius	0.8		1.58	0.79	
Mexico	0.7		0.77	0.19	0.04
Mongolia	0.4		1.14		0.38
Montenegro	1.7				1.67
Nicaragua	0.2		0.18		
Pakistan	0.1		0.10	0.04	0.02
Paraguay	0.5		0.33	0.65	
Peru	0.4		0.32	0.29	
Philippines	0.3		0.28	0.18	0.07
Puerto Rico	1.5		0.75	2.00	
Serbia	0.7		0.20	1.52	0.30
Syrian Arab Republic	0.1		0.20		0.05
Tajikistan	0.1		0.30		
Thailand	0.4		0.38	0.25	0.19
Trinidad and Tobago	0.8	0.75	1.50		
Tunisia	0.6		0.68	0.19	0.39
Turkey	0.8		0.67	0.61	0.15
Uganda	0.1		0.03		
Average[a]	0.56	0.18	0.43	0.34	0.23
Health-care level III					
Congo, Rep.	0.1				
Egypt	0.4		0.26	0.28	0.03
Gabon	0.8		0.75		
Ghana	0.1		0.09		0.09
Guatemala	0.4		0.45	0.15	
Haiti	0.1		0.10		
Honduras	0.6		0.99	0.14	
India	0.2		0.22	0.03	0.07
Iraq	0.1		0.07		
Jamaica	1.1		0.74	0.37	
Madagascar	0.1		0.05		
Morocco	0.2		0.16	0.13	0.51
Namibia	0.5		0.48		
Nigeria	0.0		0.02	0.01	0.01
Saudi Arabia	0.3		0.08	0.73	0.08
Sudan	0.1		0.08	0.05	0.03
Viet Nam	0.1		0.13	0.01	0.03
Zimbabwe	0.1			0.22	0.15
Average[a]	0.16		0.19	0.06	0.07

Country/area	*Radiotherapy centres*	*Teletherapy units*			*Brachytherapy afterloading units*
		X-ray	*Radionuclide*	*Linear accelerator*	
Health-care level IV					
Angola	0.1				
Bangladesh	0.1		0.06		
Botswana	0.5			0.53	
Cambodia	0.1				
Cameroon	0.1		0.11		0.05
Ethiopia	0.0		0.01		0.01
Indonesia	0.0		0.02		
Kenya	0.1		0.08		0.03
Myanmar	0.1		0.16		
Nepal	0.0		0.04		
Papua New Guinea	0.2		0.16		
Senegal	0.1		0.08		
United Rep. of Tanzania	0.0		0.05		
Yemen	0.0		0.04		
Zambia	0.1				
Average[a]	0.06		0.05	0.53	0.02

[a] Averages are based on data submitted by surveyed countries, weighted by the population sizes of those countries.

Table D5a. Number of patients treated annually with various teletherapy procedures (2000–2006)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Leukaemia*	*Lymphoma*		*Breast tumour*	*Lung/thorax tumour*	*Gynaecological tumour*	*Head/neck tumour*	*Brain tumour*
		Hodgkin's	*Non-Hodgkin's*					
Health-care level I								
Croatia	8	27	40	1 556	1 062	570	582	354
Czech Republic	249	451	596	4 927	2 989	2 856	1 774	653
Hungary	22	34	88	851	494	318	438	80
Japan	1 590	570	10 080	36 450	49 660	14 830	35 860	14 420
Latvia	1	12	23	616	139	503	9	39
Lithuania	5	82	61	1 035	608	1 074	533	159
Luxembourg	1	6	10	263	56	50	52	28
Malta		9	21	306	20	42	61	4
Netherlands				9 000	7 000			
Norway	8		255	1 875	253	251	363	59
Poland	420	420	420	5 460	5 040	2 940	2 940	2 100
Slovenia	10	26	163	1 099	325	212	526	86
South Africa	16	9	19	340	200	693	369	34
Spain	394	1 076	1 506	17 170	8 268	5 393	7 146	4 369
Switzerland	269	154	329	3 512	1 111	674	851	544
The former Yugoslav Republic of Macedonia		15	10	403	285	345	189	57
Total	2 933	2 891	13 621	84 863	77 510	30 751	51 693	22 986

Country	*Leukaemia*	*Lymphoma*		*Breast tumour*	*Lung/thorax tumour*	*Gynaecological tumour*	*Head/neck tumour*	*Brain tumour*
		Hodgkin's	*Non-Hodgkin's*					
Health-care level II								
Costa Rica	15	15	11	79	2	40	28	42
El Salvador	6	11	19	139	21	564	100	19
Trinidad and Tobago				189	33	165	61	
Total	21	26	30	407	56	769	189	61
Health-care level III								
Zimbabwe	22	75	104	13	295	19		19
Total	22	75	104	13	295	19	0	19

Table D5b. Number of patients treated annually with various teletherapy procedures (2000–2006)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Testis*	*Other urological tumours*	*Tumour of colon and rectum*	*Other digestive tumours*
Health-care level I							
Croatia	85	104	305	30	35	406	134
Czech Republic	792	337	1 298	224	471	2 120	618
Hungary	182	48	145	13	29	299	100
Japan	2 410	4 040	6 070	500	1 850	7 070	25 840
Latvia	462	89	171	144	91	176	78
Lithuania	682	188	234	14	76	384	176
Luxembourg	15	3	50	9	3	48	20
Malta	436	33	96			63	
Netherlands			4 000				
Norway	337	54	802	56	5	320	41
Poland	420	420	1 680	420	420	1 680	420
Slovenia	309	11	128	3	26	245	128
South Africa	156	21	53	4	6	67	316
Spain	1 998	1 093	11 255	628	186	4 812	2 031
Switzerland	353	106	1 695	146	152	665	400
The former Yugoslav Republic of Macedonia	2	55	18	23	8	161	
Total	8 639	6 602	28 000	2 214	3 358	18 516	30 302
Health-care level II							
Costa Rica	12		145	23		11	20
El Salvador	4	11	13		8	20	10
Trinidad and Tobago	9	11	60	2	8	52	2
Total	25	22	218	25	16	83	32
Health-care level III							
Zimbabwe	49	22	37			33	12
Total	49	22	37	0	0	33	12

Table D5c. Number of patients treated annually with various teletherapy procedures (2000–2006)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Bone and soft tissue sarcomas*	*Palliative treatments*	*Benign diseases*	*Other*	*Total of all patients treated*
Health-care level I					
Croatia	128	1 659	9	98	7 249
Czech Republic	230	7 965	21 845	894	51 399
Finland					12 803
Germany					240 000
Hungary	42	2 310	582	545	4 310
Japan	20 310		1 190	7 800	242 510
Latvia	18	104	14	16	2 705
Lithuania	165	506	333	295	6 626
Luxembourg	9	112	10	40	787
Malta					1 091
Netherlands					38 000
Norway	62	3 598	192	453	8 984
Poland	420	13 020	420	420	42 000
Slovenia	51	1 569	26	47	4 990
South Africa	63	1 000	722	37	4 186
Spain	1 211	11 325	1 570	285	81 756
Switzerland	306	3 648	937	1 264	14 881
The former Yugoslav Republic of Macedonia	3		22		1 596
United States					840 000[a]
Total	23 018	46 816	27 872	12 194	1 605 873
Health-care level II					
China					494 208
Costa Rica	11	30		50	551
El Salvador	19		6	11	981
Trinidad and Tobago		36		77	705
Total	30	66	6	138	496 445
Health-care level III					
Zimbabwe	10				739
Total	10	0	0	0	739

[a] Estimate from the Radiological Physics Center, United States.

Table D6a. Number of paediatric patients treated annually with teletherapy (2000–2006)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Brain*	*Lymphoma*	*Neuroblastoma*	*Rhabdomyosarcoma*	*Wilm's tumour*	*Other tumour*
Health-care level I						
Croatia	22	5	3	4	2	21
Czech Republic	33	14	8	8	9	38
Hungary	17	5	3		3	8
Japan	700	80		60		1 150
Lithuania	15					1
Luxembourg	1	1				
Poland	420	420	420	420	420	420

Country	*Brain*	*Lymphoma*	*Neuroblastoma*	*Rhabdomyosarcoma*	*Wilm's tumour*	*Other tumour*
Slovenia	11	2				4
South Africa	34	1		14	8	4
Spain	56		42	21	42	77
Switzerland	7	4	3	9	4	7
Total	1 316	532	479	536	488	1 730
Health-care level II						
Costa Rica	6	11		2	1	8
Total	6	11	0	2	1	8
Health-care level III						
Zimbabwe				5	2	22
Total	0	0	0	5	2	22

Table D6b. Number of patients treated annually with special teletherapy procedures (2000–2006)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Intraoperative radiotherapy*	*Whole-body irradiation*	*Total lymphoid irradiation*	*Stereotactic irradiation*	
				Intracranial	*Extracranial*
Health-care level I					
Croatia			4		
Czech Republic		30	5	823	
Hungary		16		170	
Netherlands	200			70	
Norway		7	6	208	
Poland	150	50	20	765	110
Slovenia		15			
Spain	113	211	1	1 099	296
Switzerland	7	108		127	
Total	470	437	36	3 262	406

Table D7. Number of patients treated annually with brachytherapy (2000–2006)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Head/neck tumour*	*Breast tumour*	*Gynaecological tumour*	*Prostate tumour*	*Intravascular brachytherapy*	*Other*	*Total*
Health-care level I							
Croatia	1		369			138	508
Czech Republic	71	345	1 160			681	2 257
Finland							774
Hungary	14	13	230	47		89	393
Japan	3 940		7 850			1 560	13 350
Latvia			660				660
Lithuania			431			16	447
Luxembourg			31				31
Malta			5				5
Netherlands							2 000
Norway			148		21	19	188
Poland	120	130	5 850	240	110	1 950	8 400

Country	*Head/neck tumour*	*Breast tumour*	*Gynaecological tumour*	*Prostate tumour*	*Intravascular brachytherapy*	*Other*	*Total*
Slovenia	2		212			28	242
South Africa	6		600			250	856
Spain	417	1 655	4 017	986		90	7 165
Sweden							1 900
Switzerland	2	12	238	113	97	12	498
The former Yugoslav Republic of Macedonia			185			4	189
United States							0[a]
Total	4 573	2 155	21 986	1 386	228	4 837	37 963
Health-care level II							
China							0
Costa Rica			244				244
El Salvador			400				400
Trinidad and Tobago			80	60			140
Total	0	0	724	60	0	0	784
Health-care level III							
Zimbabwe							0
Total	0	0	0	0	0	0	0

[a] Data from the Radiological Physics Center, United States.

Table D8. Distribution by age and sex of patients undergoing teletherapy for a range of conditions (1997–2007)

Data from the UNSCEAR Global 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 and neck tumour						
I	Croatia	0	5	95	86	14
	Czech Republic	0	1	99	82	18
	Hungary	0	4	97	16	84
	Japan	0	3	97	73	27
	Lithuania	0	5	95	87	13
	Luxembourg	0	0	100	84	16
	Malta	0	9	91	66	34
	Poland	0	9	91	78	22
	Slovenia	0	2	98	81	19
	South Africa	0	9	91	82	18
	Spain	0	0	100	45	55
	Switzerland	0	3	97	73	27
	Average	0	4	96	71	29
II	Costa Rica	18	11	71	79	21
	El Salvador	0	6	94	51	49
	Average	9	8	83	65	35
Breast tumour						
I	Croatia	0	7	93	1	99
	Czech Republic	0	4	96	0	100
	Hungary	0	5	95	3	97

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Japan	0	10	90	1	99
	Latvia	0	7	93	0	100
	Lithuania	0	12	88	0	100
	Luxembourg	0	7	93	0	100
	Malta	0	1	99	2	98
	Poland	0	8	92	2	98
	Slovenia	0	7	93	0	100
	South Africa	0	20	80	6	94
	Spain	0	11	89	1	99
	Switzerland	0	7	93	1	99
	Average	0	8	92	1	99
II	Costa Rica	0	14	86	0	100
	El Salvador	0	13	87	1	99
	Average	0	13	87	0	100
Gynaecological tumour						
I	Croatia	0	11	89	0	100
	Czech Republic	0	3	97	0	100
	Hungary	0	9	91	0	100
	Japan	0	7	93	0	100
	Latvia	0	5	95	0	100
	Lithuania	0	11	89	0	100
	Luxembourg	0	0	100	0	100
	Malta	0	0	100	0	100
	Poland	0	10	90	0	100
	Slovenia	0	12	88	0	100
	South Africa	0	6	94	0	100
	Spain	0	8	92	0	100
	Switzerland	0	6	94	0	100
	Average	0	7	93	0	100
II	Costa Rica	0	25	75	0	100
	El Salvador	0	17	83	0	100
	Average	0	21	79	0	100
Prostate tumour						
I	Croatia	0	1	99	100	0
	Czech Republic	0	0	100	100	0
	Hungary	0	0	100	100	0
	Japan	0	0	100	100	0
	Latvia	0	0	100	100	0
	Lithuania	0	1	99	100	0
	Luxembourg	0	0	100	100	0
	Malta	0	0	100	100	0
	Poland	0	2	98	100	0
	Slovenia	0	0	100	100	0
	South Africa	0	0	100	100	0
	Spain	0	0	100	100	0
	Switzerland	0	0	100	100	0
	Average	0	0	100	100	0

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
II	Costa Rica	0	2	98	100	0
	El Salvador	0	0	100	100	0
	Average	0	1	99	100	0
Brachytherapy treatments						
I	Czech Republic	0	6	94	40	60
	Hungary	0	1	99	38	62
	Japan	0	5	95	11	89
	Latvia	0	6	94	2	98
	Lithuania	0	7	93	0	100
	Luxembourg	0	0	100	0	100
	Malta	0	0	100	0	100
	Poland	0	10	90	24	76
	Slovenia	0	9	91	8	92
	Switzerland	0	2	98	33	67
	Average	0	5	95	16	84

Table D9a. Typical patient teletherapy doses (Gy)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Leukaemia*	*Lymphoma*		*Breast tumour*	*Lung/ thorax tumour*	*Gynaecological tumour*	*Head/neck tumour*	*Brain tumour*
		Hodgkin's	*Non-Hodgkin's*					
Health-care level I								
Croatia	45	42	40	50	42	50	64	60
Czech Republic	24	35	40	60	64	70		64
Hungary	12		36	66	50	46	66	60
Japan	12	30	40	50	60	50		50
Latvia	6	36	40	60	50	28	68	60
Lithuania	26	35	37	45	50	45	60	50
Luxembourg	20	36	36	60	60	50.4	70	60
Norway	30		30	50	60	50	70	60
Poland	20	40	40	50	60	50	60	60
Slovenia	12	30.6	30	45	50.6	50.4	60	56
South Africa	36		60	45	50	60	54	45
Spain	12	30	40	50	60	45	60	55
Switzerland	25	30	35	60	60	50	65	60
The former Yugoslav Republic of Macedonia				50		50		60
Average	16	33	40	51	60	51	61	53
Health-care level II								
Costa Rica	27	36	40	50.4	45	45	70	54
El Salvador		40	40	100	40	45		20
Trinidad and Tobago				50		45	60	
Average	27	38	40	67	40	45	63	43

Table D9b. Typical patient teletherapy doses (Gy)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Testis*	*Other urological tumours*	*Tumour of colon and rectum*	*Other digestive tumours*
Health-care level I							
Croatia	50	60	74	35	50	50	45
Czech Republic	65	74	24	45	45	45	
Hungary	50	60	60	25.2	50	50.4	45
Japan	50	50	60	30	30	50	50
Latvia	51	60	70	36	50	50	64
Lithuania	60	54	57	45	53	40	50
Luxembourg	60	60	74	26	60	50.4	60
Norway	60	60	70	25	60	50	50
Poland	50	64	50	30	60	50	50
Slovenia	40	48	72	16.2	46.8	50.4	45
South Africa	30	66	30	30	30	45	54
Spain	60	60	76	25	50	50	50
Switzerland	50	60	75	30	45	50	55
The former Yugoslav Republic of Macedonia		66.8		25.2		50.4	
Average	54	55	67	30	39	49	50
Health-care level II							
Costa Rica	46		76	25		45	45
El Salvador		45					
Trinidad and Tobago			65			50	
Average	46	45	73	25		49	45

Table D9c. Typical patient teletherapy doses (Gy)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Bone and soft tissue sarcomas*	*Palliative treatments*	*Benign diseases*	*Other*
Health-care level I				
Croatia	10	24	12	60
Czech Republic	30	10	5	
Hungary	60	30	8	
Japan	40		35	
Latvia	60	30	50	40
Lithuania	55	30	3	43
Luxembourg	66	30		
Norway		30	12	
Poland	60	20	20	50
Slovenia	50.4	20	20	48
South Africa	40			15
Spain	60	30	30	
Switzerland	55	30	10	55
Average	42	23	8	52
Health-care level II				
Costa Rica	66	30		50
Average	66	30		50

Table D10a. Typical paediatric teletherapy doses (Gy)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Brain*	*Lymphomas*	*Neuroblastoma*	*Rhabdomyosarcoma*	*Wilm's tumour*
Health-care level I					
Croatia	55	30	30	45	20
Czech Republic					
Hungary	50	26	30		30
Japan	30	20	10	40	
Lithuania	50				
Luxembourg	54	20			
Norway					
Poland	50	20	21	50	30
Slovenia	18	12			
South Africa					
Spain	54		20	45	20
Sweden					
Switzerland	65	30		50	25
Average	39	20	21	49	29

Table D10b. Typical patient teletherapy special procedure doses (Gy)
Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Intraoperative RT*	*Total body irradiation*	*Total lymphoid irradiation*	*Stereotactic irradiation*	
				Intracranial	*Extracranial*
Health-care level I					
Croatia			42		
Czech Republic		12		30	
Hungary		12		18	
Norway				25	
Poland	20	10	36		
Slovenia		14			
Spain	15	12			
Switzerland	10	10	18		
Average	18	11	37	27	

Table D10c. Typical patient brachytherapy doses (Gy)

Data from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures

Country	*Head/neck tumour*	*Breast tumour*	*Gynaecological tumour*	*Prostate tumour*	*Intravascular brachytherapy*	*Other*
Health-care level I						
Croatia			30			32
Czech Republic		10	30			
Hungary	4	4.3	6	10		10
Latvia			35			
Lithuania			48			
Luxembourg			14			
Norway			27		20	
Poland		10	35	30		
Slovenia	20		30			19
Spain	30	10	30			
Switzerland	19	17	20	100	14	50
The former Yugoslav Republic of Macedonia			21			
Average	29	10	26	47	17	28
Health-care level II						
Trinidad and Tobago			40	145		
Average			40	145		

Table D11. Number of dedicated stereotactic installations by country

Country/area	*GammaKnife installations [E2]*	*CyberKnife installations [A6]*	*Novalis installations [B8]*
Argentina	1		
Austria	3		
Belgium	1		1
Brazil	1		
Canada	3		2
China	15	4	1
China, Taiwan	6	4	2
Croatia	1		
Czech Republic	1		
Democratic People's Republic of Korea	2		
Denmark			1
Egypt	2		
Finland			1
France	2	3	2
Germany	4	1	3
Greece	1	1	
Hong Kong	1	1	
India	3		
Iran, Islamic Rep.	2		
Italy	4	3	
Japan	46	19	6
Jordan	1		
Malaysia		1	

Country/area	*GammaKnife installations [E2]*	*CyberKnife installations [A6]*	*Novalis installations [B8]*
Mexico	2		2
Netherlands	1	1	3
Norway	1		
Philippines	1		
Republic of Korea	11	5	1
Romania	1		
Russian Federation	1		2
Singapore	1		
Spain	1	1	1
Sweden	2		
Switzerland	1		
Thailand	1		1
Turkey	3	2	
United Kingdom	3		
United States	116	87	44
Viet Nam		1	
Total	244	134	73

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18 May 2016

Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report

Volume I

Annex B (Exposures of the public and workers from various sources of radiation)

Corrigendum

1. **Page 328, table 3**

In the header, *for* Collective dose per unit release (man Sv/PBq) *read* Collective dose per unit release (man Sv/TBq)

In the first row, *for* 2.1 *read* 0.0021

In the second row, *for* 270 *read* 0.27

In the third row, *for* 0.0074 *read* 0.0000074

In the fourth row, *for* 0.044 *read* 44

In the fifth row, *for* 0.0003 *read* 0.3

In the sixth row, *for* 0.0074 *read* 7.4

In the seventh row, *for* 0.0014 *read* 0.0000014

In the eighth row, *for* 1000 *read* 1

In the ninth row, *for* 4.7 *read* 0.0047

In the tenth row, *for* 3.3 *read* 0.0033

In the eleventh row, *for* 99 *read* 0.099

In the twelfth row, *for* 98 *read* 0.098

2. **Page 367, table 72, section headed “1985-1989”, column headed “Monitored workers”**

In the row headed “Reprocessing”, *for* 17 *read* 12

3. Page 378, table 92, last row headed "Total"

For entry for the period 1990-1994, *for* 0.8 *read* 1.3

For entry for the period 1995-1999, *for* 0.9 *read* 1.8

For entry for the period 2000-2002, *for* 0.8 *read* 1.8

May 2011

Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report to the General Assembly, with Scientific Annexes—Volume I

Corrigendum

1. Annex A (“Medical radiation exposures”), page 172, figure D-II

The title *should read*

Representative isodose distributions: Intensity-modulated radiation therapy planfor a prostate tumour, showing superior conformation of the 50 Gy isodose line to the planning target volume

2. Annex B (“Exposures of the public and workers from various sources of radiation”), paragraph 155

The paragraph *should read*

155. *Effluents and solid waste*. Mining operations have been carried out in open pits, in underground mines and by in situ leaching. Uranium mill tailings are generated at about one tonne per tonne of ore extracted, and they generally retain 5–10% of the uranium and 85% of the total activity [V4]. The estimated amounts of tailings worldwide are shown in figure XVII; they total about 2.35×10^9 t. Besides the tailings, waste rock piles may also become a source of public exposure. For open-pit mining, the amount of debris produced is from 3 to 30 tonnes per tonne of extracted ore. For underground mining, about ten times less debris is produced. On the basis of information provided for 13 mining sites in Argentina [R13], Canada [M28], Germany [F2] and Spain [S29], the amount of waste rock varies from 40 to 6,000 times the amount of tailings, with an average value of about 1,600 tonnes of waste rock per tonne of tailings [I38].

ANNEX B

EXPOSURES OF THE PUBLIC AND WORKERS FROM VARIOUS SOURCES OF RADIATION

CONTENTS

Page

INTRODUCTION

1. The exposure of human beings to ionizing radiation from natural sources is a continuing and inescapable feature of life on the 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. The world population is also exposed to radiation resulting from releases to the environment of radioactive material from man-made sources, and from the use of fuels or materials containing naturally occurring radionuclides. In addition, there are 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, for example in 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 the management and control of radiation as an occupational hazard. All these exposures were regularly assessed in previous reports of the Committee, the most recent being the UNSCEAR 2000 Report [U3]. The purposes of these assessments are to improve the understanding of global levels and temporal trends of public and worker exposure, to evaluate the components of exposure so as to provide a measure of their relative importance, and to identify emerging issues that may warrant more attention and scrutiny.

2. This annex comprises three sections. Section I addresses general issues related to dose assessment for public and occupational exposure to radiation, and the special quantities for measuring and assessing exposure due to radon. Sections II and III address the exposures to ionizing radiation of the general public and of workers, respectively. The distinction between public and occupational exposure is kept for two main reasons: *(a)* the two groups exhibit significant differences with respect to age, the numbers of people exposed, the relevant exposure pathways, and the methodologies for monitoring and assessing radiation doses;[1] and *(b)* there is a difference in responsibilities for managing the protection of workers and of the public that is reflected in the different interests of users of this annex.

3. This annex supplements and updates previous UNSCEAR publications on the subject. The estimates of radiation exposure have been based primarily on the submissions to the UNSCEAR databases for assessment of doses to the public and workers, supplemented by significant reports in the open literature. The annex does not cover processes previously described in detail; whenever pertinent, reference is made to sources where more detailed information may be found. In particular, because the Committee has separately evaluated exposures due to radon (annex E of the UNSCEAR 2006 Report [U1]), to medical uses of radiation (annex A of the 2008 Report) and to accidents (annex C of the 2008 Report), in particular exposures due to the 1986 Chernobyl accident (annex D of the 2008 Report), these aspects are not dealt with extensively in this annex. Where appropriate, summaries of other evaluations have been reflected here for completeness.

4. The Committee has historically described the exposure of members of the general public to the several different natural and man-made sources of radiation. The principal objectives of the analysis of public exposures presented in section II are:

- To evaluate the radiation levels worldwide to which human beings are usually exposed;
- To assess the usual variability of exposure worldwide to different sources;
- To identify sources of concern for public exposure;
- To allow users to derive benchmarks for comparison purposes, to manage exposures and to derive relationships for their investigative work;
- To analyse temporal trends in the contributions of different sources to overall public exposure.

5. It is often not straightforward to differentiate between normal exposures and enhanced exposures to natural sources of radiation, and between these and exposures to man-made sources. An illustrative example is the common assessment of radiation exposure indoors, where the natural background radiation exposure is influenced by the presence of natural radioactivity in building materials, leading to what are sometimes treated as enhanced exposures. Another example is the impact of the urbanization process, which is known to alter natural background radiation exposure (e.g. the laying of pavement reduces exposure from radionuclides in the soil,

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[1] While doses to workers are mostly measured, doses to the public are usually assessed by indirect methods, typically using measurements performed in the environment or of environmental samples, modelling various exposure scenarios and employing data on population habits. The accuracy of assessments made usually differs with the methodology used: doses assessed for workers are normally more accurate than those for members of the public. Moreover, doses from occupational exposure relate to a specific set of people, usually healthy adults. Although assessments of doses to the public sometimes take account of the properties of different age groups or their specific habits, the values of the dose estimates do not usually apply to any specific individual within the population under consideration, but rather represent an average dose to groups of people.

whereas the use of granite and certain ceramic materials in the construction of buildings may enhance exposure). In addition, especially for developing countries, the expansion of industries (e.g. a new mining installation in an area with high levels of background radiation) may enhance public use and habitation of an area as new infrastructure becomes available, leading to changes in public exposure. Because of these difficulties, no attempt will be made here to draw a rigorous distinction between normal and enhanced exposures to natural sources of radiation. Subsection II.A, on public exposure to natural sources of radiation, includes consideration of exposures to cosmic and terrestrial sources of radiation.

6. The exposure of the general public to radiation resulting from industries deemed non-nuclear—such as the mining, milling and processing of ores that, apart from the raw material, contain uranium (U) and/or thorium (Th)—is described in subsection II.B on enhanced sources of radiation. Exposures resulting from nuclear industries (i.e. those related to the nuclear fuel cycle and to artificial radionuclides) are described in two subsections on public exposure to man-made sources. The first of these, subsection II.C, describes public exposure to man-made sources arising from peaceful uses of atomic energy (including energy generation and the operation of the associated fuel cycle facilities, the production of radioisotopes, the transport of nuclear and radioactive material, waste management and the use of consumer products). The second, subsection II.D, presents the public exposures to man-made sources related to military purposes (including atomic weapons tests and their fallout or radioactive residues, the military use of depleted uranium in war situations and sites contaminated by waste from previous practices, mostly associated with the development of nuclear weapons technology, but not including the exposures due to the Hiroshima and Nagasaki bombings). As doses received by the world population due to nuclear explosions have been described systematically in previous reports of the Committee and a major overview was presented in the UNSCEAR 2000 Report [U3], only a summary regarding the tests and the resulting worldwide exposures has been included here for completeness.

7. In section III the Committee has updated its evaluations of occupational exposures [U3, U6, U7, U9, U10] for work in six broad categories of practice: practices involving elevated levels of exposure to natural sources of radiation; the nuclear fuel cycle; medical uses of radiation; industrial uses of radiation; military activities; and miscellaneous uses of radiation (which includes educational and veterinary uses).

8. The Committee has evaluated the distributions of annual individual effective doses and annual collective effective doses resulting from occupational radiation exposures in the various practices or due to various types of source. The principal objectives of the analysis of occupational exposures remain, as in the previous assessments of the Committee, as follows:

- 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 of the major practices involving the use of ionizing radiation;
- 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;
- 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 ensuring that doses are as low as reasonably achievable), new technological developments and modified work practices;
- To compare exposures of workers in different countries and to estimate the worldwide levels of exposure for each significant use of ionizing radiation.

9. According to the International Labour Organization, the formal definition of occupational exposure to any hazardous agent includes all exposures incurred at work, regardless of source [I62]. However, for radiation protection purposes, in order 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 often taken to mean those exposures received at work which can reasonably be regarded as the responsibility of the operating management [I7, I16, I47]. Such exposures are normally also subject to regulatory control [I7]. The exposures are usually determined by individual monitoring, and the doses assessed and recorded for radiological protection purposes.

10. The terms “practice” and “intervention” have been widely used in radiological protection. The term “practice” has been used for human activities that increase the exposure or the likelihood of exposure of people to radiation or the number of people exposed. The International Commission on Radiological Protection (ICRP) had distinguished between “practices” that increase exposure or likelihood of exposure and “interventions” that reduce exposure or likelihood of exposure [I7, I47]. However, the latest ICRP recommendations [I60] use a situation-based approach to characterize the possible situations where radiation exposure may occur as “planned”, “emergency” and “existing exposure” situations. The ICRP now believes that it is more appropriate to limit the use of the term “intervention” to describe protective actions that reduce exposure, while the terms “emergency” or “existing exposure” will be used to describe radiological situations where such protective actions to reduce exposure are needed [I60]. In this annex the terms “practice” and “intervention” are applied according to the previous ICRP definitions [I47].

11. The procedures for the recording and inclusion of occupational exposures differ from practice to practice and country to country, and this may influence the

respective statistics in different ways. Some countries may overestimate the size of the exposed workforce, and thereby distort assessment of the individual and population dose distributions. Moreover, some countries report only the doses of workers in controlled areas, while other countries report the doses from both exposed and non-exposed workers. Some countries do not adequately track the doses to contract workers, who may work and accumulate exposure in different industries, possibly even in different countries. These issues are discussed in subsection III.A. These differences in monitoring and reporting practices mean that caution must be applied in interpreting the reported data.

12. Although most workers involved in practices that are subject to controls established by the national regulatory authorities are individually monitored on a routine basis, there are a significant number of workers exposed to ionizing radiation who are not individually monitored. The largest proportion of these workers are those exposed to natural sources of ionizing radiation. Before the implementation of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (the "International Basic Safety Standards") [I7], few data were recorded in national databases on occupational exposure to natural sources of radiation. Recently, however, exposures to enhanced levels of natural radiation have become a focus of attention in the field of radiation protection. Subsection III.B is devoted to natural sources of occupational radiation exposure.

13. Subsections III.C and III.D address occupational exposure to man-made sources of radiation used for peaceful and for military purposes, respectively.

I. DOSE ASSESSMENT ISSUES

14. The basic quantity used here to describe radiation exposure is the "effective dose". Although this artificial quantity was developed strictly for protection purposes, it is used here for the purposes of exposure assessment. The annual committed effective dose includes the sum of external and internal doses and is usually reported in millisieverts (mSv):

$$E = E_{ext} + E_{\mathrm{int}} \qquad (1)$$

15. The ICRP [I60] has very recently recommended new values for some of the radiation and tissue weighting factors in the definition of effective dose. However, for the evaluations here, the assessment of effective doses has been made on the basis of the earlier definition provided in ICRP Publication 60 [I47].

16. In particular, the Committee continues to use in its estimations of effective dose a radiation weighting factor (w_R) of 1 for all photon and beta emitters, including tritium. A recent report of an independent Advisory Group on Ionising Radiation to the Health Protection Agency (HPA) in the United Kingdom recommended that the ICRP consider increasing this value for tritium from 1 to 2 [A3]. The ICRP has considered this recommendation, taking into account recent reviews of the scientific basis for this value [L18, L19]. It concluded that, for assessments covered by their broad approach, i.e. that are not individual-specific, a value of 1 remains appropriate [C32].

17. In order to compare the total radiation dose from various sources incurred by different groups, the Committee uses the quantity "collective dose", which is defined as the sum of all the individual effective doses received in the group under consideration. It is expressed in units of man-sieverts (man Sv) [I7] and is accompanied by the number of individuals in the group. While this quantity was also developed strictly for the purposes of optimization of protection, it is used by the Committee to assess the relative importance of various sources of radiation exposure. The collective dose received by a group divided by the number of individuals in the group is the "average per caput dose" in this group.

18. The Committee uses the International System of Units to report data as values that can be easily used and recalled; specifically, it uses multiples and submultiples of the standard units, designated by the following prefixes:

peta	(P)	10^{15}	femto	(f)	10^{-15}
tera	(T)	10^{12}	pico	(p)	10^{-12}
giga	(G)	10^{9}	nano	(n)	10^{-9}
mega	(M)	10^{6}	micro	(μ)	10^{-6}
kilo	(k)	10^{3}	milli	(m)	10^{-3}

A. Public exposure

19. It is very rare that doses to members of the public are directly measured. Usually these doses are assessed on the basis of environmental or effluent monitoring data, using models to simulate environmental exposure scenarios. These scenarios and models have been extensively discussed in the UNSCEAR 2000 Report [U3], and only a summary of the most relevant aspects will be presented here.

20. The estimation of E_{ext} in Eq. (1) depends on the data available from environmental measurements. The main quantity used to characterize external exposure fields due to

natural sources is the absorbed dose rate in air, usually reported in nanograys per hour (nGy/h). Some authors report the air kerma, also expressed in nanograys per hour. Under the assumption that charged-particle equilibrium exists within the volume of material, the air kerma and the absorbed dose in air may be assumed to be equivalent. The factor used to transform measurements of absorbed dose in air to external effective dose to adults is 0.7 Sv/Gy, as described in the UNSCEAR 2000 Report [U3]. When describing public exposure, external exposures are assessed using effective dose rates expressed in units of either nanosieverts per hour (nSv/h) for instantaneous exposure fields, or millisieverts per year (mSv/a) for estimating the average annual exposure of individuals. The "occupancy fraction", related to the fraction of time spent indoors, I_{in}, and the "shielding factors" of buildings, SF, describing the ratio of the absorbed dose rate indoors to the absorbed dose rate outdoors, are also used to estimate average annual effective doses:

$$E_{ext} = 0.7\, D \quad [(1 - I_{in}) + SF \cdot I_{in}] \tag{2}$$

21. External doses may also be estimated from environmental concentrations of natural radionuclides in soil, C_{soil}, using appropriate dose conversion factors, DCF_{soil}, as presented in table 1:

$$E_{ext} = C_{soil}\, DCF_{soil}\, [(1 - I_{in}) + SF \cdot I_{in}] \tag{3}$$

22. Internal doses for adults are calculated using the 50 year committed effective doses (i.e. the integrated internal dose received over the 50 years following intake); for children, the committed effective doses are integrated up to the age of 70 years. Very few assessments include estimates of doses to children. Internal doses to members of the public are usually estimated on the basis of the scenarios described in the UNSCEAR 2000 Report [U3], using data on concentrations of radionuclides in the environment, such as concentration in water or food, C_k, expressed in becquerels per litre (Bq/L) or becquerels per kilogram (Bq/kg), and concentration in air, C_{air}, expressed in becquerels per cubic metre (Bq/m^3):

$$E_{\text{int}} = E_{inh} + E_{ing}$$

where

$$\begin{aligned} E_{inh} &= \sum_j e_{j,inh}\, I_{j,inh} \quad = \sum_j \; C_{j,air}\; e_{j,inh}\; IR_{inh} \\ E_{ing} &= \sum_j e_{j,ing}\, I_{j,ing} \quad = \sum_{k,j} \; C_{k,j}\; e_{j,ing}\; IR_k \end{aligned} \tag{4}$$

where j refers to radionuclides, k refers to the type of food or water, I is the intake of radionuclide, IR is the inhalation rate or the ingestion rate of foodstuff k, and e is the coefficient for conversion from intake to committed effective dose, $e_j(50)$, i.e. the committed effective dose integrated for 50 years for adults, and $e_j(70)$, i.e. the committed effective dose integrated up to the age of 70 years for children, separately for inhalation and ingestion. The dose conversion coefficients used in this annex for adults for doses due to intakes of natural radionuclides are also presented in table 1.

23. To assess doses due to the operation of nuclear power plants and other fuel cycle facilities, the dose conversion coefficients derived in the UNSCEAR 2000 Report [U3] have been used. These coefficients are specified in terms of the collective effective dose per unit release of a radionuclide. They are presented in table 2 for nuclear reactors and in table 3 for reprocessing facilities. For other fuel cycle facilities, collective doses have been estimated on the basis of the electrical energy generated and the same dose coefficients as used in [U3], namely 0.2 man Sv/(GW a) for operational uranium mining, 0.0075 man Sv/(GW a) for operational tailings piles, 0.00075 man Sv/(GW a) for releases from residual tailings piles, 0.003 man Sv/(GW a) for uranium enrichment and fuel fabrication facilities, and 0.5 man Sv/(GW a) for the disposal of low- and intermediate-level waste. The Committee has decided not to extend its estimates of doses into the far future, as was done in previous reports, because of the very large uncertainty inherent in such assessments. Thus only current doses received by members of the public are described in this annex.

24. For the assessment of exposures due to military uses of radiation, the main quantity used is also the effective dose, although sometimes the equivalent dose to specific organs, such as the thyroid, have also been reported. Both quantities are expressed in units of millisieverts, but when the term "dose" refers to a specific organ dose, this is made clear in the text. In this section, estimates for doses occurring in the past, present and near future are given. The future doses are mainly related to possible or predicted exposures due to the use of contaminated sites.

B. Occupational exposure

25. The ICRP, in its Publication 60 [I47], indicated that three important factors 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 doses and intakes; and the complexity of the measurement and interpretation procedures that make up the monitoring programme. Where doses are consistently low or predictable, other methods of monitoring are sometimes used, as in the case of aircrew for whom doses can be calculated from flight rosters. The complexity of measurement techniques results in an approach to monitoring for external irradiation that is different from that for intakes and the resulting committed dose.

26. The estimate of the effective dose, $E(t)$, needs to take into account the contribution from external and internal exposure, if appropriate. $E(t)$ can be estimated using the following expression:

$$E(t) = H_P(d) + \sum_j e_{j,inh}(50) I_{j,inh} + \sum_j e_{j,ing}(50) I_{j,ing} \tag{5}$$

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 of radionuclide j, integrated over 50 years; $I_{j,inh}$ is the intake of radionuclide j by inhalation during the time period t; $e_{j,ing}(50)$ is the committed effective dose per unit activity intake by ingestion of radionuclide j, integrated over 50 years; and $I_{j,ing}$ is the intake of radionuclide j by ingestion during time period t. Uptake through the skin and wounds can occur in some circumstances. For most forms of intake, the dose coefficients provided by the ICRP are for intakes by inhalation and ingestion and do not take into account uptake through the skin.

27. The United States National Council on Radiation Protection and Measurements (NCRP), in collaboration with the ICRP, has developed a biokinetic and dosimetric model for radionuclide-contaminated wounds. The multicompartment model uses first-order linear biokinetics to describe the retention and clearance of a radionuclide deposited on the wound site. Seven default categories have been defined to describe wound site retention: four relate to contamination with initially soluble materials (weak, moderate, strong and avid), and three relate to contamination with materials having solid properties (colloid, particle and fragment). The wound model is coupled to the ICRP systemic models for predicting urinary and faecal excretion patterns, as well as for producing wound-specific dose coefficients. However, the resulting dose coefficients are not yet available, and therefore the doses estimated in this annex were based on the dose coefficients for ingestion or inhalation [G15].

28. One of the factors regarding the uncertainty of the external dose assessment concerns how and where personal dosimeters should be worn in order 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 $H_p(10)$. In medical radiology, where lead aprons are used, 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 higher, for example in interventional radiology, two dosimeters are sometimes used, one worn under the apron and a second worn outside. The purpose of the second dosimeter is to assess the contribution to the effective dose due to the irradiation of unshielded parts of the body [N9]. Where doses are low and individual monitoring is intended only to give an upper estimate of exposure, single dosimeters might be worn outside the apron.

29. Measurements made on phantoms using X-ray beams of 76 and 104 kVp have shown that, while estimates of the effective dose without the lead apron were within 20% of the expected values, estimates with the dosimeter worn on the waist underneath the lead apron were lower than the expected values [M12]. Such results suggest that accurate estimation of effective dose using personal dosimeters under conditions of partial-body exposure remains problematic and that to be fully accurate would probably require that multiple monitors be used, which is not often done. Differing monitoring practices in medical radiology may therefore affect the validity of the data for comparison purposes. Since the position of the dosimeter in relation to the lead apron is not standardized among countries, a large apparent fluctuation of dose values could result unless algorithms that yield more precise estimates are used to convert the measured quantity to effective dose [N9]. Variations in the design of the lead apron itself and in its thickness may represent additional sources of uncertainty. These uncertainties and how they are addressed by dosimetry services could also have an impact on the comparisons made here. In this annex it is assumed that all these parameters have been properly considered in dose estimation.

30. The conversion coefficients for use in radiological protection against external irradiation are given in ICRP Publication 74 [I56]. 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 [I50], which takes account of the tissue weighting factors in ICRP Publication 60 [I47] and the new lung model in ICRP Publication 66 [I51]. It is assumed that the data provided to the Committee have been based on these conversion coefficients. A number of difficulties may be encountered in determining occupational exposure. These difficulties may be addressed in various ways, as is evident in the variety of monitoring procedures and dose recording practices adopted in countries throughout the world. While some countries have already adopted the recommendations of ICRP Publication 60 [I47], a significant proportion of countries are still using the dose limits and the quantities of ICRP Publication 26 [I43], especially for the first period analysed in the current annex (1995–1999). This may be a factor in explaining the variation in doses for a given practice among different countries. Quantities for radiation exposure and the methodologies for external and internal dose assessment have been well described in the UNSCEAR 2000 Report [U3], and because the measured quantities and the techniques described in that report remain unchanged, the issue need not be addressed further here.

31. Intakes of radioactive material are normally assessed routinely for workers employed in areas that are designated as controlled (specifically in relation to the control of contamination) or in which there are grounds for expecting significant intakes [I13, I55]. However, there are difficulties in comparing data on doses due to intakes of radionuclides in different countries because of the different approaches used for monitoring and to interpreting the results. Several international intercomparison exercises for internal dose assessment have been organized, of which the largest so far was the Third European Intercomparison Exercise on Internal Dose Assessment, organized in the framework of the EULEP/EURADOS Action Group [D11, I15]. The most important lesson from these intercomparison exercises was that there was a need to develop agreed guidelines for internal dose

evaluation procedures in order to promote the harmonization of assessments between organizations and countries. Significant differences were revealed among laboratories in their approaches, methods and assumptions, and consequently in their results. One major source of divergence at the time of the exercise was due to the particular ICRP models used. Most dosimetry services were using the models from ICRP Publications 26 [I43] and 30 [I44] for legal reasons. However, most were in the process of moving to the new generation of ICRP models (Publications 56 [I46], 60 [I47], 66 [I51], 67 [I49], 68 [I50], 69 [I52], 71 [I53], 72 [I54], 78 [I55] and 100 [I58]), partly because these are considered to be more realistic and partly because of the imminent implementation of the International Basic Safety Standards [I7] and the new Euratom directive, which are based on the new models [C29, D10, D12, H30, I14]. Similar projects aiming to harmonize internal dosimetry procedures have been carried out in different parts of the world under the auspices of the International Atomic Energy Agency (IAEA) [M20].

32. Since its Publication 60 [I47], the ICRP has revised the biokinetic and dosimetric models used in internal dosimetry, specifically: the model for the respiratory tract [I51]; the model for the alimentary tract [I56]; systemic models [I46, I49, I52] and dosimetric models [I54]. The new ICRP biokinetic and dosimetric models have changed the dose coefficients used for internal dosimetry. The ratios of the dose coefficients for workers based on the models of ICRP Publication 68 [I50] to those based on the models of Publication 30 [I44] have been calculated for about 800 radionuclides. For inhalation, about 40% of the ratios fall in the range 0.7–1.5, about 4% of the ratios are greater than 10 and about 1.4% are less than 0.1. For ingestion, about 73% of the ratios fall in the range 0.7–1.5, about 3.4% are greater than 10 and about 1.3% are less than 0.1. The analysis addressed both inhalation and ingestion of radionuclides in the workplace and included almost all the radionuclides (some 800) considered in ICRP Publication 30. The tissues considered were the lungs, stomach wall, colon wall, bone surface, red marrow, liver, thyroid, breast, testes and muscle. The solubility classes were those considered in ICRP Publication 30. Dose coefficients for the absorption types (Types F, M and S) currently used by the ICRP were compared with coefficients for Class D, W and Y compounds, respectively, as defined in ICRP Publication 30. The inhalation dose coefficients generated by the models of ICRP Publication 30 were based on the default particle size of 1 µm (AMAD) recommended in that publication, and the coefficients generated by models of ICRP Publication 68 were based on the default particle size of 5 µm recommended in that publication. As an example, the ratio of the dose coefficient from ICRP Publication 68 to that from ICRP Publication 30 for the inhalation of insoluble ^{239}Pu compound is 0.07 for bone marrow and for the inhalation of insoluble ^{238}U compound is 0.13 for the lung. The ratios clearly depend on the radionuclide and on factors such as retention in the body and solubility [L6, P9].

33. The application of different ICRP methodologies for intake and dose calculations obviously affects the results of dose assessments. This can be an important source of variation between the doses reported by different countries for the period under consideration, when most of the countries changed from ICRP Publication 26 [I43] to ICRP Publication 60 [I47] recommendations.

C. Special quantities for radon

34. The health risk due to exposure to ^{222}Rn (radon) and ^{220}Rn (thoron) comes principally from the inhalation of the short-lived decay products and the resulting alpha particle irradiation of the bronchial airways. The radiation dose delivered to the respiratory system, and the resulting potential health detriment, are a complex function of the radon decay product aerosol characteristics and the physiological parameters of the exposed individual. The radon and thoron dosimetry described in this annex is a summary of section II in annex E of the UNSCEAR 2006 Report [U1].

35. Radon and thoron decay product exposure rates are expressed by the measure of potential alpha energy concentration (PAEC), with units of joules per cubic metre (J/m^3) for the equilibrium equivalent concentration (EEC) or becquerels per cubic metre (Bq/m^3) for the working level (WL: unit of concentration of radon progeny in one cubic metre of air that has the potential alpha energy of 2.08×10^{-5} J for ^{222}Rn). The PAEC is derived from a linear combination of the activities of the short-lived decay products in each radon decay series (see paragraph 122, annex B of the UNSCEAR 2000 Report [U3]). The constants in the linear combination are the fractional contributions of each decay product to the total potential alpha energy from the decay gas. The EEC (in units of Bq/m^3) can be converted to the PAEC by the relationships:

$$1 \text{ Bq/m}^3 = 5.56 \times 10^{-6} \text{ mJ/m}^3 = 0.27 \text{ mWL } (^{222}\text{Rn})$$

and

$$1 \text{ Bq/m}^3 = 7.6 \times 10^{-5} \text{ mJ/m}^3 = 3.64 \text{ mWL } (^{220}\text{Rn}).$$

36. As discussed in annex E of the UNSCEAR 2006 Report [U1], estimates of radiation dose and the resulting risk from inhalation of radon decay products can be derived from either epidemiological studies or dosimetric models. For occupational exposure to inhaled radon decay products, the ICRP recommended in Publication 65 [I48] the use of a single conversion factor based on the results of the uranium miner epidemiological studies, by equating the radiation detriment coefficient (risk per sievert) with the miner detriment (risk per PAEC exposure). For worker exposure, this factor is 1,430 mSv/(J h m^{-3}) (rounded to 1,400 mSv/(J h m^{-3})), 5.06 mSv per working level month (WLM) (rounded to 5 mSv/WLM) or 7.95 nSv/(Bq h m^{-3}) (rounded to 8 nSv/(Bq h m^{-3})) EEC [U1]. The working level month corresponds to the exposure resulting from the inhalation of air containing 1 WL for 170 h. The countries reporting data often do not specify which dosimetric model was used to calculate the dose, although it is likely that the ICRP approach was used [I7].

37. The results of the dosimetric model agree with the conversion convention within a factor of 2 and depend on the value for the radiation weighting factor. Until further clarification of the factor is available, the Committee considers that the established value of 9 nSv/(Bq h m^{-3}) used in past UNSCEAR calculations [U3, U6, U7] is still appropriate for its purpose of evaluating average effective doses [U1].

38. It is not possible to assess the radiation dose due to inhalation of thoron decay products by epidemiological means, and the dose conversion factor must therefore be estimated using dosimetric modelling. Annex A of the UNSCEAR 2000 Report [U3] indicated that a conversion factor for thoron decay products could be derived on the basis of the recommendations given in ICRP Publication 50 [I45], which in turn were based on the results of an Expert Group of the Nuclear Energy Agency [N20]. According to reference [U3], this value is intended to include the dose to organs other than the lungs resulting from the transfer of ^{212}Pb from the lungs to these other organs. The principal dosimetric assessments of lung dose due to deposited thoron decay products support the continued use (see annex E of the UNSCEAR 2006 Report [U1]) of a conversion factor of 40 nSv/(Bq h m^{-3}) EEC.

39. For the present annex, most countries would probably have estimated doses on the basis of ICRP dosimetric factors developed after ICRP Publication 60 [I7, I47]. The ICRP is currently reviewing its biokinetic and dosimetric models, which will certainly influence dose estimation for future evaluations.

II. PUBLIC EXPOSURE

40. Public exposure has been evaluated by the Committee for two broad classes: exposure to natural radiation sources and exposure to man-made sources. In previous reports, these two classes were usually described in separate annexes. In this annex, exposures to these two types of source are considered together. Exposures to man-made sources from peaceful and from military uses of nuclear energy are described separately.

41. The data used in this section have been obtained in the same way as for previous UNSCEAR reports, i.e. from the UNSCEAR Global Survey on Public Radiation Exposures, conducted by means of questionnaires distributed to member States by the UNSCEAR Secretariat, and from the published scientific literature. There are many uncertainties associated with the information provided here, owing to the different ways in which countries collect, analyse and manage their own data. These uncertainties reflect differences in the methodologies for sampling, measuring, treating and reporting the data, as well as differences in assessment approaches, for example the use of different dose conversion factors. The Committee recognizes that there is a need to establish standard methodologies to be used worldwide in order to improve the comparison and manipulation of reported data and therefore to be able to draw more reliable conclusions.

A. Natural sources

42. Human exposure to natural radiation sources has always existed. The earth has always been bombarded by high-energy particles originating in outer space that generate secondary particle showers in the lower atmosphere. Additionally, the earth's crust contains radionuclides. For most individuals, exposure to natural background radiation is the most significant part of their total exposure to radiation. Radon is usually the largest natural source of radiation contributing to the exposure of members of the public, sometimes accounting for half the total exposure from all sources [W6].

1. Cosmic radiation

43. Cosmic radiation can be divided into different types according to its origin, energy and type, and the flux density of the particles. When only the types important for exposure of humans are taken into account, there are three main sources of such cosmic radiation: galactic cosmic radiation, solar cosmic radiation and radiation from the earth's radiation belts (Van Allen belts) [S30].

44. Besides the shielding provided by the earth's magnetic field, which is discussed in section II.A.1(c) below, life is shielded against this radiation by an air layer of approximately 10,000 kg/m^2 (1,000 g/cm^2), which is comparable to a 10 m thick water layer. As a result, at sea level the cosmic radiation contributes about 10% of the total dose rate from natural radiation to which human beings have always been exposed. However, at higher altitudes in the atmosphere or in space, cosmic rays constitute the dominant radiation fields [H20].

45. These cosmic rays interact with the nuclei of atmospheric constituents to produce a cascade of interactions and secondary reaction products that contribute to cosmic ray exposures. These decrease in intensity with increasing depth inside the atmosphere, from aircraft altitudes to ground level. The cosmic ray interactions also produce a number of radioactive nuclei known as cosmogenic radionuclides. The cosmogenic radionuclide most relevant to public exposure is ^{14}C.

(a) Galactic cosmic radiation

46. Galactic cosmic rays (GCRs) arise from sources outside the solar system, from deep space. The GCRs incident on the upper 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 (85.5% of the flux) and alpha particles (~12%), with the remainder being heavier nuclei (~1%) up to that of uranium [S30, U3].

47. These primary cosmic particles have an energy spectrum that extends from 10^8 eV to more than 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 in electronvolts. Above that point, known as the "knee", the spectrum steepens to a power of –3. The highest energy measured thus far is 3.2×10^{20} eV, which was inferred from ground measurements of the resulting cascade interactions in the atmosphere [U3].

48. It is thought that all but the highest-energy cosmic rays reaching the earth originate within our own galaxy. The sources and acceleration mechanisms that create cosmic rays are uncertain, but one possibility (substantiated by measurements from a spacecraft) is that the particles are energized by shock waves expanding from supernovas. The particles are confined and continually deflected by the galactic magnetic field. Their flux becomes isotropic in direction and is fairly constant in time [U3].

49. Above 10^{15} eV, protons begin to escape galactic confinement. This leaves relatively higher proportions of heavier nuclei in the composition of cosmic rays above this energy level. Protons with energies of greater than 10^{19} eV would not be significantly deflected by the intergalactic magnetic field. The fact that the flux of protons of such high energy is also isotropic and not aligned with the plane of the galactic disc suggests that the protons are probably of extragalactic origin. Only astrophysical theories can suggest the origins of these ultra-high-energy cosmic rays [U3].

50. The GCR fluence rate varies with solar activity, being lower when solar activity is higher. The spectrum of GCRs also changes with solar activity; when solar activity is higher, the maximum of the energy spectrum is shifted to higher energies. GCR particles have to penetrate the earth's magnetic field; because of this, a geomagnetic cut-off exists, which is much more important close to the equator than at the geomagnetic poles. The cut-off is characterized by a "rigidity", R_c. Rigidity is defined as the momentum of the cosmic ray particle divided by its charge. Owing to this influence, the number of particles penetrating the atmosphere is higher close to the earth's poles and their spectrum there is softer. Because of this, the effect of solar activity is relatively more important close to the geomagnetic poles [S30].

(b) Solar cosmic radiation

51. Another component of cosmic rays is generated near the surface of the sun by magnetic disturbances. Solar cosmic radiation (SCR) originates from solar flares when the particles produced are directed towards the earth. These solar particle events are comprised mostly of protons (~99% of the flux), with energies generally below 100 MeV and only rarely above 10 GeV. These particles can produce significant dose rates at high altitudes, but only the most energetic contribute to doses at ground level.

52. Solar particle events, in addition, can disturb the earth's magnetic field in such a way as to change the galactic particle intensity. These events are of short duration, typically a few hours, and are highly variable in their strength. They have a negligible impact on long-term doses to the general population. A long-term forecast of solar flares in terms of either intensity or energy spectrum is not possible. Solar flares are more frequent at periods of maximum solar activity, with the largest at the end of such periods. The geomagnetic field also influences the penetration of SCR to the earth's surface. Because of the lower energies, this influence on SCR is much more important than that on GCRs [S30, U3].

53. The most significant long-term solar effect is the 11-year solar activity cycle, which generates a corresponding cycle in total cosmic radiation intensity. Historical solar cycles are shown in figure I. The periodic variation in solar activity produces a similar variation in the solar wind, which is a highly ionized plasma with an associated magnetic field whose varying strength 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. An example of the effect of solar modulation on dose rate at aircraft altitudes is shown in figure II.

(c) Van Allen radiation belts

54. The Van Allen radiation belts are formed through the capture of protons (mainly) and electrons by the earth's magnetic field. The proton energy can reach several hundred megaelectronvolts; the electron energy can reach only a few megaelectronvolts and the electrons' penetration is therefore limited. There are two van Allen radiation belts, an internal one centred at about 3,000 km and an external one centred at about 22,000 km from the earth's surface. The daily equivalent dose to the skin in the internal belt could reach several tens of sieverts for protons and several thousands of sieverts for electrons. The internal radiation belt descends rather close to the earth's surface in the region called the South Atlantic Anomaly, which is centred at about 800 km east of Porto Alegre, Brazil [S30].

(d) Effects of latitude and altitude

55. *Latitude effects.* The earth's magnetic field reduces the intensity of cosmic radiation reaching the upper atmosphere. The shape of the earth's magnetic field is such that only particles of higher energies can penetrate at lower geomagnetic latitudes. This produces the "geomagnetic latitude effect", with intensities and dose rates minimal at the equator and maximal near the geomagnetic poles. The latitude effect at 20 km altitude is shown in figure III.

56. Near the earth, the geomagnetic field acts as a separator of the incident cosmic particles according to their energy (in reality, according to their rigidity). The relationship between particle energy and rigidity, which defines the threshold below which particles are unable to reach a particular location because of the effective shielding by the geomagnetic field [B23], is:

$$E = \sqrt{(RZe / A)^2 + m^2} - m$$

where E is the energy per nucleon in GeV, R is the rigidity in GV, Ze is the nuclear charge, A is the atomic weight and m is the nucleon mass in GeV [O1]. For highly energetic protons, the particle energy and rigidity are quite similar. Each geomagnetic latitude may be characterized by a cut-off rigidity, such that particles with less rigidity cannot arrive at this latitude. The cut-off rigidity (R_c) is given by:

$$R_c = 14.9 \cos^4(\lambda)$$

where λ is the geomagnetic latitude. Equatorial latitudes are the most protected regions. Only particles with rigidities greater than 15 GV and protons with energies of greater than 14 GeV are able to reach the equatorial regions [B14].

57. *Altitude effects.* 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. Neutrons, because of their longer mean free path, dominate the nucleonic component at lower altitudes. As a result of the various interactions, the neutron energy distribution peaks at between 50 and 500 MeV. A lower energy peak, at around 1 MeV, is produced by nuclear de-excitation (evaporation). Both components are important for the assessment of cosmic ray exposures.

58. Pions generated in nuclear interactions are the main source of other components of the cosmic radiation field in the atmosphere. Neutrally charged pions decay into high-energy photons; these produce high-energy electrons that in turn produce more photons and so on, resulting in the "electromagnetic" or "photon/electron" cascade. Electrons and positrons dominate the charged particle fluence rate at middle altitudes. 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 that are generated along their path.

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

(e) Exposure to cosmic radiation

60. *Exposures at ground level.* At ground level, muons (with energies mainly of between 1 and 20 GeV) constitute the dominant component of the cosmic ray field. They contribute about 80% of the absorbed dose rate in free air arising 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 the "soft" component, respectively, with reference to the difference in their penetrating power, the electrons being much more readily absorbed by any shielding. As altitude increases, electrons become more important contributors to the dose rate.

61. 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. Considering the population distribution with latitude, an average dose rate in free air at sea level of 31 nGy/h has been adopted by the Committee [U3]. This figure also takes into account the variability due to the solar cycle, estimated to be about 10%. The population distribution of the effective dose rates outdoors at sea level due to the ionizing component of cosmic rays is shown in table 4. The worldwide population considered was 4×10^9 persons [U3]. Because the main contributors to human exposure at ground level are muons, a radiation weighting factor of 1 is assumed, leading to a worldwide average annual effective dose at sea level of about 0.27 mSv.

62. The ionizing component is, however, strongly dependent on altitude. For the same latitude, a variation by a factor of about 4 in the absorbed dose rate in free air was measured in China between sea level and 4,000 m altitude in Tibet [W2]. Dose rates in Switzerland were estimated to be in the range 40–191 nSv/h, with an average value of 64 nSv/h. Combining the results for dose rates with population density, the average per caput dose rate in Switzerland was estimated to be 46 nSv/h [R23]. Estimates of cosmic ray dose rates at elevations above sea level are made using a procedure published by Bouville and Lowder [B45]:

$$\dot{E}_1(z) = \dot{E}_1(0)\left[0.21\, e^{-1.649\, z} + 0.79\, e^{-0.4528\, z}\right]$$

where $\dot{E}_1(0)$ is the dose rate at sea level and z is the altitude in kilometres. Some two thirds of the world population lives in coastal regions, but because dose rates increase with altitude, the dose rates of populations at high altitudes contribute proportionately more to the weighted average. For the directly ionizing and photon component, the population-weighted average dose rate is 1.25 times that at sea level. Using a shielding factor of 0.8 and an indoor occupancy fraction of 0.8, the worldwide average annual effective dose due to the ionizing component of cosmic radiation is estimated to be about 0.28 mSv.

63. For the neutron component, both latitude and altitude strongly affect exposure rates. A latitude-averaged fluence rate at sea level of 130 m^{-2} s^{-1} for latitude 50° N has been derived. The effective dose rate obtained, applying a weighting factor for the neutron fluence energy distribution of 0.02 pSv/m^2, is 9 nSv/h. The shape of the neutron energy spectrum at habitable altitudes is considered to be relatively invariant, and therefore it is expected to be generally valid to use a simple coefficient to convert fluence to effective dose (isotropic). On this basis, the annual effective dose at sea level and at 50° latitude due to neutrons is estimated to be 0.08 mSv.

64. Neutrons arise from collisions of high-energy protons within the upper atmosphere. 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. Florek et al. [F11], quoting results of the Los Alamos LAHET code system calculation, suggest that the equatorial neutron fluence rate at sea level is 20% of the polar fluence rate and that the fluence rate at 50° latitude is 80% of the polar fluence rate. The world population-weighted average effective dose rate at sea level due to cosmic ray neutrons thus determined is 5.5 nSv/h or 0.048 mSv/a [U3]. The population distribution for the effective dose rates outdoors at sea level due to the neutron component of cosmic rays is also shown in table 4.

65. For the neutron component of cosmic rays, there is also a substantial altitude effect. Bouville and Lowder [B45] used both measurements and calculations to derive expressions of the altitude dependence at habitable elevations around the world:

$$\dot{E}_N(z) = \dot{E}_N(0)\, b_N\, e^{az}$$

where $\dot{E}_N(0)$ is the effective dose rate at sea level due to neutrons:

$b_N = 1$ and $a = 1\ km^{-1}$ for $z < 2$ km;

$b_N = 2$ and $a = 0.7\ km^{-1}$ for $z > 2$ km [U6].

66. Combining these altitude–dose relationships with their analysis of the distribution of the world population with altitude, these investigators derived estimates for the population-weighted average dose rate due to neutrons as 2.5 times the value at sea level. Using a shielding factor of 0.8 and an indoor occupancy fraction of 0.8, the world average annual effective dose due to the neutron component of cosmic radiation is estimated to be 0.1 mSv. The population-weighted average annual doses for each hemisphere and for the world are summarized in table 5. Overall, the range of average annual effective dose to the world population is 0.3–2 mSv, with a population-weighted average of 0.38 mSv [U3].

67. *Exposures at aircraft altitudes.* Exposure to cosmic radiation increases rapidly with altitude. Persons who fly frequently are exposed to elevated levels of cosmic radiation of galactic and solar origin and to secondary radiation produced in the atmosphere, aircraft structure, etc. The cosmic particle flux depends on solar activity and solar eruptions. The radiation field at aircraft altitudes consists of neutrons, protons, and neutral and charged pions. Neutrons contribute 40–80% of the equivalent dose rate, depending on altitude, latitude and time in the solar cycle.

68. Commercial transport aircraft altitudes are typically 6,100–12,200 m, where the dose rate doubles for every 1,830 m of increased altitude. The aircraft fuselage provides little shielding against cosmic radiation [B43, W5]. Exposures of aircrew are described in section III.B.1 of this annex. The dose received during a particular flight depends on altitude, latitude and flight time. For altitudes of between 9 and 12 km and a latitude of 50° (corresponding to a flight from northern Europe to North America), the dose rate is generally in the range 4–8 μSv/h. Dose rates at lower latitudes are generally lower; hence a dose rate of 4 μSv/h may be used to represent the average dose rate for all long-haul (e.g. trans-Atlantic) flights. For short-haul flights the flight altitude is generally lower, between 7.5 and 10 km. At this altitude, the dose rate is typically 3 μSv/h. These average dose rates include an allowance for the dose received during the climb and descent phases of the flight. A study in the United Kingdom estimated an average per caput dose of about 30 μSv to the United Kingdom population due to radiation exposure during air travel. However, this value cannot be extended to the populations of all countries, because the exposure is strongly influenced by the frequency of air travel, which in turn depends on the country's economic and development level [W6].

(f) Cosmogenic radionuclides

69. The interaction of cosmic radiation with nuclei present in the atmosphere produces elementary particles and also a series of radionuclides. A comprehensive list of cosmogenic radionuclides (with their properties, production rates and average tropospheric concentrations) was included in the UNSCEAR 2000 Report [U3]. Production is greatest in the upper stratosphere, but some energetic cosmic ray neutrons and protons survive into the lower atmosphere, producing cosmogenic radionuclides there as well. Production is dependent not only on altitude but also on latitude, as well as varying with the 11-year solar cycle, which modulates cosmic ray penetration through the earth's magnetic field.

70. Except for ^{3}H, ^{14}C, ^{22}Na and ^{7}Be, which are isotopes of elements with metabolic roles in the human body, the cosmogenic radionuclides contribute little to radiation doses and are of relevance mainly as tracers in the atmosphere and, after deposition, in hydrological systems [U3]. Carbon-14 ($t_{1/2}$ = 5,730 a) arises from the interaction of slow cosmic neutrons with ^{14}N. Transformed into $^{14}CO_2$, it participates in the photosynthetic cycle. Today, the specific activity of ^{14}C is approximately 230 Bq/kg of total carbon, and the content in the human body is about 2,700 Bq, resulting in an average annual individual effective dose of about 12 μSv.

71. The production of ^{14}C from cosmic ray neutrons is relatively constant at an annual rate of 1.4 PBq, resulting in a global atmospheric inventory of 140 PBq [U10]. A best estimate of the specific activity of naturally produced (cosmic ray) ^{14}C prior to industrialization is 222 Bq/kg of total carbon [N7]. The nuclear test explosions from the 1950s and 1960s introduced an estimated 0.35 EBq. This was absorbed into the marine environment with a half-life of about 6 a. The specific activity of ^{14}C from weapons residues is currently about 0.05 Bq/kg in the atmosphere. Releases from nuclear power reactors are also very small. It has been suggested that the addition of $^{12}CO_2$ from the burning of fossil fuels would dilute the naturally produced ^{14}C and that the measurement of the ^{14}C/C ratio could then be used as an indicator of the carbon addition to the planet on a global scale [S44]. Ongoing measurements and recent data available are not conclusive in this respect, as current specific activity levels of ^{14}C are still slightly higher than those observed in 1950 [R18].

72. Tritium ($t_{1/2}$ = 12.3 a) results from the interaction of cosmic rays with nitrogen and oxygen nuclei; the tritiated water produced participates in the water cycle. Its concentration level is about 400 Bq/m^{3} in continental water and 100 Bq/m^{3} in the oceans. On average a human ingests 500 Bq/a, with a resulting average annual dose of 0.01 μSv.

73. Beryllium-7 ($t_{1/2}$ = 53.6 d) has a concentration of 3 mBq/m^{3} in air. It reaches the earth in rainwater, thus contributing to an annual commitment for individuals of approximately 1,000 Bq through the ingestion of fresh vegetables, delivering an annual effective dose of 0.03 μSv.

74. The annual commitment of ^{22}Na ($t_{1/2}$ = 949.7 d) is approximately 50 Bq, but this contributes an annual effective dose of approximately 0.15 μSv, significantly more than for tritium. The radiation exposure of populations due to cosmogenic radionuclides is therefore dominated by the production of ^{14}C and is slightly greater than 12 μSv/a [M22].

2. Terrestrial radiation

75. Naturally occurring radionuclides of terrestrial origin, also termed primordial radionuclides, are present in various degrees in all environmental media, including the human body. Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in sufficient quantity to contribute significantly to population exposure. Exposures to radon have been described in annex E of the UNSCEAR 2006 Report [U1].

(a) Sources of external radiation exposure

76. The main contribution to external exposure comes from gamma-emitting radionuclides present in trace amounts in the soil, mainly ^{40}K and the ^{238}U and ^{232}Th families. Information on outdoor exposure comes from direct measurements of dose rate or from evaluations based on measurements of radionuclide concentrations in soil. The 2004 UNSCEAR Global Survey on Public Radiation Exposures, which also sought information on the numbers of people exposed, has provided information on the distribution of doses according to specified ranges and on the average and range of radionuclide concentrations in soil. Data on absorbed dose rates in air for various countries, including data for high- and low-background areas, are given in table 6.

77. Additional information on both external dose rates and radionuclide concentrations in soil is available in the recent literature, as there has been expanded interest in mapping countrywide exposures. Some data already collected and complementary to earlier reports [U3] are presented in table A-1, with average and maximum values for ^{238}U, ^{232}Th and ^{40}K concentrations in soil shown in figures V–VII. The new data do not affect significantly the current worldwide average values of 33 Bq/kg for ^{238}U, 32 Bq/kg for ^{226}Ra and 45 Bq/kg for ^{232}Th. The average value for ^{40}K, 412 Bq/kg, is also close to the previous value (420 Bq/kg). Although the average concentrations of natural radionuclides in soils are low, there is a large variation, with reported levels of up to 1,000 Bq/kg for ^{238}U, 360 Bq/kg for ^{232}Th and 3,200 Bq/kg for ^{40}K. Therefore, for the purposes of global dose assessment, these data need to be linked with corresponding population distributions.

78. The data on worldwide average outdoor dose rates presented in table 6 confirm the previous [U3] average value of 58 nGy/h. The data available to date on the distribution of the population with respect to the outdoor absorbed dose rates in air due to terrestrial gamma radiation are presented in table 7. The mean value for this distribution is in the range 50–59 nGy/h.

79. Indoor exposures depend on radionuclide concentrations in outdoor soil and in building materials. The relative contribution from each source is highly dependent on the type of house and building material. Information on distributions of indoor exposures derived from direct measurements is not extensive, but these can be assessed on the basis of information on soil, shielding and building material, and then linked with the number of people exposed in order to estimate population exposures. Extensive information is being gathered worldwide regarding activity concentrations in building materials. New information, complementing that in reference [U3], is given in table A-2. In general, average

values for natural radionuclides are higher in most building materials than in soils, with granite and marble presenting the highest average values for ^{226}Ra (77 Bq/kg) and with granite also presenting the highest average values for ^{232}Th (84 Bq/kg) and ^{40}K (1,200 Bq/kg).

80. Table 6 also confirms the previous value of 1.4 for the ratio of indoor to outdoor exposure rates. Therefore the value for the worldwide average indoor absorbed dose rate in air of 84 nGy/h given in reference [U3] is considered to be still valid. Using 0.7 Sv/Gy as the conversion coefficient from absorbed dose rate in air to the effective dose received by adults, and 0.8 for the indoor occupancy fraction, the average annual effective dose due to external exposure to natural terrestrial sources of radiation is 0.48 mSv, with 0.41 mSv related to indoor occupancy and 0.07 mSv to outdoor occupancy. The average levels for countries are mostly in the range 0.3–0.6 mSv.

81. Equation (3) is useful for calculating average outdoor gamma ray exposure rates from global soil concentrations in table A-1. These average and standard error soil concentrations are: ^{40}K: 400 ± 24 Bq/kg; ^{238}U: 37 ± 4 Bq/kg; and ^{232}Th: 33 ± 3 Bq/kg. The table 1 DCF_{soil} coefficients are 0.0417, 0.462 and 0.604 nGy/h per Bq/kg, for ^{40}K, ^{238}U and ^{232}Th, respectively, and the calculated outdoor terrestrial gamma ray exposure rate is estimated as 54 nGy/h. Using 0.7 Sv/Gy as the conversion coefficient from absorbed dose rate in air to the effective dose received by adults, and 0.2 for the outdoor occupancy fraction, the average annual effective dose due to external exposure to natural terrestrial sources of radiation is 0.066 mSv, in close agreement with the estimated average based on absorbed dose rate measurements. For indoor environments, the estimated dose rate is then 0.43 nGy/h. This can be taken as the contribution from the soil material, and the difference between this value and the worldwide average value can mainly be attributed to the contribution from building materials to indoor exposure.

82. Figure VIII shows the distribution of population with respect to external dose rates outdoors for 38 countries. From the left-hand figure, it can be seen that the largest population fraction is in the 50–59 nGy/h range, confirming the previous estimates for external dose rate outdoors. From the right-hand figure, it can be seen that about 90% of the world population for which data have been provided for this annex falls within the range of about 20 to over 100 nGy/h. The Committee has decided to revise the range previously adopted for external dose rate (0.3–0.6 mSv/a) to 0.3–1.0 mSv/a.

(b) Internal exposures due to radionuclides other than radon

83. Internal exposures arise from the intake of terrestrial radionuclides by inhalation and ingestion. Doses due to inhalation result from the presence in air of dust particles containing radionuclides of the ^{238}U and ^{232}Th decay chains. The dominant components of exposure due to inhalation are the short-lived decay products of radon, which because of their significance were considered separately in annex E of the UNSCEAR 2006 Report [U1].

84. The inhalation of natural radionuclides other than radon and its decay products makes only a minor contribution to internal exposure. These radionuclides are present in air because of the resuspension of soil particles. The decay products of radon are present because of radon gas in air. Assuming a dust loading of 50 μg/m^3 and ^{238}U and ^{232}Th concentrations in soil of 25–50 Bq/kg, the concentrations in air would be expected to be 1–2 μBq/m^3, and this is generally what is observed. There is, however, a large variability associated with this value, as local levels may be affected by several factors, such as climate, soil class and concentrations in soil. Other factors affecting the variability of natural radionuclide concentrations in air are the contribution to the dust loading of air from burning fuels, because, while organic content is usually deficient in uranium compared with soil, fly ash contains much higher concentrations of uranium. In addition, at coastal locations, concentrations of uranium in air may be an order of magnitude lower than in continental or industrialized areas inland.

85. In the UNSCEAR 1993 Report [U6], representative values of the concentrations of terrestrial radionuclides in air were selected. Because the database has changed very little, most of those values are still considered valid. The highest concentration, 500 μBq/m^3, is for ^{210}Pb. The concentrations of the other radionuclides are: 50 μBq/m^3 for ^{210}Po; 1 μBq/m^3 for ^{238}U, ^{226}Ra, ^{228}Ra and ^{228}Th; 0.5 μBq/m^3 for ^{232}Th and ^{230}Th; and 0.05 μBq/m^3 for ^{235}U. The age-weighted annual effective dose due to the inhalation of radionuclides from the uranium and thorium series in air was estimated to be about 0.006 mSv [U3].

86. Doses from ingestion are mainly due to ^{40}K and to the ^{238}U and ^{232}Th series radionuclides present in foods and drinking water. The ingestion of natural radionuclides depends on the consumption rates of food and water and on the radionuclide concentrations. Reference food consumption profiles were derived in the UNSCEAR 2000 Report [U3] and are summarized in table 8. Although the tabulated values are in reasonable agreement with other assessments, substantial uncertainties are implicit in their mode of derivation. Moreover, there are large deviations from this profile for various parts of the world because of differences in dietary habits (for example, milk consumption in Asia and leafy vegetable consumption in Africa are lower). The values in table 8 are to be seen only as reference values; actual values vary widely.

87. The concentrations of naturally occurring radionuclides in foods vary widely because of differences in the background levels in soil, the climate and the agricultural conditions that prevail. There are also differences in the types of local food included in categories such as vegetables, fruits and fish. It is therefore difficult to select reference values from the wide ranges of concentrations reported.

The relevance of specific nuclides to the dose depends on the soil composition, and the ratio of uranium to thorium varies from place to place, as shown in figure IX, leading to large variations in the activity ratios between their daughters, e.g. the ^{226}Ra/^{228}Ra ratio. The soil type also affects the retention/mobility of radionuclides in soil and their availability to plants [F17]. The annual intakes of radionuclides from the uranium and thorium series in various countries have an approximately log-normal distribution for each radionuclide and span an order of magnitude. The highest concentrations are for ^{210}Pb and ^{210}Po, which have similar distributions. The lowest concentrations are for ^{230}Th and ^{232}Th, which also have similar distributions, while ^{226}Ra and ^{238}U have intermediate concentrations [U3].

88. Because drinking water is important for the intake of uranium and radium radionuclides, it is necessary to ascertain that this source of ingestion intake has been included in dietary intake estimates. The radionuclide contents in natural water and tap water have been reviewed; spring and mineral water have also been of particular interest. Some new data are available and are summarized in table A-3. Worldwide there is a huge variability in concentrations of natural radionuclides in drinking water. Figure X shows the ranges cited by countries for uranium. There is a variation of about eight orders of magnitude among individual water samples. The consequence of such variation is a high variability in the values for global per caput doses. Figure XI shows the distribution of average values for ^{238}U given in table A-3, where there is a variation of three orders of magnitude among worldwide average values.

89. Several authors have emphasized the disequilibrium between ^{234}U and ^{238}U in water. A survey of levels in natural bottled water from northern Italy has shown ratios of ^{234}U/^{238}U concentrations ranging from 0.99 to 1.63 [R21]. A survey of water from the Euphrates River showed ratios in the range 0.75–3.11. A survey that included measurements of tap and well water in the United States showed ratios in the range 1.16–2.92. At one location, a value of 5.5 was observed; at another location, a ratio of 0.37 was observed for spring water [F9]. Average ratios are of the order of 1.5, which means that doses due to water ingestion for ^{234}U are underestimated if they are based on ^{238}U measurements alone assuming radioactive equilibrium.

90. Uranium is retained in the body primarily in the skeleton. It has been found that the concentrations in various types of bone (vertebrae, rib and femur) are approximately similar but show a large variability among different countries and different age groups [F9]. An earlier estimate was that 70% of the body content of ^{238}U was in the bone. Assuming the reference concentration of ^{238}U in bone to be 100 mBq/kg, this would correspond to 500 mBq in the skeleton and 710 mBq in the whole body. The average concentration in soft tissues would then be 3 mBq/kg, with higher concentrations measured in the lungs and kidneys. Reference values for concentrations in tissues are presented in table 9. The distributions of measured values in bone for radionuclides of the uranium and thorium series are presented in figure XII [U3].

91. Following intake by ingestion and inhalation, thorium is deposited mainly on bone surfaces, where it is retained for long periods. Metabolism models assume that 70% of the body content of thorium is retained in the skeleton. From the reference concentrations given in table 9 and assuming the cortical and trabecular bone masses to be 4 kg and 1 kg, respectively, it may be estimated that the body burdens are 210 mBq of ^{230}Th and 70 mBq of ^{232}Th. The distributions of uranium and thorium concentrations in bone are typically log-normal within a country. The combined values for various countries have an approximately log-normal distribution and extend over an order of magnitude, with the variability being caused primarily by differences in intake of the radionuclides in food and water. The distributions for ^{238}U and ^{230}Th concentrations in bone are similar; somewhat lower concentrations are reported for ^{232}Th. As these data are limited, they remain to be confirmed as truly representative.

92. Radium is retained primarily in bone, and concentrations have been measured in many countries. Lead also accumulates in bone. By contrast, polonium is distributed mainly in soft tissues. Even in the absence of direct intake, both lead and polonium would still be present in the body because of the decay of ^{226}Ra, but direct dietary intake is of the greatest importance in establishing the content in the body. Early measurements showed the ^{210}Pb/^{210}Po concentration ratio to be 0.8 in bone, 0.5 in the lungs and generally unity in other soft tissues. Some enhancement of ^{210}Po in the liver and kidneys has also been observed. 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 three times that of non-smokers.

93. The published measurements of ^{210}Po in human tissue were summarized and the averages reported by Fisenne [F9]. The total concentration in the organs and the annual organ equivalent dose are shown in figure XIII. The various measurements of ^{210}Po in tissue were from Finland, Japan, the Russian Federation, the United Kingdom and the United States. The published measurements in bone were reported from the same countries and additionally from France, Germany, New Zealand and Poland.

94. The annual effective dose due to radionuclides from the uranium and thorium series in tissue at the reference concentrations in the human body was evaluated in the UNSCEAR 2000 Report [U3] as 0.12 mSv. Evaluation of the internal doses due to ingestion of radionuclides from the uranium and thorium series was also reviewed in the UNSCEAR 2000 Report [U3] using the reference values of concentrations in foods and worldwide average consumption rates for infants, children and adults. For adults, the estimated annual dose is 0.120 mSv. These two results are in close agreement. The main contributor to this dose is ^{210}Po.

95. 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 0.0117% for ^{40}K in natural potassium, a specific activity for ^{40}K of 2.6 × 10^8 Bq/kg and a rounded dose conversion coefficient of 0.003 mSv/a per Bq/kg, the annual equivalent doses in tissues from ^{40}K in the body are 0.165 and 0.185 mSv 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.

96. The total annual effective dose due to inhalation and ingestion of terrestrial radionuclides is assessed to be 0.29 mSv, of which 0.17 mSv is due to ^{40}K and 0.12 mSv to the long-lived radionuclides in the uranium and thorium series.

(c) Inhalation of radon

97. Exposure to radon has been described in annex E of the UNSCEAR 2006 Report [U1]. The Committee has decided to keep its previous estimates of 1.15 mSv and 0.1 mSv for the average annual per caput effective doses due to natural sources of radon and thoron, respectively [U3]. This represented approximately one half of the estimated dose due to all natural sources of ionizing radiation. Combining the data presented in table 1 of annex E of the UNSCEAR 2006 Report [U1] with recently updated information available from the European Commission [D14], the distribution of average radon concentration indoors among countries is shown in figure XIV. The average values for individual countries ranged from 9 to 184 Bq/m^3. The currently available data fit a log-normal distribution ($r = 0.98$) with a geometric mean of 45 Bq/m^3 (similar to the previous estimated value of 40 Bq/m^3) with a geometric standard deviation of 2.1.

(d) Areas with elevated radiation levels due to natural sources

98. Several areas of the world are known to have levels of exposure due to natural sources of radiation that are in excess of those considered to be “normal background”. There is no specific value of dose rate or of activity concentration in the environment that defines what constitutes an “enhanced natural radiation area” (ENRA). Some references cite criteria such as a dose rate of greater than 300 nGy/h or an indoor ^{222}Rn concentration in air of the order of 150 Bq/m^3. However, these are not adequate reference levels, because situations exist in which those levels are clearly not applicable (for example in areas with high levels of exposure to cosmic radiation; areas where the exposure is due to high levels of ^{226}Ra and/or ^{222}Rn in water, often called “dynamic ENRAs”; or areas where the total dose, including external and internal exposures, is higher than the usual range).

99. Despite the lack of specific criteria, such areas are of interest mainly because they have been used to illustrate high chronic levels of radiation to which human beings are currently exposed and to consider the relevance of such exposures to epidemiological studies on the effects of low-dose and low-dose-rate exposures. Some of these areas are listed in table 10. The origins of the higher exposures and the characteristic levels that define the area as an ENRA are included.

100. The results of this preliminary literature review indicate that public exposure to natural radiation may be of special concern in ENRAs. However, most of the currently available data fail to give the number of persons involved; the information provided on “dose distributions” typically relates only to the exposure fields and not to population. Only three countries—the Czech Republic, the Islamic Republic of Iran and Spain—had responded by April 2006 with information on the population dose distribution; their data for high-background areas are presented in table 11.

3. Summary on exposures to natural radiation sources

101. Although it is recognized that a large effort has been made to map natural radiation sources (mainly radon, the most relevant radionuclide), the available information cannot be correlated with other exposure pathways for which data are not yet presented in such a degree of detail. The countrywide radon maps already available for most European countries [D14] and for Costa Rica [M25, M30] have been provided to UNSCEAR. In addition, distributions of external dose rates are available for some countries, and for the United States, the distributions of uranium, thorium and potassium are available on countrywide maps [U28]. Knowing the cumulative exposure to different sources on a geographical basis could change the current exposure assessment and lead to more precise estimates of the distribution of exposures worldwide. This aspect will be further discussed in the conclusion of section II.E of this annex. The new information available does not currently allow estimates to be made to characterize worldwide average exposures to natural radiation that are significantly more accurate than those provided in previous reports. It was therefore decided to maintain the same numerical values but to slightly extend some ranges (see table 12).

102. The values in table 12 are to be seen as “average” values, but it should be kept in mind that the worldwide exposure to each pathway usually follows a log-normal distribution. Therefore they should be seen only as reference values and not as specific to any particular place. In fact, as some exposure pathways are correlated with each other, the actual distribution may vary significantly among different places.

103. Besides the large variability in environmental concentrations and in population habits throughout the world, the rate at which dose is accumulated may also vary as the

individual ages. A study performed in the United Kingdom found that inhalation doses for infants and children are within 20% of those for an adult, while terrestrial gamma rays give effective doses for infants and children that are larger than those for adults by about 30% and 15%, respectively. The variation of ingestion doses between individuals is comparable to that of doses from terrestrial gamma rays [K8].

104. Regarding public exposure during aircraft flights, although the estimated doses received by passengers during individual flights are low, collective doses may be quite high because of the huge number of flights worldwide. In addition, doses to specific individuals who fly frequently may make an appreciable contribution to their overall exposure to natural sources.

B. Enhanced sources of naturally occurring radioactive material

105. Activities related to the extraction and processing of ores can lead to enhanced levels of naturally occurring radioactive material (NORM) in products, by-products and wastes. An assessment of the situation related to sites with technologically enhanced levels of NORM has been performed in countries of the European Union [V4]. Nine important categories were identified. This annex uses a similar approach and discusses the disposal or use of waste within the category that generates the waste. Eight of the categories are addressed here: uranium mining and milling; metal mining and smelting; phosphate industry; coal mines and power generation from coal; oil and gas drilling; rare earth and titanium oxide industries; zirconium and ceramic industries; and applications using natural radionuclides (typically radium and thorium). The ninth category (disposal of building material, which is recognized to be of little concern) is not considered here.

106. At least for Europe, the first three categories represent the major contaminating industries with respect to the overall amount of waste produced, though radionuclide levels in products and/or waste from the second three categories may be particularly elevated [V4]. Apart from uranium mining and milling, applications using natural radionuclides and, more recently, zirconium industries, activities related to the other categories have generally not been fully evaluated from the perspective of public exposure, though attempts to characterize them according to the radionuclide content of materials have been made in previous UNSCEAR reports [U3, U6].

107. For past industries, the main concern is related to the sites where residues were left before present standards of radiological protection were established. Many of these sites have already been cleaned up, and residual doses and/or radionuclide contents are known. For industries currently in operation, the main focus relates to effluents, releases from waste and the relevant exposed groups of the population. Descriptions of environmental liabilities (such as waste rock piles, waste basins and contaminated areas) can be a valuable starting point for a database that can be used for future assessments of exposure and dose. The features of uranium mining and milling and the related exposures are described below, together with other fuel cycle exposures, in the section on exposures due to nuclear power production, section III.C.1 of this annex.

1. Metal mining and smelting

108. The metals considered include aluminium, copper, iron (and steel), lead, niobium, tin, zinc, gold and others. The NORM activity in feed material for metal smelting is generally low, and the same is true for most slags and other waste. The concentration of radionuclides in intermediary products and wastes, however, will depend on the content initially present in the ore and on the type of process used to extract the metal. In the case of thermal processes, a large part of the radionuclide content will be concentrated in metallic slags, as, for example, in those from the tin industry [V6].

109. The activity levels in the niobium industry may be high, with pyrochlore containing 10,000–80,000 Bq/kg of ^{232}Th [V4]. In one niobium facility in Brazil, activity levels in waste ranged up to 200,000 Bq/kg of ^{228}Ra (in barium sulphate) and 117,000 Bq/kg of ^{232}Th (in the slag). Exposure of the public due to feedstock or the metal products is not expected. The main pathways for public exposure include contamination of groundwater with radium isotopes and external exposure to slag with high thorium content (if this is not disposed of in an acceptable manner) [I22, P11]. Exposures due to inhalation of resuspended material from tin and niobium slag used as landfill have also been cited [V4].

110. In South Africa, the gold deposits from deep underground mines have low-grade uranium associated with them. Since 1952, 170,000 t of U_3O_8 have been recovered as a by-product of gold mining. Some 6 billion tonnes of mining tailings, containing about 500,000 t of uranium and 200 kg of ^{226}Ra, have been deposited. New tailings are being deposited at a rate of 86 million tonnes annually. Elevated ^{226}Ra concentrations, up to 1.7 Bq/L, have been observed in the discharges. Annual doses to nearby populations have been estimated as up to 0.04 mSv due to the ingestion of water and up to 0.086 mSv due to the ingestion of fish. Annual doses due to ingestion of land food products are much lower, ranging up to about 0.002 mSv. Annual doses to the public due to the inhalation of radon and of dust from the tailings piles have been estimated to be about 0.04 and 0.02 mSv, respectively [W18].

2. Phosphate industry

111. Phosphate rock is used extensively, firstly as a source of phosphorous for fertilizers and secondly for making phosphoric acid and gypsum. Ores typically contain about

1,500 Bq/kg of uranium and radium, although some phosphate rocks contain up to 20,000 Bq/kg of U_3O_8 [P7]. In general, phosphate ores of sedimentary origin have higher concentrations of nuclides of the uranium family. The magmatitic minerals, such as those from Kola (Russian Federation) and Phalaborwa (South Africa), present lower concentrations of nuclides of the uranium family and higher concentrations of nuclides from the thorium family, although the total activity is lower than that from sedimentary minerals [V6]. In 90% of cases, the ore is treated with sulphuric acid. The fertilizers become somewhat enriched in uranium (up to 150% relative to the ore), while 80% of the ^{226}Ra, 30% of the ^{232}Th and 5% of the uranium are left in the phosphogypsum.

112. The processing of phosphoric rocks may generate gaseous and particulate emissions that contain ^{238}U and ^{226}Ra; when discharged to the environment, these nuclides lead to radiation exposure of the population. Local dump sites for phosphogypsum are usually not protected from rainfall and become hydraulically connected to surface waters and shallow aquifers [V4]. The use of phosphate fertilizers in agriculture and of gypsum in building materials is a further source of possible exposure of the public [P7]. Elevated radon exposure of the public can further be expected in sites being developed for housing [V4].

113. For somewhat more than half a century, phosphate ores of marine origin containing ^{226}Ra have been processed in Belgium to produce calcium phosphate for use in cattle fodder. The wastewaters are discharged into two small rivers, one of which is the Laak. Enhanced concentrations of ^{226}Ra are observed along the riverbank, mostly confined to a 10 m strip along both sides of the river, including flooding zones. As of 1999, no dwellings had been built on top of these higher-activity areas and no crops for direct human consumption were grown there, so no immediate threat to the population existed [P6].

114. Prior to 1990, France discharged about 3 million tonnes of phosphogypsum into the Baie de la Seine. After 1990, waste was stored on land. In the United Kingdom, the annual discharge of ^{210}Po exceeded 0.5 TBq in the period 1980–1983. In 1993, about 10 million tonnes of phosphogypsum waste were generated within the European Union, with 15% being recycled (for example as building materials), 25% discharged to sea and 60% stored on land [E16]. The import of phosphate ore to European Union countries decreased by about a factor of 2 between 1985 and 1992, reflecting an increasing tendency to import phosphoric acid directly rather than import the ore itself. This reduced the disposal of uranium to sea, bringing about a large decrease in environmental concentrations of ^{210}Po, but in the process transferring the waste disposal problem back to the ore-producing countries such as Morocco [E13].

115. Phosphate rock can be melted in a furnace at high temperature with sand, iron oxide and coal for the production of elemental phosphorus. The residual solids in the furnace contain ferrophosphorus and calcium silicate, also known as slag [I22]. The slag, which contains ^{226}Ra concentrations ranging from 750 to 1,100 Bq/kg, has been used as construction material in the United States, specifically in communities in south-eastern Idaho. Surveys for external exposure were conducted in 1,472 residences. It was estimated that fewer than 12% of the residences in Soda Spring contained slag, while in Pocatello and Fort Hall no houses were found containing the slag. The highest individual dose rate was estimated to be 1.3 mSv/a, and only nine individuals were identified as receiving more than 1 mSv/a above background. A significant fraction of the public roads, however, contained slag: 27% in Pocatello, 23% in Soda Spring and 20% in Fort Hall [A13].

3. Coal mining and power production from coal

116. The average specific activity of both ^{238}U and ^{232}Th in coal is generally around 20 Bq/kg (range 5–300 Bq/kg). Coal mines in Freital, Germany, which have uranium concentrations of 15,000 Bq/kg coal, are an exception [V4]. During the burning of coal, the organic compounds are converted into gases (water vapour and carbon dioxide), while the inorganic elements, which include the significant naturally occurring radionuclides, are concentrated in the ashes [V6]. In general, the radionuclide enhancement factor in ash is about 10. Leaching from fly ash is low, and therefore there are few restrictions on the use of fly ash in landfill and road construction. The use of fly ash for building construction, however, results in radiation exposure from both direct irradiation and radon exhalation. Dumping fly ash may increase the radiation level around the dump site. The most significant exposure pathways are ingestion and inhalation of the isotopes ^{210}Pb and ^{210}Po [V4]. However, recent studies in the United Kingdom confirm earlier indications that the incorporation of pulverized fuel ash into building materials is unlikely to contravene either current national legislation or the European Union directive [H17, H18].

117. The content of natural uranium in coal from Brazil ranges from 30 to 2,000 parts per million. It is estimated that the burning of 2.2×10^6 t of coal per year discharges about 270 t of U_3O_8 equivalent into the environment [P7].

118. About 50 underground coal mines are located in the Upper Silesian Coal Basin, in the southern part of Poland. The total water outflow from these mines is about 800,000 m^3/d. Waters with high radium content (up to 390,000 Bq/m^3) are found mainly in the southern and central parts of the basin where a thick layer of impermeable clay overlies the coal seams. Radium-bearing waters from coal mining are discharged into surface settling ponds and later into rivers. In some cases, radium isotopes are co-precipitated with barium in these ponds or are absorbed on bottom sediments [C7, W19].

119. Slags derived from coal mined in the vicinity of the town of Tatabánya in Hungary have elevated concentrations

of ^{226}Ra (850–2,400 Bq/kg). The slag has been used as filling and insulating material for building houses, blocks of flats, schools and kindergartens, and to fill playgrounds and roads [N13].

4. Oil and gas drilling

120. During the extraction of oil and natural gas, the natural radionuclides from underground formations are brought to the surface. Elevated activities of ^{226}Ra and ^{228}Ra present in NORM are often released by oil and gas industries, particularly in production waters. During the extraction process, radium is co-precipitated along with barium and strontium. A portion of the radium is deposited during the scale formation process and another portion is discharged to the sea with effluents. Mean concentrations in wastewater are 2 and 2.3 Bq/L for ^{226}Ra and ^{228}Ra, respectively. Although these high activities of radium are present in production water for some platforms, water and sediments sampled at a distance of more than 250 m from the production site had normal background levels, showing that water mixing sufficed to reduce concentrations in the environment [J2, V6].

121. The most important radionuclides in scales and other precipitates are the isotopes of radium, with specific activities ranging from 100 to 1,000 Bq/kg. Activity concentrations in sludges are typically a factor of 100 lower. Concentrations of ^{210}Pb and ^{210}Po in sludge and scales can vary between 20 and 1,000 Bq/kg [V4]. The sludges on the Bacia de Campos oil platforms in Brazil have about 105,000 Bq/kg (maximum 340,000) of ^{226}Ra and 78,000 Bq/kg (maximum 286,000) of ^{228}Ra [M14].

122. Activity levels in scales are of the same order as those in uranium mill tailings and other materials that are regulated because of their potential for ^{222}Rn release. The ^{222}Rn emanation fraction for pipe scale, however, is generally lower than that for typical mill tailings [W10]. The disposal of scale from oil extraction industry installations and of sludge containing NORM can be of environmental significance, with contamination of land being the major concern. The average radium concentrations in soils sampled at an oilfield contaminated with NORM in eastern Kentucky, United States, were 32,560 ± 340 Bq/kg [R2].

123. Tank battery sites, which separate water and sediment from the oil produced, have historically been used for the initial processing of crude oil. The sediment remaining in the pit is an oily, viscous material often called “sludge”. This sludge can be radioactive if NORM is associated with the matrix. A radiological survey conducted on six previously remediated tank battery sites revealed average gamma radiation exposure rates ranging from 27 to 100 μGy/h [H19]. In older scales, the concentrations of ^{228}Th will have increased because of ingrowth. Scales and sludges, particularly those from gas fields, may also contain relatively high levels of ^{210}Pb and ^{210}Po [E13].

124. Waterborne pathways may make a noticeable contribution to the radiation exposure of persons resident on farmland contaminated with residual NORM arising from crude oil recovery operations. Persons living in such areas would incur external gamma exposure and exposure from radon inhalation [R2]. The exposure from dissolution of ^{226}Ra is increased in cases where contaminated soil is located near seawater [A9].

5. Rare earth and titanium oxide industries

125. Bastnaesite and monazite are the most important minerals containing rare earth metals. Bastnaesite has an activity concentration of 900–1,200 Bq/kg for radionuclides in the ^{238}U decay series and 700–7,000 Bq/kg for radionuclides in the ^{232}Th decay series. Monazite, on the other hand, has an activity concentration of 10,000–50,000 Bq/kg for radionuclides in the ^{238}U series and 5,000–350,000 Bq/kg for radionuclides in the ^{232}Th series. In Europe, minimal amounts of waste are produced by these industries [I22, V4].

126. The Brazilian experience is somewhat different. As a consequence of monazite processing for the production of rare earth chlorides, carried out from 1949 to 1992, basically three different kinds of waste were produced: *(a)* the light-mineral fraction (activity concentration 170–320 Bq/g) from the monazite physical purification; *(b)* “cake II” (average content 20% thorium hydroxide and 1% uranium hydroxides, approximate activity concentration 1,820 Bq/g) from the monazite alkaline digestion; and *(c)* mesothorium cake ($Ba(Ra)SO_4$) (approximate activity concentration 4,360 Bq/g). It is estimated that about 3×10^4 t of cake II and 1×10^5 t of mesothorium cake were produced annually. These wastes and residues were disposed in shallow ground silos or in rubber drums, or were buried in trenches. Areas that used the light-mineral fraction as landfill later had to be decontaminated [L1].

127. Similar situations occurred in the United States, with waste originating from a Rare Earths Facility that operated from 1932 until 1973 to produce rare earths and radioactive elements such as thorium, radium and uranium using an acid leaching process. Production of these elements generated radioactive mill tailings that contained residual levels of thorium, radium and uranium. Over several decades, the mill tailings were available for use as landfill material by residents and contractors. Winds also may have spread some of the mill tailings to nearby neighbourhoods. Clean-up actions were performed in the mid-1980s for approximately 120 residential properties in the West Chicago area in Illinois, and later for more than 2,170 properties (covering approximately 400 hectares (1 ha = 10,000 m^2) in and around West Chicago [E5].

128. For titanium production, activity concentrations in the ore are about 300–600 Bq/kg for the ^{238}U decay series and 35–600 Bq/kg for the ^{232}Th series. Specific activities of radium sulphate precipitates in pigments or scales may

be as high as 400,000 Bq/kg, and ^{228}Th levels may be higher than 1 × 10^6 Bq/kg. Exposure pathways include external irradiation and migration of radionuclides from landfill [V4].

129. Scales formed during titanium dioxide pigment production have ^{238}U series activity concentrations ranging from <10^2 to 1.65 × 10^6 Bq/kg and ^{232}Th series activity concentrations ranging from 4 × 10^3 to 2 × 10^6 Bq/kg (the maximum value could apply equally to ^{228}Ra or ^{228}Th). However, the pigments themselves are essentially free of radioactivity [I22].

130. The use of the ensuing waste can also lead to public exposure. During the production of titanium dioxide, most naturally occurring radionuclides originally present in the ore are precipitated as metallic hydroxides, except for radium isotopes (the radium chlorides remain partially soluble and are discarded with wastewaters) [V6]. The processing of monazite in France for rare earth extraction, beginning in 1976, led to the input of significant quantities of ^{232}Th and ^{228}Ra to La Rochelle Bay, within authorized annual limits of 37 GBq and 74 GBq, respectively. Improved waste treatment beginning in 1990 reduced the annual discharges to about 0.5 GBq of ^{232}Th and 6 GBq of ^{228}Ra [E13].

6. Zirconium and ceramics industries

131. The average activity concentrations in zircon and zirconia, respectively, are 600 and 300 Bq/kg for ^{232}Th, and 3,000 and 7,000 Bq/kg for ^{238}U. Except for refractory bricks, where ^{238}U activity concentrations of 10 Bq/kg have been reported, the activity concentrations in the products are comparable to those in the feed material. Long-lived radioactive dust constitutes the main source of radiation exposure, which is mainly due to thorium in the dust [V4]. The zirconium industry and the industrial uses of zirconium may be a source of occupational exposure; only the reuse of solid waste could possibly lead to public exposure [V6]. Doses from gamma radiation emitted from large stockpiles of zircon sand are mainly an issue for workers, but in principle, individuals outside a zircon milling plant may also receive exposure via this pathway if they are sufficiently close to the facility. The critical group would be individuals working in the industrial area surrounding the plant, with a maximum conservative annual effective dose estimated to be about 200 µSv. Individuals may also receive exposure from material deposited outside the plant by storm water runoff and from the inhalation of airborne dust emitted from stockpiles and openings in the plant buildings. In studies from several countries, applying conservative approaches, the maximum annual effective dose received by an individual outside the facility was estimated to be less than 1 µSv from discharges to water and 56 µSv from emissions to atmosphere. In nearby population centres, the dose was found to be negligible [I41].

132. The activity concentrations of uranium and thorium series radionuclides in spent foundry sands or waste are likely to be of the order of 1,000 Bq/kg or less because of the dilution of zircon with other constituents. It is expected that an annual effective dose of the order of 100 µSv is the maximum that could be received by a member of the public as a result of the disposal of these materials in landfill facilities. For the manufacture of zirconia by fusion of zirconium minerals, the main exposure pathways to members of the public are discharges of radionuclides in liquid effluent (floor washings) and stack emissions, and the migration of radionuclides from the landfill disposal of furnace dust. Concentrations of ^{210}Pb of up to 200,000 Bq/kg and ^{210}Po of up to 600,000 Bq/kg in furnace dusts have been found. The maximum dose received by a nearby resident from the release of radionuclides in liquid effluents is negligible. The dose received as a result of plume inhalation and exposure to material deposited from stack emissions was estimated as 37 µSv, of which over 35 µSv was due to dust inhalation. The dose received by a future site user after closure of a landfill facility containing 50 t of furnace silica dust (excluding the dose from indoor radon, for which no realistic estimate was made) was 4.5 µSv, of which 3.8 µSv was due to external gamma exposure.

133. For the manufacture of zirconium compounds by chemical dissolution of zirconium minerals, the main potential exposure pathways to members of the public are those associated with the landfill disposal of pipe scales and silica-containing residues. Chemical processing can produce scales and other residues with radium (^{226}Ra + ^{228}Ra) concentrations of up to a few thousand kilobecquerels per kilogram. A future resident living after closure on a landfill site into which 20,000 t of solid residue had been disposed was estimated to receive a dose of 750 µSv/a, mostly from external gamma radiation. For the chlorination of zircon and the production of zirconium metal, the sludge from the zirconium–hafnium separation process, owing to its radium content and large volume, gives rise to radiological issues similar to those associated with radium-rich mine tailings. Consequently, sludge stockpiled in ponds and piles represents a potential source of public exposure through the migration of radionuclides into the surrounding environment, particularly if the sludge is stored long-term rather than being used elsewhere, for example as a soil conditioner. Although there are obvious benefits in using sludge as a soil conditioner rather than storing it indefinitely in piles, there are radiological implications associated with the use of sludge in this manner. If the ^{226}Ra activity concentration in the sludge is of the order of about 1,000 Bq/kg, this corresponds to a radon flux density per unit ^{226}Ra activity concentration similar to that of normal rocks and soil. Sludge deposited on agricultural fields has been found to give rise to a gamma dose rate of 0.1–1 µSv/h at a height of 1 m and to a radon flux density of 0.44 Bq m^{-2} s^{-1}.

134. Products from the zircon industry, such as ceramic tiles and sanitary ware, have activity concentrations far below 1 Bq/g and would not normally be regarded as giving rise to exposures of concern. However, since these products are essentially building materials, some consideration of their radiological impact on members of the public is warranted. The potential exposure pathways are through

external gamma radiation and inhalation of radon released from the product. Several studies in different countries have found doses attributable to the use of glazed tiles in dwellings to be in the range 19–113 μSv above background. White or near-white porcelain tiles have a higher zircon content than glazed tiles and would therefore be expected to give rise to correspondingly higher doses. The use of porcelain tiles containing about 13% zircon in residences may give rise to doses of up to 120 μSv. The zircon content of glazes applied to sanitary ware is similar to that of glazes applied to ceramic tiles, but since the surface area of sanitary ware glaze in a typical home is far smaller, the radiological impact of the zircon used in the glazes applied to sanitary ware is very small compared with that of ceramic tiles. For refractories, the only potentially significant source of public exposure is the burial of spent refractories at a landfill disposal site. Calculations show that the annual effective dose received by a member of the public from the disposal of furnace lining bricks and refractory nozzles in a landfill, including the dose received as a result of future, uncontrolled residential use of the site, is likely to be no more than a few microsieverts. There are no significant public exposure pathways for the use of zircon as a source of zirconia in glass. For the use of fused zirconia in other applications, the disposal of reject material at a landfill facility is not likely to lead to any significant migration of radionuclides into the surrounding environment. The production processes of zircon ceramic tiles, sanitary ware, ceramic pigments and abrasives do not give rise to any significant exposure pathways to members of the public [I41].

7. Applications of radium and thorium

135. Radium has been extracted from uranium-rich ores. High contamination levels were recorded in soil surrounding a luminizing facility in London, with ^{226}Ra levels of between 0.4 and 400,000 Bq/kg, and with levels for “hot spots” of up to 4,000,000 Bq/kg. Similar concentrations were found in the vicinity of a watch factory at Dieppe, France. Exposures to the public are mainly due to external exposure and radon inhalation [V4].

136. An extensive radiological survey identified several contaminated areas in the vicinity of the former Olen radium facility in Belgium. The major contaminated site was the Bankloop brook, whose bed and banks were contaminated over a distance of 1,400 m with radium and chemical waste (heavy metals) to a depth of up to 1 m. The contamination was mainly confined to a narrow strip 5–10 m wide on one or both sides of the brook. About 64% of the total volume of contaminated soil and sediments, which had an associated external dose rate of over 0.15 μSv/h, was in a residential area. At the mouth of the Bankloop, about 3 hectares of farmland (a former area of flooding) were found to be contaminated with radium up to a depth of 1 m (from deep ploughing). The area is used for pasture. The average dose rates are about 0.3 μSv/h, and the maximum value measured was 5.5 μSv/h.

137. Also close to the site is an area that had previously been lower than its surroundings. The difference in level was removed between 1955 and 1960 by depositing residues of cobalt production, the debris of a building formerly used for radium production and a limited amount of radium extraction residues. The area is 9–10 hectares in size and contains mixed radium and chemical waste to a depth of 3 m. No direct public exposure occurred, because a security fence surrounded the area. Material in the dump contained radium with concentrations of up to 34,000,000 Bq/kg. Some nine or ten stretches of road and several isolated points were found to contain contaminated pavement to a depth of about 0.3 m. About 5% of the 11,000 dose rate measurements performed had values of greater than 0.2 μSv/h. One dwelling (with contaminated material under the veranda) had an average radon concentration in air of 720 Bq/m^3 on the veranda and 370 Bq/m^3 in the living room. Radon measurements were performed in 846 dwellings; only six showed average radon concentrations in air that were greater than 150 Bq/m^3 [V5].

138. Thorium is extracted from the same minerals used for rare earth extraction. Specific activities of feed material are in the range 10^3–10^4 Bq/kg. Thorium has been used in a large number of products and processes. Levels in the products (gas mantles, glass and tungsten) are typically higher than those in the original ore by a factor of 100 [V4]. Discarding industrial waste and gas mantles may require particular attention in order to avoid public exposure [V6].

8. Other exposure situations

139. From 1994 to 1999, there were 53 instances where evidence of radioactivity in ferrous scraps was discovered by steel companies in Taiwan, China. These involved 15 orphan radioactive sources, 16 ^{60}Co-contaminated rebars, 20 NORM-contaminated scraps and 2 cases whose cause was unknown. For the NORM, five possible industrial processes may have been involved: oil production and treatment; heavy mineral sand processing and rare earth processing; copper mining and processing; recovery of ammonium chloride by lime absorption in the ammonium–soda process; and uranium enrichment processes and tailings [C9, C10].

140. At least eight heavily used streets (approximately 3–5% of all civic road surfaces in the downtown area of Tayoyuan City, Taiwan, China) were found to exhibit unusual levels of radiation. Crushed rock debris and coarse sands separated from the asphalt pavement were identified as the source. The activity concentrations of ^{232}Th and ^{238}U were found to range up to about 4,000 and 1,000 Bq/kg, respectively. The dose rate on the road surface reached about 1.3 μSv/h, compared with the usual background level of 0.08 μSv/h on Taiwan [C8].

141. In the town of Monte Alegre, Brazil, an urban area was constructed using stones taken from a nearby uranium anomaly as landfill. The urban area has about 20,000 inhabitants,

and ^{222}Rn concentrations in air indoors are in the range 9–310 Bq/m^3, with an average of about 75 Bq/m^3. A small rural settlement of 3,000 people close to the anomaly shows indoor radon concentrations in air in the range 35–462 Bq/m^3, with a mean value of 116 Bq/m^3 [B27, M21].

142. There has been some concern about the exposure due to waste arising from water treatment. All natural waters contain certain concentrations of naturally occurring radionuclides. These may be enriched in the waste (mainly filter sludge), and the handling, transport and disposal of this waste may cause radiation exposure of operating personnel and of the public. A study performed in Europe concluded that, while the exposure of operating personnel due to direct gamma radiation and the exposure of the driver and the public during the transport and unloading of waste are of no concern, there are two exposure pathways that do need to be considered. The first is the exposure of operating personnel to radon. The dose due to inhalation will be highly dependent on both the radon content in the water and the ventilation of rooms [H23]. An analysis of raw water samples in Germany indicated a median value of 5.9 Bq/L of ^{222}Rn, with only about 1% of samples having concentrations of greater than 500 Bq/L of ^{222}Rn. The "activity transfer factors" reported for radon are about 50 Bq/m^3 and 0.1 Bq/m^3 for 1 Bq/L in water for unventilated and ventilated rooms, respectively. The annual doses for a worker working 2,000 hours in a year in such areas, assuming a ^{222}Rn concentration of 500 Bq/L in water, would be 155 mSv and 0.3 mSv for unventilated and ventilated rooms, respectively. The annual doses corresponding to the geometric mean concentration of 5.9 Bq/L of ^{222}Rn in water would be 2 mSv and 0.004 mSv for unventilated and ventilated rooms, respectively. The second pathway that may deserve attention relates to the use of waste sludges as a fertilizer on arable land. Using very conservative approaches, the estimated annual doses range from 0.02 mSv to 2 mSv for adults, depending on the origin of the water generating the sludge, with the dose for infants being about one order of magnitude higher than that for adults [H23].

143. A similar analysis was performed in the United Kingdom. Exposure scenarios relating to the treatment of tap and mineral waters include the transport, the unloading and the use of the sludges on arable land as a fertilizer. For transporting sludges resulting from the treatment of mineral water with high measured radon content, the annual dose to a member of the public was conservatively estimated as 8×10^{-3} μSv. The corresponding value for sludges resulting from tap water treatment is also negligible. The dose resulting from a single unloading event was found not to exceed 10 μSv for any type of sludge and for any exposure group, even using very conservative approaches [H23].

144. Sludges from tap water treatment can be directly used in agriculture, as fertilizers, while sludges from the treatment of mineral water are fed into a sewage plant, where they are diluted with sludges of other origin, reducing the final radionuclide concentration. Land contamination due to the spread of sludge will depend on the radionuclide concentration in the sludge and on the thickness of the sludge layer on the land. The use of the land for agricultural production can give rise to public exposure via the ingestion pathway. Annual doses in the United Kingdom due to the use of sludges from water treatment as fertilizers were estimated to be in the range 0.01–0.3 mSv for sludges from mineral water and 0.02–33 mSv for sludges from tap water treatment [H23].

145. There are also several sites with residues from former installations around the world. Most of these sites are contaminated with radium from former luminizing industries. Some European countries, such as the United Kingdom and Belgium, as well as the United States and Canada, have such contaminated sites. However, these sites have already been identified and most of them have already been remediated, so that the current levels of public exposure are very low.

9. Summary on exposure to enhanced NORM

146. Several types of facility worldwide that are not related to the use of nuclear energy may give rise to exposures of members of the public from enhanced concentrations of naturally occurring radionuclides in industrial products, by-products and wastes. A large effort is under way at both the national and the international level to assess exposure to NORM and to develop strategies to address existing situations that give rise to exposure [E16, I22]. Table 13 presents a summary of the dose estimates for members of the public in the United Kingdom due to the release of NORM from some typical industries [W6]. Besides these, NORM can also expose people as a result of several common practices, such as the agricultural use of sludges from water treatment, or the use of residues as landfill or building material. Although doses to the public are usually low, of the order of a few microsieverts or less, some critical groups could receive doses in the millisievert range, which may deserve attention. The Committee encourages the further development of inventories and methodologies for dose assessment in order to have a more comprehensive view of the issue in the context of public exposure.

C. Use of man-made sources for peaceful purposes

1. Nuclear power production

147. The Committee has routinely collected data on releases of radionuclides due to the operation of nuclear fuel cycle installations. The UNSCEAR 1993 Report [U6] provided an overview of annual releases of radionuclides for each of the basic types of reactor and other fuel cycle installations since the practice of commercial nuclear power generation began. Data for individual mines, mills, reactors and reprocessing plants were provided for the years 1985–1989. In the UNSCEAR 2000 Report [U3], the data for an additional period, 1990–1997, were assessed.

The present annex provides additional operational data for the period 1998–2002 for nuclear power reactors and for the period 1998–2003 for uranium mining.

148. The generation of electrical energy by nuclear means has grown steadily ever since it started in 1956. The relatively rapid expansion that occurred from 1970 to 1985, an average increase in energy generation of over 20% per year, slowed to a pace averaging just over 2% per year from 1990 to 1995. Although there has been an increase in the decommissioning and the shutdown of nuclear reactors, nuclear energy production is still growing, although with lower rates of increase in generated energy: about 0.2% from 1996 to 2000 and about 0.1% from 2000 to 2005. In addition, the number of countries using nuclear power has increased [I27, I28, I31].

149. The nuclear fuel cycle includes: mining and milling of uranium ore and its conversion to nuclear fuel material; fabrication of fuel elements; production of energy in the nuclear reactor; disposal of irradiated fuel or its reprocessing, with recycling of the fissile and useful materials recovered; and storage, release, treatment and disposal of radioactive waste. For some types of reactor, 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 material between the various installations.

150. Radiation exposures of members of the public resulting from discharges of radioactive material from installations of the nuclear fuel cycle were assessed in previous UNSCEAR reports [U3, U6, U7]. In this annex, the trends in normalized releases and the resultant doses due to nuclear power reactor operation are presented for the years 1998–2002. Doses are estimated using the environmental and dosimetric models described in annex A, “Dose assessment methodologies”, of the UNSCEAR 2000 Report [U3].

151. The doses to exposed individuals vary widely from one installation to another, between different locations, with different population habits 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). Only exposures to members of the public are considered in this section. Occupational exposures associated with nuclear power production are addressed in section III of this annex, “Occupational radiation exposure”.

(a) Uranium mining and milling

152. In the period 1998–2003, a total of about 35,000 t of uranium was produced annually in 24 countries (table 14). The major producer in this period was Canada, with about 30% of world production, followed by Australia, with 21% of total production. Since the beginning of the nuclear era, 37 countries have been involved in uranium production. The cumulative production up to 2003 is presented in figure XV. Canada produced about 21%, the United States 20% and Germany 12% of the total amount of uranium produced globally up to 2003, except for the amount produced in the former Soviet Union (about 20% of total production) and the production in China before 1990 [O16, O17, O21]. Annual production has decreased since 1990 but since 2000 has been quite stable (figure XVI).

153. There are a large number of mining areas being decommissioned. The countries that have declared mining areas decommissioned or under decommissioning through their National Reports to the Joint Convention on Spent Fuel and Radioactive Waste Management [I38] are Argentina [R13], Australia [C26], Bulgaria [R9], Canada [M28], the Czech Republic [C31], Denmark [N5], France [F14], Germany [F2], Slovenia [R12], Spain [S29] and the United States [U24]. Other countries with environmental liabilities resulting from uranium mining are Brazil [F5], Estonia [R3], Kazakhstan [K12], Romania [B18] and Ukraine [R19].

154. Milling operations involve the processing of the ore to extract the uranium in a partially refined form, known as yellowcake. In 2003, there were 294 uranium milling installations in operation and eight under construction worldwide; 149 installations had already been decommissioned and 231 were shut down or being decommissioned [I28].

155. *Effluents and solid waste.* Mining operations have been carried out in open pits, in underground mines and by in situ leaching. Uranium mill tailings are generated at about one tonne per tonne of ore extracted, and they generally retain 5–10% of the uranium and 85% of the total activity [V4]. The estimated amounts of tailings worldwide are shown in figure XVII; they total about 2.35×10^9 t. Besides the tailings, waste rock piles may also become a source of public exposure. For open-pit mining, the amount of debris produced is from 3 to 30 tonnes per tonne of extracted ore. For underground mining, about ten times less debris is produced. On the basis of information provided for 13 mining sites in Argentina [R13], Canada [M28], Germany [F2] and Spain [S29], the amount of waste rock varies from 40 to 6,000 times the amount of tailings, with an average value of about 1,600 tonnes of waste rock per tonne of tailings [I38].

156. Tailings are often confined because of the associated risk. At some locations, exposure to radon may be of considerable concern, but it is sometimes not addressed. For example, at some tailings locations, exposure to radon may become important where the site is subsequently used for housing, as has happened in eastern Germany, the Czech Republic and other eastern European countries [V4]. Problems may also arise from exposure via aquatic pathways, since acid drainage can leach uranium from waste piles [A14, F5]. The erosion of covers, structural failure of embankments, seepage to ground or surface water and

emanation of radon are some of the more important mechanisms for release of pollutants to the environment.

157. Critical exposure pathways tend to be site-dependent. The radionuclides of greatest concern for atmospheric pathways are ^{222}Rn, its decay progeny, and airborne particulates containing thorium, radium and lead. The main concern for aquatic pathways is ^{226}Ra, although ^{238}U, ^{230}Th and ^{210}Pb may be equally important [V4]. Many abandoned sites exist, and only a few have been remediated. Problems associated with public exposure resulting from past practices include radon release, water contamination, the proximity of contamination to human settlements, the removal of wastes for construction, large inventories and appreciable aerial dispersion [V4].

158. Some remediated sites related to former uranium mines have follow-up monitoring and assessment programmes on contamination in the environment. Although some limited descriptions of these are available in the literature, little or no useful information exists on exposures to actual population groups, because most assessments were performed conservatively to demonstrate compliance with regulations limiting doses to hypothetical critical groups.

159. There are few new data on releases of radionuclides due to mining and milling operations. Previous UNSCEAR reports have estimated the average release of radon for underground mines as approximately 75 TBq/(GW a). There were no estimates of releases due to open-pit operations. In the UNSCEAR 1993 Report [U6], the average normalized radon release from mills in Australia and Canada was estimated from the limited data available to be 3 TBq/(GW a) [U6]. These values are not expected to change with current mining and milling practices. The long-lived precursors of ^{222}Rn, namely ^{226}Ra (half-life 1,600 a) and ^{230}Th (half-life 80,000 a) are present in mill tailings and constitute a long-term source of radon release to the atmosphere. On the basis of the UNSCEAR 2000 Report [U3], the normalized radon releases are 3 and 1 TBq/(GW a) for operational and abandoned tailings, respectively, and these values are used here. The in situ leach facilities have no surface tailings and little radon emission after closure.

160. *Dose estimates.* The methodology used by the Committee to estimate the collective dose due to mining and milling is described in the UNSCEAR 1977 and 1982 Reports [U9, U10]. Dose estimates are based on representative release rates from a “model” mine and mill site having the typical features of existing sites. The results are therefore not applicable to any particular site without due consideration of site-specific data, and rather are meant to reflect the overall impact of mining and milling facilities. The collective effective dose per unit electrical energy generated is estimated to be 0.2 man Sv/(GW a) during operation of the mine and mill, and 0.0075 man Sv/(GW a) per year of release from the piles of residual tailings of operational mining and milling sites.

161. With the current production of about 35,000 t/a and with the assumption that 12 countries produce more than 500 t/a, the average annual individual effective dose of 25 μSv (which assumes that the collective dose is received by the population within 100 km of the mine and mill sites) is still valid for the major producing countries. Considerable deviations from the representative values of parameters selected are possible for the more general conditions of present practice. There are locations in Brazil, for example, where acid leaching may be responsible for high concentrations in drainage waters from the mining area [A14, F5]. Also, very high population densities are reported in areas surrounding the mills in China. In some cases, previously abandoned tailings may not have been so carefully secured as they might have been. Although careful management of tailings areas would be expected in the future, the extremes in management approaches (from leaving the tailings uncovered to providing secure and covered impoundment) could increase or decrease the estimated exposure by at least an order of magnitude.

(b) Uranium enrichment and fuel fabrication

162. 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).

163. There were 29 uranium conversion/recovery facilities in operation and 1 under construction in the world in 2003; 2 had already been decommissioned, and 14 had been shut down or were being decommissioned. For uranium enrichment, there were 21 operating facilities, 2 under construction, 5 decommissioned and 7 shut down or being decommissioned. For fuel fabrication or heavy-water production, there were 66 operating facilities, 5 under construction, 23 decommissioned and 27 shut down or being decommissioned [I28]. Nominal capacities for uranium enrichment, hexafluoride conversion and fuel fabrication by country are presented in table 15, while countries with nuclear fuel production facilities are shown in figure XVIII [I35].

164. The releases of radioactive material from conversion, enrichment and fuel fabrication plants are generally small and consist mainly of uranium series isotopes. For the “model” installations, the normalized collective effective dose due to these operations was estimated to be 0.003 man Sv/(GW a). Inhalation is the most important exposure pathway. The collective doses to local and regional groups resulting from liquid discharges comprise less than 10% of the total exposure. The average annual collective dose for the period 1998–2002 is estimated to be 0.8 man Sv. Considering that 18 countries have nuclear fuel enrichment and/or fabrication facilities, the estimated annual individual

effective doses would be about 0.2 μSv for local population groups and about 0.1 nSv for regional groups.

(c) Nuclear power reactors

165. Reactors used for electrical energy generation are for the most part classified according to their coolant systems and moderators: light-water-moderated and -cooled pressurized- or boiling-water reactors (PWRs, WWERs, and 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, in which the moderator material is used to slow down the fast fission neutrons to thermal energies. In fast-breeder reactors (FBRs), there is no moderator, and fission is induced by fast neutrons; the coolant is a liquid metal. FBRs make only a minor contribution to energy production. A list of reactors that operated in the period 1998–2002 and their installed capacities is presented in table A-4, and the worldwide distribution of operational reactors for the same period is shown in figure XIX. The electrical energy generated by these various types of reactor up to 1997 has been presented in previous UNSCEAR reports, and values for individual reactor sites for the period 1998–2002 are given in table A-5 [I31]. A summary for each reactor type is presented in table 16.

166. The average energy generated by nuclear power from 1998 to 2002 was 278 GW(e)/a (net gigawatts of electrical power per year), ranging from 264 GW(e) in 1998 to 288 GW(e) in 2001. The tendency for increasing amounts of energy to be generated by nuclear power continues. The net installed electrical energy capacity of nuclear power plants, the number of operating reactors and the average net installed capacity per unit power reactor are still increasing worldwide (figure XX). In the period 1998–2002 covered by this annex, there were 452 operational reactors. Of these, 23 had started operating in the period, 14 were shut down and 8 had not generated energy in the period. Between 2003 and 2005, 10 new reactors started operation and 8 were shut down. In the same period, there were also 22 nuclear power reactors being built in 10 countries. By 2007, the number being built increased to 30 reactors in 13 countries [I31]. The time trend for total energy generated by reactor type is shown in figure XXI.

167. PWRs contribute the largest fraction of the total nuclear energy generated worldwide, about 67% for the period 1998–2002, followed by BWRs, with a contribution of about 24%. The contributions of other reactor type are: about 5% for HWRs, 3% for LWGRs and 2% for GCRs. FBRs contribute very little, only about 0.1% of the total energy generated. The average contribution for each reactor type can be seen in figure XXII for the period 1998–2002 covered by this annex and for the period 1970–1997. The current smaller contribution from GCRs reflects the interruption in nuclear power production (later resumed) by some reactors in the United Kingdom.

168. The Committee derived average releases of radionuclides from reactors on the basis of reported data; these averages have been used to estimate the resulting exposures for a reference reactor. The geographical location of the reactor, the release points, the distribution of the population, food production and consumption habits, and the 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 but nevertheless serve as standardized measures for analysing longer-term trends from the practice.

169. *Effluents.* Information on effluents released from operating nuclear power plants have been provided by United Nations Member States for the UNSCEAR Global Survey on Public Radiation Exposures, and by the International Atomic Energy Agency (from its DIRATA database [I30]). Data have been published by the European Commission [E15, V2] and the United States [N16, N17, N18, N19]. For the Republic of Korea, data were obtained from the national report to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [I38, R11]. Most of the available data are related to PWRs (including WWERs), BWRs and HWRs, with only very limited information for AGRs GCRs, LWGRs and FBRs. The radioactive material released in airborne and liquid effluents from reactors during routine operation for the period 1998–2002 are reported in tables A-6 to A-12. For airborne effluents, the releases of noble gases (table A-6), tritium (table A-7), ^{131}I (table A-8), ^{14}C (table A-9) and particulates (table A-10) are given. For liquid effluents, the releases of tritium are given in table A-11 and of other radionuclides in table A-12.

170. The normalized releases have traditionally been compiled separately for each reactor type. This is justified because of the different composition of the releases, mainly for noble gases, and different “dose factors” are required to estimate the doses for different reactor types. With relatively complete data, little extrapolation is needed for estimating the collective doses resulting from the total releases, and the normalized values are retained by reactor type mainly for convenience. The results are presented in table 17. These values are intended only for use in estimating the contribution of operating nuclear power plants to the overall public exposure and should not be used for comparison between different reactor types for other purposes. The choice of a specific type of reactor for generating purposes must take into account several aspects, such as the safety of the reactors; the impact of the complete fuel cycle, including waste generation; and the industrial infrastructure available in each country—factors that are not covered in this annex. In addition, effluent releases are dependent on the reactors’ age (the performance of older reactors is usually different from that of more modern reactors) and also on improvements in waste management systems. Also, reactors that have had long

shutdown periods for maintenance operations may present higher than usual values because, while effluent discharges may be enhanced, the power generated is zero. The information used in this annex includes the total energy generated and the total effluents released in each year, and these figures do not explicitly take account of the difference due to maintenance periods. Only those reactors that have not generated energy during a whole year have been excluded from this analysis. On the whole, the values for the average release per unit energy generated are consistent with results from previous UNSCEAR reports. In general, normalized releases are decreasing with time.

171. The largest contributions to the activity of the effluents released are associated with tritium and noble gases. From the information available, the release of noble gases per unit energy generated is higher for LWGRs than for other reactor types. The amount of tritium release in both atmospheric and liquid releases is higher for heavy-water reactors. Normalized values for noble gases released from nuclear power plants over different time periods are shown in figure XXIII. Except for LWGRs, all other reactor types show a decrease in the noble gas activity released per unit energy generated; this may reflect improvements in waste management procedures and in the design characteristics of modern reactors.

172. *Local and regional dose estimates.* The concentrations in the environment of released radionuclides are generally too low to be measurable except close to the nuclear facility and then only for a limited number of radionuclides. Therefore dose estimates are based on effluent data. Environmental transfer and dosimetric models were reviewed in annex A, “Dose assessment methodologies”, of the UNSCEAR 2000 Report [U3]. Again, because of the variability in annual releases, normalized releases, in TBq/(GW a), are averaged over a five-year period to estimate collective doses. The dose conversion factors used in estimating doses were the same as those used in the UNSCEAR 2000 Report [U3] and were summarized in table 2.

173. The collective doses estimated for local and regional population groups combined are presented in table 18. The collective dose for 1998–2002 is lower than that for the period 1990–1994 given in the UNSCEAR 2000 Report [U3]. The main reasons for this are the lower values for noble gas releases from BWRs and the absence of a contribution from GCRs in the United Kingdom that were not in operation in the period 1998–2002. The average annual collective dose to local and regional groups due to effluents released from nuclear power plants in the period 1998–2002 was estimated as about 75 man Sv. (If the estimates were to be made using a simpler approach, i.e. considering the total effluent releases from all reactors of a specific type divided by the total power generated by those reactors, the averages would be less sensitive to the performance of individual reactors and would probably be a more representative estimate of the worldwide average dose. The results of such a calculation would provide a value for the annual collective dose of about 42.6 man Sv.)

174. To estimate values for the per caput local and regional doses, it is assumed that the total collective dose relates to model population groups around all nuclear power plants: the local population is assumed to lie within a 50 km radius surrounding a nuclear power plant and its population density is taken to be 400 km^{-2}; the regional population is assumed to lie within a 2,000 km radius from the nuclear power plant and its population density is taken to be 20 km^{-2}. Using the model site described in reference [U3], with 444 operational reactor units and an average of two reactors per site, the Committee has estimated that the per caput effective dose due to each site would be about 0.1 μSv annually for local groups (50 km radius) and only a fraction of a nanosievert for the regional groups within a 2,000 km radius surrounding a site.

175. The annual doses estimated for critical groups used for licensing and effluent control of nuclear power plants are considered to apply to the area within a 3 km radius of the reactors and in most countries are constrained by an annual dose limit in the range 200–300 μSv, but actual doses are usually much lower than this. Considering that more than 80% of the collective dose is due to airborne effluents, and taking the difference between the values for dilution factors for the representative source and long-term average conditions as defined in annex A of the UNSCEAR 2000 Report [U3] for the distance of 1 km for the critical group, it can be assumed that, for the period 1998–2002, the expected maximum annual effective doses to critical groups within 1 km of reactor sites due to effluent releases from nuclear power plant operation are of the order of 0.02 mSv.

176. Some information was also available for releases from some shut down reactors. These releases cannot be treated as “operational” releases, because they are not associated with the generation of nuclear energy. The values of the total releases from some shut down reactors are presented in table 19. A comparison of total releases from these reactors with those from operational reactors of a similar type and power shows that releases from shut down reactors are significantly smaller than those from the equivalent operational reactors, although some exceptions may be found, mainly related to old and low-powered shut down reactors.

(d) Fuel reprocessing

177. The reprocessing of spent fuel is performed to separate out and recover reusable uranium and plutonium from waste. Most spent fuel from reactors is retained on site in interim storage, pending decisions on ultimate disposal or retrievable storage. It is estimated that about one third of the spent fuel already produced has been submitted to the reprocessing stage of the nuclear fuel cycle [I34]. France, Japan and the United Kingdom are the main countries operating commercial reprocessing plants.

178. *Effluents.* Relatively large quantities of radioactive material are involved at the fuel reprocessing stage, and the

potential for its release in waste discharges is greater than for other stages of the fuel cycle. Routine releases have been largely in releases of liquid effluents to the sea. Operating standards have been considerably improved at reprocessing plants over the years, with substantial reductions in the amounts released.

179. In 2003, there were 13 fuel reprocessing plants in operation, 3 under construction, 13 decommissioned and 18 shut down or being decommissioned [I28]. Information on releases from some of these installations for the period 1998–2002 is presented in table A-13 for airborne effluents and in table A-14 for liquid effluents. The origins of these data were countries' responses to the UNSCEAR Global Survey on Public Radiation Exposures, the IAEA DIRATA database [I30] and the open literature [E15, V2]. Included are data for the reprocessing facilities at La Hague (France), Karlsruhe (Germany), Krasnoyarsk and Tomsk-7 (Russian Federation), Dounreay and Sellafield (United Kingdom) and Tokai (Japan).

180. Collective doses from nuclear fuel reprocessing can be estimated from the normalized releases per unit energy generated, the electrical energy equivalent of the fuel reprocessed and the collective dose per unit release of radionuclides [U6]. Previous UNSCEAR reports used dose factors based on the electrical energy equivalent of the fuel reprocessed. The same methodology cannot be used here, because information on the amount of fuel reprocessed is not available. Doses were thus estimated on the basis of the activity released in the effluents, using the dose conversion factors presented in table 3. The data collected are currently not complete, and this necessarily introduces large uncertainties into the resulting estimates. Using only the available reported data, the average annual collective dose is estimated as 30 man Sv, with about 8 man Sv due to airborne effluents and about 22 man Sv due to liquid effluents, as shown in table 20. The estimate for the total collective dose since the beginning of reprocessing is 4,828 man Sv. The largest contribution to the total dose estimate is still associated with the release of ^{14}C. The actual values for the total doses, however, are probably a little larger than these estimates, because some data are missing that would be needed to estimate doses accurately.

181. The estimate of the annual collective dose is still in the range 20–30 man Sv; if this were exposing a single local population group (say, 3.1×10^6 persons within a 50 km radius), the per caput effective dose would be about 10 μSv per year of operation. The corresponding value for regional groups would be about 0.12 μSv/a. Considering that five installations have contributed to this collective dose, the average effective doses would be of the order of 2 μSv for local population groups and 0.024 μSv for regional groups.

(e) Globally dispersed radionuclides

182. Radionuclides that are long-lived and easily dispersed in the environment can give rise to doses to people across the whole planet. 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 in dose calculations increase when the integration is carried out for very long periods of time—hundreds or thousands of years or even longer. Considering the 100-year truncated dose coefficients of 0.004 man Sv/(GW a) for ^{3}H, 6.3 man Sv/(GW a) for ^{14}C, 0.12 man Sv/(GW a) for ^{85}Kr and 0.0008 man Sv/(GW a) for ^{129}I releases [U7], and a continuing practice of about 300 GW a energy production per year, the worldwide maximum per caput effective dose rate would be about 0.18 μSv/a.

(f) Solid waste disposal

183. Solid wastes arise at various stages in the nuclear fuel cycle. They include low- and intermediate-level wastes, mainly from reactor operation; high-level waste 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 more advanced disposal sites also exist. High-level waste and spent fuel are currently retained in interim storage tanks pending the development of adequate methods for disposal and the selection of disposal sites.

184. The radiological impact assessment of a high-level waste repository has to rely on modelling of the long-term behaviour of the waste and the migration of released radionuclides both near the site and at greater distances over a long period of time. To carry out such performance assessments, a number of site-specific data are needed, including those called for by waste characterization and transport models. Such assessments have been performed, mainly for use in formulating design criteria for the hypothetical repositories.

185. Information on spent fuel has been obtained from the National Reports of countries that are parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [I38]. The direct comparison among different countries is difficult because inventories are specified in different ways: some declare the total mass stored, while others declare the uranium mass or the heavy-metal (HM) mass. Other countries report the volume, and a few present the activity (but sometimes it is not clear if the value given refers to the uranium component or if it includes activity from fission products). From the material provided by a few countries that have declared their total inventory of spent fuel by nuclear power plant and also declare that they do not reprocess their spent fuel, average values for the annual spent fuel generation per unit installed electrical capacity have been estimated and are presented in table 21.

186. Considering the number of operating years, the type of reactor and the net electrical capacity, a total amount of about 210,000 t of HM in spent fuel is estimated to have been generated worldwide up to the end of 2002 from nuclear power plants that were operational in the period 1998–2002. This amount includes the material that has already been reprocessed, which amounts to about 90,000 t worldwide [I34]. Because this figure also includes material reprocessed from reactors already shut down, there are at least some 120,000 t of HM in spent fuel from nuclear power plants being stored, most of it currently in temporary storage conditions.

187. Before final disposal, all such material will have to be manipulated and transported, which will give rise to both occupational and public exposures. Public exposure due to the transport of spent fuel is discussed in section II.C.2 of this annex. The transport of radioactive material 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. The transport of radioactive and nuclear material is addressed as a separate item in this annex. For the nuclear fuel cycle, doses may be estimated using the factor of 0.1 man Sv/(GW a), as in previous UNSCEAR reports [U3, U9, U10].

188. The routine operation of nuclear power plants generates large amounts of long-lived and high-activity radioactive waste. Although there is information on waste inventories for several countries, only a few of these inventories are described in detail with respect to the specific origin of the waste. Some countries report the volume after treatment and conditioning while others report the weight produced; care is needed in interpretation. Nevertheless, on the basis of information provided by Argentina [R13], Canada [M28], Hungary [R10], the Republic of Korea [R11], Spain [S29] and Switzerland [D6] in their National Reports to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [I38], the annual amount of radioactive waste generated by different types of reactor per unit installed capacity was estimated, and these results are also presented in table 21.

189. Doses due to solid waste disposal have been estimated on the basis of the projected eventual migration of radionuclides through the burial site into groundwater. These estimates depend critically on the assumptions about the containment of the solid waste and the site characteristics, and accordingly are generally highly uncertain. The approximate normalized collective effective dose due to low- and intermediate-level waste disposal is, however, relatively low, of the order of 0.5 man Sv/(GW a), and is due almost entirely to ^{14}C [U6, U9]. The worldwide average annual per caput effective dose rate would be about 1 nSv per year of practice.

190. The decommissioning of nuclear facilities gives rise to radioactive waste, and decommissioning experience is being accumulated. Worldwide a considerable number of installations have been shut down or are being decommissioned. The 2003 list includes 231 uranium milling facilities, 14 uranium conversion/recovery plants, 7 enrichment facilities, 27 fuel fabrication/heavy-water production facilities and 18 fuel reprocessing plants. Also, 107 commercial nuclear power plants had been shut down or were undergoing decommissioning. There were also 21 research reactors and several research units undergoing decommissioning.

191. According to the information provided by countries in 2005 under the arrangements for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, the largest decommissioning programme in 2005 was that of the United States, which was decommissioning 16 nuclear power reactors, 20 research reactors, 66 radioactive installations and about 1,186 sites formerly used for activities related to defence [U24]. France was decommissioning 9 nuclear power reactors, 15 research reactors, 3 small reactors used for defence activities and 16 other installations [F14]. Germany had 17 nuclear power reactors and 14 research reactors undergoing decommissioning [F2]. All these processes will generate large amounts of radioactive waste, including spent fuel from both research and power reactors, which will have to be handled, transported and disposed of. With the information available it is not possible to estimate the total amount and activity of the waste to be disposed of. The amount of waste will be highly dependent on the facility type, size and operational history. As an example, the Republic of Korea has estimated that some 620 m^3 of waste with an activity of about 1.24×10^{12} Bq will be generated by the decommissioning of two research reactors, and some 380 m^3 of waste with an activity of about 6.5×10^5 Bq by the decommissioning of one conversion facility. The decommissioning of two nuclear power reactors in Canada, at Douglas Point and at Gentilly-1, has left a total of 300 and 80 t, respectively, of uranium in spent fuel. The expected total volumes of conditioned waste from existing United Kingdom facilities to the end of their lives are 1.5×10^6 m^3 of low-level waste, 2.4×10^5 m^3 of intermediate-level waste and 1.5×10^3 m^3 of high-level waste [I38].

192. There are also currently five reprocessing facilities with a capacity of greater than 1 t/a undergoing decommissioning and two more for which decommissioning is planned [I34]. Information related to exposures from the decommissioning of such facilities is scarce and relates more to the level of compliance with regulatory constraints than to actual public exposure. While worker exposure may arise from dismantling, demolition and waste management operations, public exposure will depend on the criteria adopted for residual radioactivity at the site and on the transport of waste to disposal sites. The information available indicates that the exposure of the public due to decommissioning will be very low and will be constrained in the long term by national regulations regarding acceptable levels for residual radioactivity in recycled materials and in the environment. Estimates of doses due to waste rock and tailings were, however, included in the doses estimated for uranium mining and milling.

193. During the decommissioning of facilities, many materials may be recycled. Different criteria are being applied by different countries, but the information currently available is not sufficient to estimate the contribution from recycled materials to public exposure [B13, I19, I24, I40, L13].

(g) Summary of estimates of doses due to nuclear power production

194. The estimated doses to members of the public due to the generation of electrical energy by nuclear power are summarized in table 22. For local and regional population groups, a normalized factor of 0.27 man Sv/(GW a) has been determined. This is slightly lower than the value derived in the UNSCEAR 2000 Report [U3], 0.44 man Sv/(GW a). For all activities related to the production of energy, a normalized collective effective dose of 0.72 man Sv/(GW a) was determined. Using this coefficient, with an average of 278 GW(e)/a per year produced in the 1998–2002 period, an annual collective dose of about 200 man Sv is estimated for all operations related to energy production. The annual per caput doses to representative local and regional populations surrounding nuclear power installations are less than 10 µSv. The collective doses from globally dispersed radionuclides are delivered over very long periods and to an assumed "maximum" population of the world. If the practice of nuclear power production were limited to the next 100 years at the present capacity, the maximum annual per caput effective dose to the global population would be less than 0.2 µSv.

2. Transport of nuclear and radioactive material

195. This section describes exposures related to the "normal transport" of radioactive material. Normal transport refers to operations that occur without loss or damage to the package and without an accident involving conveyance. Events in which the shipment is not timely, the package or conveyance is damaged or the contents are lost or destroyed, are considered to be transport accidents or incidents [I20]. Accidents and incidents do occur during transport, but their consequences are normally limited by built-in safety features of the package together with the controls required for transport, including emergency response procedures [H28]. The consideration of accidents is outside the scope of this annex and is discussed in annex C, "Radiation exposures in accidents", of the UNSCEAR 2008 Report.

196. Radioactive materials of natural or artificial origin are used widely around the world and are transported within and between countries. A wide range of different materials are transported, from small quantities of radiopharmaceuticals for medical purposes to highly radioactive spent nuclear fuel and vitrified waste arising from the nuclear fuel cycle. The handling and transport of these radioactive materials can give rise to the radiation exposure of workers and of members of the public. In a lay sense, the term "public" is often taken to include transport workers (i.e. transport workers are often considered as a subset of the "public" who are generally exposed to the highest dose rates [V23]). However, in this annex, exposure of this group of workers will, whenever possible, be considered separately from the exposure of members of the general public, such as pedestrians, passengers and bystanders.

197. The data on numbers of packages are generally well known for nuclear fuel cycle operations, but for other transport operations the number can in most cases only be estimated. There is also a large variation between countries in the number of packages, because some countries have nuclear fuel cycle operations and some have major suppliers of radionuclides [H29]. The IAEA estimates that 10 million shipments of radioactive material are transported annually. Each shipment is made up of either a single package or a number of packages [I5]. The vast majority, some 95%, of these shipments are unrelated to the nuclear fuel cycle, only 5% being related to fuel cycle transport [W16].

198. Road, rail, air and sea transport are all commonly used for the transport of nuclear fuel cycle material, of radioactive material to be used in medicine, industry and research, and of waste. Air transport of nuclear fuel cycle material is carried out only to a limited extent [W14]. The available data indicate that exposures under normal conditions of transport are low. At least for the United Kingdom and the United States, the transport of fuel cycle material contributes significantly less to the exposure of transport workers than does the transport of non-fuel-cycle material [I5].

199. Mobile radiography sources are relatively numerous throughout the world. For example, there are about 850 in France, and about one half of these are transported daily by users from storage to their place of use. The transport dose for radiography operators due to these sources has not been included in this annex because of the difficulty in distinguishing between doses arising from the transport of radioactive material and doses resulting from the radiography operations themselves [C3, H4].

200. The number of fuel transports in Germany is shown in figure XXIV for the period 1994–2002. The number includes transports of irradiated and non-irradiated fuel and of waste by rail, road, sea and air. The overall number of transports decreased from 1994, reaching a minimum in about 1999, and started a relatively slow growth up to 2002. In 2002, the major contributor to the number of transports was the international transport of non-irradiated fuel by road, which accounted for nearly 50% of all nuclear fuel transports, with the international sea transport of non-irradiated fuel accounting for about 20% [B48].

(a) Transport by land routes

201. Most transport operations include the initial road transport from the production site to the railway station, airport, harbour or collection centre. During this part of the

journey, vehicles may pass through residential or crowded areas and along busy roads and highways. In certain places the pedestrian density may be unusually high, while in others there may be only people waiting at bus stops to represent the potentially exposed population. Passengers in vehicles near the delivery vehicle will also be exposed. Overall, the exposure of such members of the public is expected to be much lower than of the exposure of workers involved in actual transport and cargo operations. Collective doses will depend mainly on the population density along the transport route [V23]. Although it would appear that both collective and individual doses to the public are low [I5], data are scarce.

202. A survey was performed in Mumbai, India, regarding the carriage of radioactive material in "Type A" packages [I33] for use in medicine, industry and research; such material is supplied by the Bhabha Atomic Research Centre, Mumbai, to a large number of users all over India. Packages delivered to the air cargo terminal are ultimately sent to various parts of the country. Radiation doses to the urban public due to shipments of radioactive material are likely to be much greater in Mumbai than in any other city in India. Essentially it is the pedestrians and the passengers travelling in nearby vehicles who are exposed to radiation during the transport of radioactive material. The estimated radiation exposures were found to be low, but collective doses could theoretically be large because of the relatively high pedestrian and passenger density in Mumbai. Measured dose rates, used to estimate public exposure, ranged from 1 to 55 μGy/h for passengers in vehicles beside the delivery van and for pedestrians on sidewalks. The annual collective dose resulting from the transport of radioactive consignments in Mumbai was estimated to be about 0.1 man Sv [V23].

203. The collective doses accruing to the general public due to incident-free road transport of sealed spent sources generated by nuclear application institutes in India were estimated for the year 2001 [U43]. The main contribution to collective dose was due to the transport of decayed ^{192}Ir sources that had been used for industrial radiography, brachytherapy and nucleonic gauges, with a collective dose to both transport workers and to the public of about 46 man Sv.

204. Analysis of the shipments by road for the period 1987–2000 by authorized carriers in Italy concluded that doses mainly arise from transport operations associated with radioisotope supply and distribution, and with the transport of non-nuclear radioactive waste. Negligible doses arise from transport operations associated with the nuclear fuel cycle, because of the very small number of shipments of nuclear material. The greater part of the exposures to people due to the shipment of radioactive material for industrial and medical uses arises from transport for medical purposes, with an estimated maximum annual individual effective dose of 0.0012 mSv [C3].

205. In France, spent fuel is carried mainly by rail. Roads are used only between certain power plants and the nearest railway station, and then between the rail terminal and the La Hague reprocessing facility. Also, transport of waste between the various producers and the storage centre at La Hague is accomplished principally by rail and only partly by road. The contribution of waste transport to the irradiation of workers and the public remains very low. Members of the public residing along the (road and rail) transport routes or near the sites of storage in transit may receive doses due to the transport of radioactive material. The annual collective dose received by the public was estimated to be at most about 0.10–0.15 man Sv, about half of the dose received by workers [H4].

206. Collective doses were assessed for population groups in the vicinity of the transport routes within Germany and were related to the incident-free transport of radioactive material and spent fuel. The population groups outside nuclear facilities considered in this assessment included railway personnel in shunting yards, populations in the vicinity of shunting yards and rail routes, and railway passengers. Collective dose estimates for three types of spent fuel management are presented in table 23. Comparison with estimates for low-level waste showed that the main contributor to the collective dose for all population groups would be the transport of low-level waste from PWRs to the depository at Gorleben, which exceeded the exposure due to the transport of spent fuel from PWRs by two orders of magnitude. The transport of spent fuel accounts for less than 1% of the total dose. The annual dose to a hypothetical "critical group" passenger who passes every shipment of radioactive material from the reprocessing facility to the depository was estimated to be 0.08 mSv. Inhabitants who spend the entire year within a distance of 1 km from the railway track would receive a conservatively estimated annual dose of 0.03 mSv [B7].

207. A study was performed in the former German Democratic Republic related to an impact assessment of the transport of waste to the Endlager für radioaktive Abfälle Morsleben (ERAM), a former salt mine located in Saxony-Anhalt. After a temporary shutdown, ERAM restarted disposal operations in 1994. From then to the end of 1996, some 11,000 m^3 of waste, primarily low-level solid waste from operating nuclear power plants and from decommissioning, were delivered and placed in deep geological formations. The preferred mode of transport for waste shipments was rail, except for a small fraction of the journey within 40 km of the repository site. Estimates of annual doses to members of the public were generally less than 0.1 mSv [S12].

208. Some 500,000 packages of radioactive material are shipped annually within the United Kingdom by road and around 4,000 movements annually by rail. About 52,000 of these packages are shipped to and from hospitals; about 15% of these contain technetium generators. Doses to members of the public due to the transport of radioactive material tend to be very low. The estimated maximum individual doses were less than 20 μSv/a. The estimated collective dose to the public due to the movement of radioisotopes to and from

hospitals was 0.013 man Sv, with a further 0.005 man Sv due to exports. The estimated collective dose to the public due to the movement of spent nuclear fuel flasks within the United Kingdom was no more than about 0.001 man Sv [W7]. A study on the transport of NORM in the United Kingdom found that the annual dose to any member of the public from the shipment of any type of NORM would be much less than a microsievert [H30].

(b) Transport by sea

209. Spent fuel from Japan is transported by sea in dedicated vessels for reprocessing in Europe, arriving at sea terminals close to the reprocessing plants and then undergoing short road/rail journeys. Spent fuel flasks are handled by cranes at the sea terminals, with limited access by workers. Some spent fuel is likewise transported by sea from continental Europe to the United Kingdom. The limited transport of high-level waste, for example from La Hague in France to storage facilities elsewhere in Europe and in Japan, follows procedures similar to those for spent fuel transport [W14].

210. Non-irradiated nuclear fuel material (such as ores, concentrates and chemical derivatives) are shipped around the world in various types of container, while irradiated material is generally transported by special ships dedicated for this purpose. Packages containing radioactive material are usually carried in containers on board ships or in vans and lorries. The containers are usually loaded with material for the nuclear fuel cycle, while the vehicles usually carry packages of radionuclides for medical or general industrial use [B11].

211. In 1994 radioactive material was carried on some 1,100 voyages to, from or in transit through the United Kingdom. Of these voyages, about 55% were of nuclear fuel cycle material (50% non-irradiated and 5% irradiated), and the remaining 45% involved radionuclide consignments for medical and general industrial use. The carriage of nuclear fuel cycle material on freight vessels and dedicated ships leads to the possible exposure of the crew, a small number of passengers and dockworkers. The transport of packages containing radionuclides in vehicles on ferries may result in the exposure of both crew and passengers. Exposures to passengers are low, with annual individual doses unlikely to exceed 0.032 mSv [B11].

212. A study performed in Egypt assessed the exposure of populations living alongside the Suez Canal due to the intensive transport of radioactive material by ships passing through the canal. The quantities of radioactive material that potentially exposed coastal populations are presented in table 24. The estimated average annual collective doses to the public in the period 1986–1992 in the towns of Port Said, Ismailia and Suez are 4.11×10^{-8}, 3.01×10^{-8} and 5.04×10^{-8} man Sv, respectively. The transport of low-activity material, such as uranium (as U_3O_8), represented the largest contribution to the collective dose to the public within the Suez Canal area. Harbour workers, with an annual collective dose of about 3×10^{-4} man Sv, were the population group that received the largest individual doses [S1].

(c) Transport by air

213. A major producer of radionuclides for worldwide medical use is located in the United Kingdom. The radionuclides are packaged and then sent by road either for domestic delivery or for export via a number of airports. Packages containing radioactive material arrive at the airport in light trucks and are then unloaded and checked in the carrier's warehouses. The packages are sorted and grouped according to destination. The majority of packages transported by air are either excepted or Type A. Excepted packages have surface dose rates of less than 5 μSv/h. However, some Type A packages containing technetium generators have surface dose rates approaching 1 mSv/h. Measurements have indicated typical dose rates close to packages containing technetium generators of around 40 μSv/h, with surface dose rates of up to 800 μSv/h [W3].

214. An extensive survey on the routes, kinds of airplane, cargo operations, crew flight schedules and numbers of passengers was carried out in the United Kingdom in 2001. Aircrew and passengers may be exposed to packages stored in holds during flight. The number of packages transported by air in the United Kingdom in 2001 is shown in table 25. A number of the carriers stated that they did not consider "excepted" packages to be "radioactive material" and therefore exclude this category from package totals. For passengers, measured dose rates ranged from 0.5 to 9 μSv/h in the main cabin area, and from 4 to 15 μSv/h in the front seats. Half the passengers were exposed to dose rates of less than 1 μSv/h, and the average passenger dose rate was 3 μSv/h. No information was provided regarding frequent flyers and couriers, but it was considered that frequent flyers using short-haul flights (which have a Radioactive Traffic Factor of 1 in 475) are unlikely to receive a significant dose due to radioactive cargo [W3]. (The Radioactive Traffic Factor (RTF) is the ratio of flights carrying radioactive cargo to the total number of flights.) Estimates of collective doses due to air transport in the United Kingdom are presented in table 26.

(d) Summary on the exposure to radioactive material during transport

215. In general, doses to members of the public due to the normal transport of radioactive material are verifiably very low. Some results of initial surveys on this topic are presented in table 27. More recent surveys produced similar results (table 28). In Germany, the highest conservatively estimated annual dose to members of the public due to nuclear fuel shipments was typically less than 0.1 mSv. In France, these shipments are estimated to give rise to a maximum annual dose of 0.2 mSv, while shipments of waste at a

storage facility are estimated to give rise to a maximum annual dose of 0.12 mSv, and shipments by road could lead to an annual dose of up to 0.07 mSv owing to the vehicles waiting at traffic lights. In the Netherlands, the estimated maximum annual dose due to both nuclear and non-nuclear shipments was 0.02 mSv [I5]. More recent estimates predicted annual doses of less than 0.002 mSv for critical groups [E6]. In the United Kingdom, 0.02 mSv was the maximum annual dose estimated for sea and air passengers, while annual exposures due to road and rail transport were less than 0.01 mSv [I5].

3. Applications other than nuclear power

(a) Production of radioisotopes

216. Radioisotopes are widely used in industry, medicine and research. Radiation exposures may occur owing to trace amounts being 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.

217. Estimates of doses resulting from radioisotope production and use are uncertain, owing to the limited availability of data on the commercial production of the radioisotopes and on the release fractions during 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 due to radioisotope production and use is of the order of 100 man Sv [U6].

218. An important use of radionuclides is in medical diagnostic examinations and 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 reactions, e.g. ^{123}I, ^{201}Tl). The most important radioisotope, used in 80% of all diagnostic examinations, is ^{99m}Tc (from ^{99}Mo). In many countries the production, isolation and incorporation of the radioisotopes into generators, diagnostic kits or pharmaceuticals are often carried out in different facilities, which hampers quantification of the releases resulting from the overall production.

219. Limited data on ^{131}I releases from hospitals were cited in the UNSCEAR 1993 Report [U6]. 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 a small fraction (e.g. 5×10^{-4}) of the amounts administered to patients. This seems to be confirmed by the very low concentrations of ^{131}I measured in the surface waters and sewage systems of several countries [U6], although such information seems not to be systematically collected or reported.

220. With the global annual usage of ^{131}I in therapeutic treatments estimated at 600 TBq, a release fraction of 5×10^{-4} and a dose coefficient of 0.03 man Sv/TBq for ^{131}I released in liquid effluents (taken from annex A, “Dose assessment methodologies”, of the UNSCEAR 2000 Report [U3]), the annual collective dose is estimated to be only 0.009 man Sv. The use of hold-up tanks should reduce the release of ^{99m}Tc, the other major radionuclide, to negligible levels as well.

221. In the United Kingdom, radioactive material, including radiolabelled materials for use in medicine, research and industry, is manufactured at two sites: Amersham and Cardiff. At Amersham, the total annual dose to critical groups in 2003 due to liquid discharges was assessed to be less than 5 μSv. Summing freshwater fish consumption and external exposure, doses to critical groups were estimated to be of the order of 5 μSv in 2003. The doses estimated for the critical group for terrestrial food were also less than 5 μSv in 2003. At Cardiff, the laboratory produces radiolabelled products containing ^{3}H and ^{14}C to be used in research and medical diagnostic kits. The dose to the most exposed group of seafood consumers was 24 μSv in 2003, including a contribution from external exposure. The hypothetical critical group for terrestrial foodstuffs comprised infants who ingested food produced on land conditioned by pelleted sludge from the wastewater treatment works. It was assessed that in 2003 the highest dose would have been less than 16 μSv, with doses from non-foodstuff pathways being less than 1 μSv [W6].

222. According to the results of a 2006 survey conducted by the IAEA, there were 246 cyclotrons operating in 39 IAEA Member States. The IAEA has estimated that worldwide there are about 300 cyclotrons currently operating that are involved in some aspect of radionuclide production. The number of cyclotron institutions that distribute radiopharmaceuticals, and in particular ^{18}F-labelled fluorodeoxyglucose (^{18}F FDG), is significant and growing [I37]. No information on public exposure due to the operation of cyclotrons has been found.

(b) Research reactors

223. Research reactors, given their wide variety of designs and modes of operation, as well as their wide range of uses, differ from reactors producing electrical energy. Research reactors are used for testing nuclear fuels and various materials, for investigations in nuclear and neutron physics, biology and medicine, and for the production of radioisotopes. The use of research reactors is globally much more widespread than the use of reactors for energy production. In 2003 there were 70 countries listed as having operated research reactors; among the 57 countries that still operate research reactors, there were 274 in operation; and 8 countries had a total of 10 research reactors under construction. The number of reactors is presented in figure XXV according to operational status and nominal power [I29].

224. Three sites in the United Kingdom—Dounreay, Harwell and Winfrith—house research reactors that have been or are in the process of being decommissioned. At Dounreay, the critical group of people who consumed food from the terrestrial environment was estimated to have received 6 μSv in 2003, which also includes a contribution from weapons test fallout. At Harwell, although there was no evidence that fish from the river were consumed, an assumed annual consumption rate of 1 kg was used in the dose assessment, leading to a dose estimate of 11 μSv for 2003. The dose to the critical group of local consumers from gaseous discharges was estimated to be less than 5 μSv. Doses estimated for Winfrith are of similar magnitude [W6].

(c) Consumer products

225. A number of products bought for everyday use contain low levels of radionuclides. Some of these items contain low levels of NORM, but the majority of consumer products containing radioactive substances have had the radioactive material deliberately added in order to make use of its chemical and radioactive properties. Historically the most significant radionuclide for use in radioluminous consumer products was ^{226}Ra. However, production of items luminized with radium ceased a few decades ago, with radium being replaced by ^{147}Pm and ^{3}H because these radionuclides are less radiotoxic. For timepieces containing tritium compounds, some leakage of the radioactive source may occur, because tritium is very mobile. Tritium emits only very weak beta radiation that cannot penetrate the skin, so that it contributes to the effective dose only when the tritium has entered the body [W6].

226. Ionization chamber smoke detectors are used to give an early warning of fire. Modern smoke detectors contain a small foil of ^{241}Am with an activity of not greater than 40,000 Bq. The dose rate at a distance of 2 m from a detector is about 2.4×10^{-5} μSv/h, assuming that the detector contains the maximum amount of activity. In the United Kingdom, about 80% of homes have a smoke detector fitted. Assuming an exposure of 8 h/d at a distance of 2 m from the detector results in an estimated annual dose of 0.07 μSv [W6].

227. Glass to which uranium is added to produce a yellow or green colour is called Vaseline glass. It was very popular in the 1800s and is still produced in the United States and the Czech Republic. The gamma dose rate close to the surface of the glass item is very low and was measured as less than 0.1 μSv/h. A typical surface dose rate due to beta radiation was 15 μSv/h, while the beta doses measured a few centimetres from the surface were negligible. Individual doses for some collections of uranium glass could be up to 0.5 mSv annually. However, for a large collection with a range of items, a typical maximum dose would be an order of magnitude lower. Uranium salts have also been used in the glaze on ceramic products such as tableware and tiles. They were also used as a colourant in ceramic tableware produced in the 1930s and 1940s in the United States. These items may now be found on collectors' markets. It was found that handling such items may give rise to very low levels of contamination on the skin, and the use of this tableware for eating could lead to very low ingestion doses [W6].

228. Some members of the public have collections of fossils, rocks or minerals. In some parts of the United Kingdom the native rocks contain significant concentrations of uranium and its decay products. The overall dose from such specimens under normal conditions of handling and display are only a small fraction of the overall dose from natural radiation. Photographic lenses used to have ^{232}Th added to them in order to increase the refractive index. Photographers carrying a camera with such lenses around the neck for several hours a day on many days of the year could receive an annual effective dose of a few hundred microsieverts. Currently these lenses are out of use in United Kingdom. A summary of doses associated with exposure to consumer products is presented in table 29 [W6].

229. The United States Nuclear Regulatory Commission (NRC) has assessed the potential individual and collective (population) radiation doses associated with selected products containing "by-product" material[2] [U35]. The dose assessments were in general based on reasonable assumptions, although in some cases the NRC noted that there was an absence of reliable data on the actual use of the products by individuals either in the workplace or elsewhere. The estimates reported are for effective dose equivalent to the average member of the critical group. The individual and collective dose estimates discussed here are restricted to doses estimated for the normal life cycle of a particular product or material, covering distribution and transport, intended or expected routine use, and disposal occurring over a 1 year time period. Actual or expected quantities of radioactive material in products and materials, when known, were used for estimating doses; otherwise, a value was used equal to the maximum allowed under the United States legislation on exempted quantities.

230. The estimates of individual doses incurred annually during the normal life cycle of a product or material associated with the current exemptions for by-product material in the United States ranged from less than 1×10^{-5} mSv to 0.2 mSv. A summary of individual effective doses from by-products in the United States is presented in table 30. The estimated individual doses were equal to or greater than 0.1 mSv annually for two products: *(a)* instruments used for measuring ionizing radiation that contain by-product material, with an estimated annual dose of 0.2 mSv received by a laboratory technician working with a bench-top instrument; and *(b)* spark gap irradiators containing ^{60}Co, with an estimated annual dose of 0.1 mSv received by a maintenance worker installing and maintaining spark gap irradiators.

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[2] By-product material here includes any radioactive material associated with the operation of nuclear reactors, except for the source material for nuclear fuel and the special nuclear material which constitutes the fuel in a reactor. Source material is the raw material from which nuclear fuel is made; it includes uranium or thorium in their natural isotopic abundances.

231. The estimates of collective dose incurred during the normal life cycle of these products ranged from 0.1 to 40 man Sv for 1 year's distribution of products. For two categories of products, the estimated collective doses were equal to or greater than 10 man Sv: *(a)* the collective dose arising from the use of timepieces with hands or dials containing ^{3}H or ^{147}Pm was estimated to be 40 man Sv, which was incurred mainly because of the large number of individuals who wear such timepieces (wristwatches); *(b)* the collective dose arising from the use of electron tubes containing by-product material was estimated to be 10 man Sv over the tubes' useful lifetime of 10 years. In this case, most of the collective dose would result because of the large number of people exposed to radiation from electron tubes in the home and workplace. However, individual doses are normally very low, usually less than 0.1 mSv/a.

232. The estimates of individual doses incurred annually during the normal life cycle of a product or material associated with the current use for source material ranged from less than 1×10^{-5} mSv to 40 mSv. The estimated annual individual doses exceed 10 mSv for the following two cases (table 30): *(a)* chemical mixtures, compounds, solutions or alloys containing less than 0.05% by weight source material; and *(b)* rare earth metals and compounds, mixtures and products containing not more than 0.25% by weight source material. The high estimates in these cases result from the large volumes of exempted material present in workplaces and the high concentrations of uranium and thorium in this material. These estimated doses would be reduced substantially for the case of the workers using respiratory protection.

233. The estimated annual individual doses were equal to or greater than 1 mSv but less than 10 mSv for three materials: *(a)* for unrefined and unprocessed ore containing source material, the estimated dose of 3 mSv/a to a truck driver results from the large volume of exempted material that is handled and the relatively high concentration of uranium in the material; *(b)* for incandescent gas mantles, the estimated annual dose to a person using only gas lanterns for light would be 2 mSv and that to an individual who uses portable camping lanterns would be 0.1 mSv; *(c)* for welding rods containing thorium, the estimated annual dose of 8 mSv to a dedicated grinder of welding rods probably represents an unusual situation that would occur only at construction sites where many welders are employed.

234. The estimates of collective dose incurred during the normal life cycle of a product or material associated with the current exemptions in the United States for source material ranged from 0.001 man Sv to 700 man Sv for 1 year's distribution. There are five situations for which collective dose estimates are equal to or greater than 100 man Sv: *(a)* for chemical mixtures, compounds, solutions or alloys containing less than 0.05% by weight source material, the collective dose is a combination of estimated doses due to the use of ophthalmic glass, doses due the use of phosphate slag for building construction, and doses to future on-site residents from the disposal of coal ash, phosphate slag and water treatment sludge; *(b)* for incandescent gas mantles, the users of portable camping lanterns contribute most to the collective dose. The current trend towards the use of gas mantles not containing thorium and the use of other lighting devices should significantly reduce this collective dose estimate; *(c)* for welding rods containing thorium, the collective dose estimate is 300 man Sv, although this is predominantly received by professional welders over a 1 year time period, and only a fraction of it can be related to public exposure; *(d)* for glassware, the dose due to the display of large numbers of items (in homes and museums) contributes to the collective dose; *(e)* for thorium in finished optical lenses, the estimated doses to users of 35 mm photographic cameras contribute most of the collective dose.

235. There are also two situations where the collective doses were equal to or greater than 10 man Sv but less than 100 man Sv: *(a)* for rare earth metals and compounds, mixtures and products, the contributors to collective dose are bastnaesite and cerium concentrates (industrial workers), television faceplates and waste disposal (future on-site residents at landfills); *(b)* for glazed ceramic tableware, the estimated doses are due to the display of large numbers of items (in homes and museums).

(d) Other sources of public exposure

236. Estimated potential annual doses from exposures at hospitals, institutions of higher education and other research laboratories where radioactive material is used in the United Kingdom ranged from 0.02 to 13 μSv. The highest annual dose estimated for an industrial site was 170 μSv, but the calculation assumed authorized discharge levels as opposed to actual discharge levels, which are generally much lower. Landfill sites may also give rise to exposure of members of the public. Doses in 2003 to the critical group of people who live close to the Drigg disposal facility in the United Kingdom were 46 μSv (including components due to deposits from the Chernobyl accident and to weapons tests fallout). Low levels of radioactive material may be disposed of at some landfill sites. It is estimated that the annual dose incurred by ingesting water containing a leachate arising from a landfill that accepts ^{125}I in waste would be 5 μSv. Tritium has also been detected near some landfill sites. A person drinking water from a nearby borehole with about 1,000 Bq/L would receive an annual dose of less than 12 μSv [W6].

237. The use of radioactive substances in an unsealed form is widespread in medicine. These substances are employed in nuclear medicine and radiotherapy departments for medical diagnosis and for treating cancers and other diseases with internal irradiation, and also in clinical biology and medical research laboratories. These uses result in significant volumes of radioactive waste, only a small part of which is transferred to specialist radioactive waste processing centres, while the major part is stored on the site until the activity has decreased to a level allowing the waste to be treated

as normal hospital waste. In view of the large number of establishments and departments involved and the multiple ways of managing the waste, regulatory systems have been put in place. However, chance incidents, such as the discovery of radium needles or radioactive waste in areas normally accessible to the public, or of quantities of radioactive iodine in river waters, although without consequences for public health, have nevertheless alarmed the general public [E12].

238. “Orphan radioactive source” is a term utilized by nuclear regulators to denote radioactive sources that are outside official regulatory control. Orphan sources include: sources that were never subject to regulatory control; sources that were subject to regulatory control but have since been abandoned, lost or misplaced; and sources that were stolen or removed without proper authorization. Exactly how many orphan sources there are in the world is not known, but the numbers are thought to be in the thousands. The NRC reports that United States companies have lost track of nearly 1,500 radioactive sources within the country since 1996, and more than half have never been recovered. A European Union study estimated that every year up to about 70 sources are lost from regulatory control within the Union. Although the majority of these sources would not pose a significant radiological risk, the risk of accidents is the major concern arising from orphan sources. Sealed sources or their containers can be attractive to scavengers for the scrap metal trade because they appear to be made of valuable metals and may not display a radiation warning label. Cases where unsuspecting people or even members of the public have tampered with sources have led to serious injury and in some cases death. Some of the more notable such accidents are described in annex C of the present report.

239. Orphan sources are a widespread phenomenon in the Newly Independent States (NIS) of the former Soviet Union. For example, a legacy of Georgia’s sharp economic decline after the break-up of the Soviet Union was a loss of control over radioactive sources used in industry. The collection and sale of scrap metal from abandoned factories has provided a means of livelihood for some persons, and some orphan sources have been found in shipments of scrap. Not all the incidents reflect deliberate attempts to steal radioactive sources. The great majority of the trafficking incidents detected appear to involve opportunists or unsophisticated criminals motivated by the hope of profit. In some cases, the theft of sources was incidental to the theft of vehicles. As many as 300 radioactive sources have been recovered in Georgia since the mid-1990s, and these sources have caused at least one death and many injuries to the public. In 2006, two abandoned and potentially dangerous radioactive devices were successfully secured, one in the village of Iri, where background radiation levels were elevated to 12 times above normal in the village centre, and the other in the village of Likhaura. The radioisotope in both sources was ^{137}Cs. In Moldova, several large devices containing about 130 TBq (3,500 Ci) of powdered ^{137}Cs chloride used for agricultural purposes in the former Soviet Union were found abandoned or stored in precarious conditions [G13, I36, W8].

4. Summary on exposures due to peaceful uses of man-made sources of radiation

240. A summary of dose estimates related to public exposures due to peaceful uses of man-made sources of ionizing radiation is presented in table 31. Currently available information does not allow estimates of global doses to be made, although individual doses are very low for sources unrelated to nuclear power production. Although individual doses may be up to a few millisieverts per year for specific population groups, in connection with some specific practices and exposure scenarios, the worldwide average annual per caput dose is of the order of microsieverts.

D. Use of man-made sources for military purposes

1. Nuclear tests

(a) Global fallout

241. Nuclear test explosions in the atmosphere were carried out at a number of sites, mostly located in the northern hemisphere, between 1945 and 1980. The periods of most active testing were 1952–1958 and 1961–1962. In all, 502 atmospheric tests, with a total fission and fusion yield of 440 Mt, were conducted. The number and yields of worldwide atmospheric nuclear explosions as estimated by UNSCEAR [U3] are summarized in table 32 and figure XXVI. After the Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water was signed in Moscow on 5 August 1963, nuclear test explosions were mostly conducted underground [I9]. A summary of all atmospheric and underground nuclear weapons tests by country is presented in table 33. Besides these, there were 39 safety tests that took place above ground, in which more or less fully developed nuclear devices were subjected to simulated accident conditions (i.e. the nuclear weapon cores were destroyed by means of conventional explosives, with no or very small releases of fission energy) [I12].

242. The earlier atmospheric tests remain the principal source of current radiation exposure worldwide due to nuclear weapons testing. Table 34 provides estimates of the activity of radionuclides released and globally dispersed in all atmospheric nuclear tests [U3]. Radioactive debris from an atmospheric nuclear test is partitioned between the local ground or water surface and the tropospheric and stratospheric regions, depending on the type of test, the location and the yield. The subsequent precipitation of the debris and its deposit on to the earth is termed “local fallout” when deposited locally, and “tropospheric fallout” and “stratospheric fallout” when deposited globally [I9].

243. Local fallout can contain as much as 50% of the total fallout produced in the case of above-ground tests, and includes large radioactive aerosol particles that are deposited within about 100 km of the test site. Tropospheric fallout consists of smaller aerosols that are not carried across the

tropopause after the explosion and that deposit with a mean residence time in the atmosphere of up to 30 days. During this period the debris becomes dispersed, although not well mixed, in the latitude band of the initial injection and following trajectories governed by wind patterns. From the viewpoint of human exposure, tropospheric fallout is important for nuclides with half-lives of a few days to two months, such as ^{131}I, ^{140}Ba and ^{89}Sr.

244. Stratospheric fallout, which makes up a large part of the total fallout, consists of those particles that are carried up into the stratosphere, disperse and later give rise to worldwide fallout, the major part of which occurs in the hemisphere of the initial injection. Stratospheric fallout accounts for most of the worldwide residues of long-lived fission products. The exposure of humans to fallout comprises internal irradiation (inhalation of radioactive material in surface air and ingestion of contaminated foodstuffs) and external irradiation from radioactive material present in surface air or deposited on the ground [I9]. Atmospheric processes related to dispersion and deposition of nuclear test fallout were comprehensively reviewed in the UNSCEAR 2000 Report [U3].

(i) Doses from global fallout

245. The basic input for calculations of doses due to fallout radionuclides has been the measured deposition density of ^{90}Sr. The measured annual hemispheric deposition for representative middle-latitude sites is given in table 35. General procedures for deriving dose estimates from the measured or calculated deposition densities of radionuclides were described in detail in reference [U3], and only a summary of the main conclusions from previous reports will be presented here for completeness.

246. Estimates of the total annual effective doses due to radionuclides produced in atmospheric nuclear testing are summarized in table 36, and the variation with time of the average per caput effective doses from nuclear weapons fallout is presented in figure XXVII. These results are for the average deposition of fallout radionuclides weighted according to hemisphere and the world population. Doses for specific regions of the world can be obtained by adjusting these results for the latitudinal distribution of deposition determined from ^{90}Sr measurements.

247. The estimated global average annual per caput effective dose due to atmospheric nuclear weapons testing was highest in 1963 (0.11 mSv) and subsequently declined to less than 0.005 mSv in the 2000s. External exposure generally made the largest contribution to annual doses; initially it was due to short-lived radionuclides and subsequently to ^{137}Cs. The annual doses at present are due almost equally to external exposure (53%) and internal exposure due to ingestion (47%). The dose from ^{14}C (30% of the total) now exceeds that from ingestion of other radionuclides [U3].

248. The short-lived radionuclide ^{95}Zr (with its decay product ^{95}Nb) was the main contributor to external exposure during active testing. Of the radionuclides contributing to external exposure, only ^{137}Cs has a half-life of greater than a few years, thus it became the most important contributor to annual doses after approximately 1966. At present it is the only radionuclide contributing to continuing external exposure from deposited radionuclides.

249. Several radionuclides contribute to exposure via the ingestion pathway. For the short-lived radionuclides (^{131}I, ^{140}Ba, ^{89}Sr), the exposures occur within weeks or months following deposition. Further exposure via ingestion of longer-lived radionuclides comes from ^{55}Fe and the transuranic elements. Committed doses due to the transuranic radionuclides are very low and the contributions to annual doses negligible. During active testing, ^{137}Cs was the most significant component, owing to its more immediate transfer to diet and subsequent delivery of dose. Because of the continuing transfer of the long-lived ^{90}Sr to diet, as well as the longer retention of ^{90}Sr in the body, this radionuclide became the most important contributor to dose beginning in about 1967. The short-lived radionuclides have been relatively insignificant contributors to ingestion exposure. Important contributors to inhalation exposure were ^{144}Ce, the transuranic radionuclides, ^{106}Ru, ^{91}Y, ^{95}Zr and ^{89}Sr. Deposition (and thus concentrations of these radionuclides in air) decreased rapidly after atmospheric testing ceased in 1980. Even for the long-lived transuranic radionuclides, inhalation exposure became insignificant after 1985.

250. One further contribution to the annual exposure comes from the globally dispersed radionuclides ^{3}H and ^{14}C. For both radionuclides, there is no external exposure component and only negligible exposure from inhalation; exposure arises almost entirely from ingestion. The long-lived radioisotope ^{14}C is the dominant contributor, accounting for 70% of the total effective dose commitment to the world population. However, if only 10% of the ^{14}C dose commitment is included in the comparison, i.e. if dose commitments are truncated approximately to the year 2200 (by which time all other radionuclides will have delivered effectively all of their doses), ^{14}C contributes only 19% to the truncated effective dose commitment to the world population. About one quarter of the collective dose will have been delivered by the year 2200. The global estimates include a contribution from the doses to people close to the sites used for atmospheric tests. Although this contribution is small in global terms, some local doses were substantial [I9].

(ii) Local and regional exposures

251. Local fallout can constitute as much as 50% of the total produced by surface tests and includes large radioactive aerosol particles that are deposited within about 100 km of the test site [I9]. A summary of the estimated yields in different atmospheric layers was shown in figure XXVI. Since atmospheric nuclear weapons tests were conducted in

relatively remote areas, the exposures of local populations did not contribute significantly to the global collective dose from this practice. Nevertheless, individuals living downwind of the test sites received higher doses than average.

252. Areas within a few hundred kilometres of the test site are generally designated as “local” and those within a few thousand kilometres as “regional”. A detailed description of the main characteristics of all tests can be found in reference [U3]. The locations of the main test sites are shown in figure XXVIII.

253. *Nevada test site (United States test site).* The Nevada Test Site (NTS) in the United States was the location for 86 atmospheric nuclear tests, carried out from 1951 to 1962. In addition, 38 of the approximately 800 underground tests involved releases of radioactive material. Although small in comparison with releases from the atmospheric tests, they were sufficient to be detected off-site [S22]. Additional cratering tests also injected debris into the atmosphere. Relatively few underground tests led to releases that affected local areas [U3].

254. Estimates of external exposures due to atmospheric tests at the NTS were derived from survey meter and film badge measurements for 300 communities in the local areas (at distances of less than 300 km) around the test site in Nevada and in south-western Utah. 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; the population-weighted average was 2.8 mSv. Exposures resulted primarily from short-lived gamma emitters (with half-lives of less than 100 days). The collective external whole-body dose within the 300 km closest to the NTS was about 500 man Gy, and 12,000 man Gy for the area within about 800 km of the test area [S22], arising primarily from the exposure of areas with large populations.

255. Internal exposures resulting from atmospheric testing at the NTS were estimated from deposition measurements using an environmental transfer model. Absorbed doses to organs and tissues from internal exposure were substantially less than those from external exposure, with the exception of the thyroid, to which ^{131}I from the ingestion of milk contributed relatively higher doses. Estimates of absorbed doses to the thyroid in 3,545 locally exposed individuals ranged from 0 to 4.6 Gy, with an average of 0.098 Gy. Mean thyroid doses for residents of Utah, Nevada and Arizona were estimated to be 0.17, 0.05 and 0.012 Gy, respectively [U3].

256. *Bikini and Enewetak Atolls, Marshall Islands (United States test sites).* In 1946, Bikini Atoll was the first site in the Marshall Islands to be used for nuclear weapons testing by the United States. In 1948, Eniwetok, a neighbouring atoll, replaced Bikini as the test site. In 1954, Bikini was reactivated as a test site and was used until nuclear weapons testing in the Marshall Islands was ended in 1958. Bikini Atoll was the site of 23 of the 66 tests, which were conducted under water, at ground level and above ground. The yields of the tests at Bikini Atoll amounted to about 72% of the total yield for the two test sites in the Marshall Islands.

257. Bikini Atoll, located 850 km north-west of the capital of the Marshall Islands, Majuro, comprises more than 23 islands and islets. Bikini, Eneu, Nam and Enidrik Islands account for over 70% of the land area. Bikini and Eneu are the only islands of the atoll that have had a permanent population. Before nuclear weapons testing started, the population of Bikini Atoll (at that time 167 people) was evacuated and resettled.

258. The test resulting in the most significant local exposures was the thermonuclear test Castle Bravo on 1 March 1954 at Bikini Atoll. Unexpectedly heavy local fallout occurred east of the atoll owing to a sudden and unusual change in wind direction, predominantly from the west rather than the east, on the day of the test, and an unexpected increase in fission yield. High radiation doses were received by the inhabitants of Rongelap Island (67 persons, including three in utero), about 210 km from Bikini Atoll, and by some Rongelap islanders temporarily residing on Ailinginae Atoll, about 150 km away (19 persons, including one in utero). Further east, exposures occurred at Rongerik Atoll (28 United States servicemen) and Utirik Atoll (167 persons, including eight in utero). These individuals were evacuated within a few days of the initial exposures [I9, U3].

259. Effective doses as a result of external exposures, mainly from short-lived radionuclides, ranged from 1.9 Sv on Rongelap Island and 1.1 Sv on nearby Ailinginae Atoll to 0.1 Sv on Utirik Atoll. The collective effective dose was about 160 man Sv [I9]. Equivalent doses to the thyroid, caused by several isotopes of iodine and tellurium and by external gamma radiation, were estimated to be 12, 22 and 52 Sv on average, and 42, 82 and 200 Sv maximum, to adults, nine-year-old and one-year-old children, respectively, on Rongelap Island. Exposures due to residual radiation on Utirik and Rongelap Atolls of residents who returned to these islands in 1954 and 1957, respectively, were of the order of 20–30 mSv from external irradiation and 20–140 mSv from internal exposure over the subsequent 20-year period.

260. External exposure of the servicemen on Rongerik Atoll due to the Castle Bravo test was 0.8 Sv. The Japanese fishing vessel Lucky Dragon was also in this area at the time of the test, and 23 fishermen were exposed. Their external exposures from 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 returned to its port. Thyroid doses to these fishermen were estimated at 0.2–1.2 Gy due to ^{131}I on the basis of external counting; however, since other short-lived iodine isotopes were also present, total doses to the thyroid due to inhalation over a period of five hours were estimated to have been 0.8–4.5 Gy [U3].

261. No other tests seem to have resulted in significant exposures to the population in the Pacific region, even

though press and other official spectators did observe the two Crossroads explosions, in 1946, from relatively short distances. Military and test personnel probably received some exposure from handling radioactive debris during clean-up operations [S22].

262. In 1968, following radiological surveys that had been carried out since 1958, resettlement of the Bikinian people on the atoll was approved, and in 1969 the atoll was cleared of debris. Fruit trees, including coconut, breadfruit, pandanus, papaya and banana, were replanted. Eventually, 139 Bikinians resettled there. Further radiation survey and sampling programmes showed, in 1978, a tenfold increase in the body content of ^{137}Cs for the inhabitants of Bikini Atoll; this was mainly due to increased consumption of coconut fluid for lack of adequate supplies of freshwater. In response to the high uptake of caesium in the population, the residents were again relocated [I9]. During the temporary resettlement of Bikini Atoll from 1971 to 1978, total whole-body exposures were estimated at 2–3 mSv/a [U3].

263. *Johnston Island (United States test site).* The United States used Johnston Atoll, located about 1,330 km south-west of Honolulu, Hawaii, as a launch site for 12 high-altitude nuclear tests beginning in 1958. All tests were intended as airbursts, but three resulted in unintended non-nuclear destruction that led to contamination of the atoll with radioactive debris. The contamination was primarily in the form of particulate debris, much of it being metal from the rockets accompanied by considerable amounts of fissionable plutonium and/or uranium.

264. The atoll had been a United States military installation for several decades and currently is a wildlife sanctuary. There is no evidence of native populations ever having lived on the atoll, and certainly none were present during the years of nuclear testing. Hence there is no evidence that members of the public within the immediate region were exposed to the radioactive debris from the aborted tests. The nine successful tests, because of their large yields and high altitude of detonation, contributed mostly to global fallout, as the closest populated islands would have been those of Hawaii [S22].

265. *Amchitka Island (United States test site).* The three tests on Amchitka Island, Alaska, represent 15–16% of the total effective energy released during the United States underground nuclear testing programme from 1951 to 1992. Long Shot was detonated at a depth of 716 m in 1965, Milrow was detonated at a depth of 1,220 m in 1969, and Cannikin, the largest United States underground nuclear test, was detonated at a depth of 1,790 m in 1971 [D2].

266. *Christmas Island and Malden Islands, Kiribati (United States and United Kingdom test sites).* Christmas Island and the Malden Islands in Oceania were used by the United States and the United Kingdom for testing nuclear devices. Both islands are now part of the Republic of Kiribati. The land area of Christmas Island is about 390 km^2 and its 1990 population was about 2,500. There were six British nuclear tests on Christmas Island in the period 1957–1958 and 24 United States tests in 1962 in the vicinity of the island [H7].

267. Nearby Malden Island is an uninhabited atoll today, and has been so since the British occupation in 1956. There were three British nuclear tests near Malden Island. The tests in the Pacific at Malden Island and the Christmas Islands were airbursts over the ocean or explosions of devices suspended from balloons at 300–450 m over land [U3]. Local fallout would have been minimal following these tests. Little or no information is available on exposure of the public or of civilian test personnel at either site, although Fijian troops that participated in the tests and afterwards were involved in clean-up operations made claims related to these events [S22].

268. *Monte Bello, Emu and Maralinga, Australia (United Kingdom test sites).* The United Kingdom nuclear weapons testing programme included 21 atmospheric tests at sites in Australia and the Pacific. Twelve tests were conducted between 1952 and 1957 at three sites in Australia: the Monte Bello Islands, Emu and Maralinga. The Maralinga tests included seven nuclear explosions and hundreds of minor trials involving chemically generated explosions of radioactive material. Tests conducted at the Emu site, about 200 km north of Maralinga included two nuclear explosions and five smaller-scale experiments in 1953. These tests in continental Australia led to residual radioactive contamination of the two areas, covering some hundreds of square kilometres in total [H7]. These were mainly surface tests, with yields of 60 kt or less. Trajectories of the radioactive cloud were determined for each of these tests, and local and countrywide monitoring of air and deposition were performed.

269. Estimates of local external exposures were not made for the earlier tests; for the tests in 1956 and 1957, the external effective doses were less than 1 mSv. The numbers for local populations were not indicated [U3]. Estimates of internal exposures were also made for the overall Australian population. The average effective dose was 70 μSv, 83% of which was due to internal exposures, and the collective effective dose was 700 man Sv for the overall population of Australia [S22]. A number of safety tests conducted at the Maralinga and Emu sites in South Australia resulted in the dispersion of ^{239}Pu over some hundreds of square kilometres [U3].

270. *Semipalatinsk, Kazakhstan (Soviet test site).* The Semipalatinsk test site is located in the north-east corner of Kazakhstan, 800 km north of the former capital Almaty, 400 km east of the present capital Astana and about 200 km south-west of the border with the Russian region of Altai. At this site, 456 nuclear tests were conducted, including 86 atmospheric and 30 surface tests. Five of the surface tests were not successful and resulted in dispersion of plutonium in the environment. The site covers about 19,000 km^2. The local populations most affected lived

mainly in the Semipalatinsk region of Kazakhstan (now part of the Ust-Kamenogorsk region of Kazakhstan) and the Altai region of the Russian Federation, east and north-east of the test site. Traces of radioactive contamination were also found in southerly and south-easterly directions after some tests [S22, U3].

271. The earliest tests were above ground (atmospheric and surface) and were carried out in the northern technical area Š. The centre of the first (surface) explosion historically is referred to as "Ground Zero". The 340 underground tests were conducted in widely separated technical areas in the south (between 1961 and 1989) and east (from 1968 to 1989). This total includes four cratering nuclear explosions where the explosive charge was placed at a shallow depth below ground. Chagan was the first and largest of these tests. It resulted in a lake about 0.5 km in diameter and 100 m deep, with cliffs up to 100 m high, called Lake Balapan, or the "Atomic Lake". A much smaller lake was formed by the Tel'kem-2 test. Of the tests carried out deep underground, 13 resulted in the release of radioactive gases to the atmosphere.

272. The only settlements within the nuclear test site during the 40-year test period were the town of Kurchatov, north of technical area Š (built for servicing the test site), and the small settlements of Akzhar and Moldari along its northern edge. Two tests led to the most significant exposures of the population of Kazakhstan: the first test, on 29 August 1949, and the first thermonuclear test, on 12 August 1953. These and two additional tests (24 September 1951 and 24 August 1956) are stated to have contributed 85% of the total collective effective dose from all tests combined. The accumulated effective doses for several districts were in the range 0.04–2.4 Sv. The collective effective dose for ten districts was estimated to be 3,000–4,000 man Sv. Representative average doses for seven villages close to the site (in Kazakhstan) were estimated to be 0.2–900 mGy for whole-body exposure and 0.3–3.8 Gy for thyroid exposure. Absorbed dose to the thyroid from ingestion of radioiodines is quite uncertain, but may have been as high as 8 Gy for children in the Akbulak settlement [I10, S22, U3].

273. *Novaya Zemlya, Russian Federation (Soviet test sites).* Novaya Zemlya is an island located at the most northerly edge of Europe. Soviet testing on Novaya Zemlya began in 1955. Novaya Zemlya was the site of the world's largest nuclear weapons test, a 50 Mt detonation at an altitude of about 3.5 km. In all, 91 atmospheric nuclear tests took place on Novaya Zemlya, and tests performed on the island account for about one half of the total energy yield of all nuclear tests carried out in the entire world. Only one test, in 1957, was conducted directly on the ground surface. In addition, there were two tests on the water surface and three tests under water at the site. There were also 17 underground tests that vented, in most cases resulting in on-site contamination only.

274. The nearest village, Amderma, is 280 km away, and the much larger population centre of Arkhangelsk is approximately 1,000 km away. Three villages lie at intermediate distances [S22]. Very little information is publicly available concerning the local doses resulting from those tests. It is likely, however, that doses to local residents were relatively low, as most of the atmospheric devices were exploded at high altitude so that the expanding fireballs did not touch the ground surface. Preliminary information has been presented in the open literature concerning external radiation doses at the regional scale. The average external dose for the population of the eastern part of the Russian Federation (35 million) due to regional fallout in the years 1955–2000 is about 1 mSv [L24]. Concerning ingestion exposure, it is known that ^{137}Cs is abundant in lichen, reindeer and other environmental media. The ^{137}Cs concentrations in reindeer meat are much greater than those in milk, fish, geese or ducks, and reindeer herders are likely to receive much higher internal doses than the urban residents in the area, who consume reindeer meat only occasionally. The estimated internal dose due to ^{137}Cs (and to a lesser extent to ^{90}Sr) for reindeer herders has averaged about 1 mSv annually since the early 1960s; average annual doses to urban residents are estimated to be lower by a factor of 100.

275. *Kapustin Yar, Russian Federation–Kazakhstan (Soviet test site).* Kapustin Yar is located 250 km north-west of the Caspian Sea. Soviet testing at Kapustin Yar began in 1957. In all, 10 atmospheric nuclear tests took place at Kapustin Yar over six years. Very little information is publicly available about exposures resulting from the nuclear tests launched from Kapustin Yar. All the Kapustin Yar tests were high-altitude explosions (10.4–300 km), which in general contribute more to global fallout than to local fallout [L25, S22].

276. *Reganne and In Ecker, Algeria (French test sites).* Between 1960 and 1966, France conducted a series of four atmospheric and 13 underground nuclear tests at Reganne and In-Ecker, remote sites located in the south of Algeria. The French nuclear testing programme began with four low-yield surface tests in 1960 and 1961 at a site near Reganne in the Algerian Sahara, about 50 km south-east of Reganne (a village/oasis of a few thousand inhabitants) and about 150 km south of Adrar, a city with approximately 50,000 inhabitants. No information was found regarding local exposures following these tests. It is claimed that 15 people were probably contaminated when radioactive vapour and aerosol escaped through a fissure in the rock during a test in May 1962 that was performed under adverse wind conditions. Nine soldiers received about 600 mSv, mainly due to external irradiation (>90%) [S22, U3]. No early radiological or clinical effects were observed [B12]. Some residual contamination remains at both this site and 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. No information has been located on estimates of doses to the public from the tests conducted in Algeria by France [I32].

277. *Mururoa and Fangataufa (French test sites).* The Mururoa and Fangataufa Atolls in French Polynesia, situated

in the South Pacific Ocean, have evolved from extinct submarine volcanoes, and each rests upon a massive igneous volcanic basalt substratum capped by a sedimentary carbonate coral reef platform hundreds of metres thick and surrounded by ocean water thousands of metres deep. France conducted 193 nuclear experiments above and beneath the atolls of Mururoa and Fangataufa between July 1966 and January 1996. Of these, 178 were nuclear tests, in which nuclear devices were exploded with large releases of fission energy, and 15 were safety trials. Forty-one were atmospheric tests (37 at Mururoa Atoll and 4 at Fangataufa Atoll, between July 1966 and September 1974), and 137 were underground nuclear tests (127 at Mururoa Atoll and 10 at Fangataufa Atoll, between June 1975 and January 1996). Of the 15 safety trials, all of which were carried out at Mururoa Atoll, 5 were atmospheric and 10 were underground safety trials [I12].

278. The atmospheric nuclear tests were mostly carried out at a detonation altitude that was sufficient for the fireball not to reach sea level, thereby minimizing the production of local fallout. There were, however, four atmospheric nuclear tests (three at Mururoa Atoll and one at Fangataufa Atoll) in which the devices were mounted on barges floating in the lagoon. Most of the residual radioactive material presently in the accessible environment of the atolls was produced by these nuclear tests. Five atmospheric safety trials were conducted on the northern part of Mururoa Atoll.

279. The underground nuclear tests were conducted in the basalt basement at depths of between about 500 and 1,100 m in shafts drilled vertically beneath the rims of the lagoons. Much of the residual radioactive material associated with the underground nuclear tests was trapped in molten basalt rock that solidified as glass-like lava, but some radionuclides were deposited on fractured basalt rock that collapsed into the cavity-chimney and remained available for exchange with water in the cavity-chimney. The ten underground safety trials were carried out in shafts drilled vertically beneath the rim on the north-eastern part of Mururoa Atoll. The three underground safety trials that involved some fission energy release took place in carbonate formations at depths in excess of 280 m [I12].

280. The closest inhabited atoll was Tureia (population 140) 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 in 1974) was located 1,200 km to the north-east, 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 one occasion, however, material was transferred to the central South Pacific by westerly moving eddies within a few days of the tests. French scientists have identified five tests where regional population groups were more directly exposed. A single rainout 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 ~20% of local needs, and consumption is low in any case, which limited ingestion exposures. Estimated effective doses to maximally exposed individuals from the five events combined 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 [U3].

281. *Lop Nor test site (Chinese test site)***.** The Chinese nuclear weapons testing programme was carried out at the Lop Nor test site in western China; 22 atmospheric tests and 12 underground tests were conducted between 1964 and 1988 [S22, U3]. Limited information is available in the literature on local deposition following the tests. External exposures in cities or towns within 400–800 km downwind of the test site are estimated to average about 0.044 mSv, assuming 80% indoor occupancy and a building shielding factor of 0.8 [S22].

282. The adult thyroid dose estimates range from 0.06 mGy in Taiyuan to 2.5 mGy in Lanzhou. Thyroid doses of infants would have been about 10 times higher. The average thyroid dose received by the Chinese population as a result of the tests conducted at Lop Nor was estimated to be about 0.14 mGy. Even though the average deposition density of ^{90}Sr seems to have been lower in China than in the rest of the northern hemisphere, internal doses from ^{90}Sr are estimated to be higher in China as a consequence of the diet of the Chinese population. The average effective dose resulting from intake of ^{90}Sr was estimated to be 0.27 mSv, most of this due to tests not conducted on Chinese soil.

(b) Underground tests

283. There have been 1,877 underground nuclear tests. Some gaseous radionuclides were unintentionally vented during a few underground tests, but available data are insufficient to allow an accurate assessment of the radiological impact. The total explosive yield of the underground tests is estimated to be 90 Mt, much smaller than for the earlier atmospheric tests. The yields for the tests performed by India, Pakistan and the Democratic People’s Republic of Korea (DPRK) are not included in this total. Although most of the debris remains underground, it is a potential long-term source of human exposure. The total number of tests performed by each country is shown in figure XXIX.

284. The most recent test prior to the Committee’s report was performed by the DPRK, on 9 October 2006. Between 21 and 25 October 2006, elevated levels of atmospheric ^{133}Xe were observed in Yellowknife, Canada. The measurements could not be traced back to known nuclear facilities, and applying atmospheric modelling to backtrack the dispersion shows that the amount measured is consistent (to within an order of magnitude) with simple leak scenarios assumed for a low-yield underground nuclear explosion on the Korean peninsula [S3].

(c) Nuclear weapons production

285. In addition to actual weapons tests, the installations where nuclear material was produced and weapons 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 [U6]. Especially in the earliest years of weapons production, pressures to meet production schedules and the lack of stringent waste discharge controls resulted in higher local exposures than in later years. Also, at some sites, weapons are now being dismantled.

(i) United States

286. Nuclear weapons plants in the United States included: Fernald, Ohio (materials processing); Portsmouth, Ohio, and Paducah, Kentucky (enrichment); Oak Ridge, Tennessee (enrichment, separation, manufacture of weapon parts, laboratories); Los Alamos, New Mexico (plutonium processing, weapons assembly); Rocky Flats, Colorado (manufacture of weapons parts); Hanford, Washington (plutonium production); and Savannah River, South Carolina (plutonium production). There are many more sites at which such operations were conducted and where wastes were stored or disposed of. Estimates of historical releases of radioactive material during different periods of operation of the nuclear installations have been reviewed in reference [U3].

(ii) Former Soviet Union

287. There are 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 addition, accidents contributed to background levels of contamination and to the radiation exposure of individuals living in the local and regional areas.

288. *Chelyabinsk.* The Mayak nuclear material 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 material into the Techa River occurred between 1949 and 1956. The available information on exposures to the local population was summarized in the UNSCEAR 1993 Report [U6]. The individuals most highly exposed as a result of the releases into the Techa River were residents of villages along the river, who used the river for drinking water, fishing, waterfowl breeding, watering 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, with an average individual effective dose of about 300 mSv, ranging from 36 to 1,400 mSv [A7]. Doses due to external irradiation decreased in 1956, when residents of the upper reaches of the river were moved to new locations and the most highly contaminated parts of the flood plain were enclosed. For some inhabitants, however, the Techa River contamination remains a significant source of exposure to the present day.

289. *Krasnoyarsk.* The Krasnoyarsk nuclear material production complex is located about 40 km from the city of Krasnoyarsk. The radiochemical plant for irradiated fuel reprocessing began operation in 1964. In 1985, a storage facility was put into service for spent fuel assemblies from reactors in the Soviet republics of Russia and Ukraine. There are plans to reprocess fuel from the civilian nuclear fuel cycle at the Krasnoyarsk site in the future.

290. Radioactive waste discharges from the Krasnoyarsk complex enter the Yenisei River. Trace contamination can be found along the river from the complex to the estuary, about 2,000 km away. An estimate for the collective dose resulting from radioactive discharges from the Krasnoyarsk complex during 1958–1991 was about 1,200 man Sv [U3]. The most important contributor (70%) to this dose was fish consumption. External exposure due to the contaminated flood plain accounted for 17% of the collective dose. The main radionuclides contributing to the internal dose due to fish consumption were ^{32}P, ^{24}Na, ^{54}Mn and ^{65}Zn. The main contributors to the external dose (over 90%) were gamma-emitting radionuclides, primarily ^{137}Cs, ^{60}Co and ^{152}Eu. Individual doses varied over a wide range, from 0.05 to 2.3 mSv/a. The major portion of the collective dose (about 84%) was received by populations living within 350 km of the site of the radioactive discharges.

291. In 1992, the direct-flow reactors of the Krasnoyarsk complex were shut down. This reduced considerably 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. Estimates of average annual doses for the period 1993–1996 were 30 µSv for external doses and 20 µSv for internal doses. With a local population of 200,000, the annual collective effective dose is estimated to be 10 man Sv.

292. *Tomsk.* The Siberian nuclear material 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. Radionuclides in liquid waste are discharged into the Tom River, which flows into the Ob River. An estimate for the collective dose due to radioactive discharges from the Siberian complex between 1958 and 1996 is 1,200 man Sv [U3]. During the period 1990–1992, three of the five reactors of the Siberian Complex were shut down, reducing considerably the amount of radioactive discharges to the Tom River and the annual collective dose to the population. The collective effective dose was estimated to be 200 man Sv. The largest contributor (73%) to this dose was from fish consumption. The main radionuclides contributing to the internal dose due to fish

consumption were ^{32}P and ^{24}Na. About 80% of the collective dose was received by the populations living within 30 km of the site of the radioactive discharges [U3].

(iii) United Kingdom

293. The production of nuclear material and the fabrication of weapons began in the 1950s in the United Kingdom. The work was continued for several years at sites such as Springfields (uranium processing and fuel fabrication), Capenhurst (enrichment), Sellafield (plutonium 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, radionuclide discharges were associated almost wholly with the military fuel cycle.

294. 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 at Chapelcross in Scotland.

(iv) France

295. A nuclear programme in France began in 1945 with the creation of the Commissariat à l’énergie atomique. The nuclear research laboratory at Fontenay-aux-Roses began activities the following year. The first experimental reactor went critical in 1948 and a pilot reprocessing plant began operation in 1954. A second experimental reactor 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 operated until 1968, 1980 and 1984, respectively. A full-scale reprocessing plant 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, being completed in 1966 and 1990. The systematic reporting of radionuclide discharge data may also reflect the reprocessing of commercial reactor fuel.

(v) China

296. 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. A nuclear weapons development programme was initiated in China that led to the first nuclear explosion by that country in 1964. 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. Weapons were assembled at the Jiuquan complex. Assessments of exposures due to nuclear weapons production in China have been reported and doses to populations surrounding specific installations have been estimated [U3]. This experience relates to the military fuel cycle, since China’s commercial nuclear power programme started only in the 1990s.

2. Residues in the environment

(a) Nuclear test sites

297. As described earlier, radioactive debris from an atmospheric nuclear weapons test is partitioned between the local ground or water surface and the tropospheric and stratospheric regions, depending on the type of test, the location and the yield. The subsequent precipitation or depositing of the debris is termed “local fallout” when it is locally dispersed, and “tropospheric fallout” and “stratospheric fallout” when globally dispersed.

298. Exposures due to global fallout were described earlier in this annex. Local fallout can constitute as much as 50% of the production for surface tests, and includes large radioactive aerosol particles deposited within about 100 km of the test site. In some tests, the contributions to total fallout exposure of doses to people close to the sites have been substantial, and these sites must be considered actual or potential sources of public exposure. This subsection focuses on recent efforts towards estimating potential exposures associated with present and future occupation of former nuclear test sites.

(i) Maralinga and Emu

299. As a result of the nuclear weapons tests, residual radioactive contamination in the Maralinga and Emu areas covers some hundreds of square kilometres. The possible exposures associated with present and future occupation of these areas would be mainly of local aboriginal populations, who are likely to constitute the majority of future inhabitants of the areas. The migratory lifestyle of the aboriginal people in the areas makes an assessment of population doses uncertain, and only best estimates for doses to individuals will be discussed here. The assessment has been limited to consideration of the consequences of existing surface contamination. The consequences of the removal of activity from the burial pits known to exist in the areas have not been considered [H7].

300. The possible exposure pathways foreseen are:

- Inhalation of material resuspended from the ground, including both natural wind-driven resuspension and resuspension arising from mechanical disturbance of both soil and fire ash;

- Ingestion of foodstuffs and associated soil (contamination of foodstuffs with soil and fire ash) and water ingestion; special consideration of deliberate soil ingestion (a practice called “pica”) is also discussed;
- Contamination of sores and wounds;
- External gamma irradiation due to radioactive material on the ground;
- Beta irradiation due to radioactive material on the ground and on skin and clothing.

301. A further potential exposure pathway, the handling of contaminated objects and fragments, has not been included in this assessment. Measurements have been made of these contaminated items, and doses resulting from prolonged proximity to or handling of such items may be considerable. There is, however, no information on the likelihood and duration of such exposures, and for this reason an assessment of dose has not been attempted.

302. Doses are calculated to the aboriginal population having a semi-traditional lifestyle. It may be assumed that doses to other groups will be lower, with the exception of persons carrying out particular activities such as souvenir hunting for contaminated fragments. There is also considerable difficulty in estimating individual doses realistically because of the great variability in the radionuclide levels in different areas. In areas contaminated by the atomic explosions (the “major trials”), the significant radionuclides currently are neutron activation products, principally ^{60}Co and ^{152}Eu, and fallout radionuclides, principally ^{90}Sr, and ^{155}Eu. More significant radionuclide levels remain as a result of the various chemically triggered explosions (the “minor trials”).

303. The dose assessment for different contaminated zones, identifying the critical groups and the most relevant radionuclides, is shown in table 37. The calculated doses assume 100% residence in the area over the period of a year and that caught food is obtained and cooked locally (for kangaroo, a representative and site-independent average concentration for the meat was used). There is therefore a degree of conservatism incorporated into the calculations, which is substantial for the smaller zones. A considerable range of annual effective dose estimates exists, from 0.5 mSv in the area of Emu–Totem I (at the limit of aerial detection of ^{137}Cs) to 500 mSv at Inner Taranaki. As expected, the highest doses would be incurred from occupancy in the regions immediately surrounding the test sites. Continuous occupancy in such areas is very unlikely because of their small size. Considerably lower but still significant doses would be incurred at the outermost contour lines defined by aerial survey.

(ii) Mururoa and Fangataufa

304. The aim of recent assessments of the situation at the Mururoa and Fangataufa Atolls was to estimate the radiation doses that people anywhere in the South Pacific would receive due to the residual radioactive material already present in the accessible environment of Mururoa and Fangataufa and their surrounding waters. The main scenario addressed was the release of residual radioactive material currently underground at the atolls into the lagoons or directly into the surrounding ocean as a result of the normal migration of the residual radioactive material through the geosphere, modified by the hydrogeological effects of the nuclear testing. Particular attention was paid to three radionuclides of potential radiological significance—^{239}Pu, ^{137}Cs and ^{90}Sr—and additionally to ^{3}H, which was a useful tracer for validating models.

305. There are no records of previous permanent indigenous habitation of the Mururoa and Fangataufa Atolls, although some intermittent habitation of Mururoa Atoll has occurred. The study postulated hypothetical dwellers on the atolls eating largely local seafood and locally grown produce, and estimated the upper bound of doses that might be incurred if the atolls were actually to be inhabited. It also provided a conservative estimate of the doses being received by the present population of Tureia Atoll, the nearest inhabited land (about 130 km from the Mururoa and Fangataufa Atolls).

306. The most important contributors to the overall radionuclide release rates were the 12 nuclear tests carried out at Mururoa Atoll early in the nuclear test programme. In terms of activity, tritium dominated the early releases, but with activity concentrations that were of no radiological significance. Since the tests, other radionuclides, including ^{137}Cs and ^{90}Sr, have been effectively retained underground within the basalt basement, most of their activity decaying and only small amounts being released. Plutonium continued to be released over long periods of time but at very low rates. The modelling predicted that concentrations of ^{137}Cs and $^{239+240}$Pu in the lagoon water would be unlikely to exceed present levels at any time in the future. Concentrations of ^{90}Sr and ^{3}H could rise marginally above current levels, but only during the next few decades. The dispersion of residual radioactive material throughout the ocean will lead to long-term concentrations of some radionuclides, which will decrease to background oceanic levels beyond about 100 km from the atolls. Thus at Tureia Atoll the predicted concentrations will be around background levels [I12].

(iii) Bikini

307. In 1997, the official journal of the Health Physics Society, *Health Physics*, devoted a complete issue [H16] to the consequences of nuclear weapons testing in the Marshall Islands. The information presented in this section is mainly related to the prevailing radiological circumstances and their implications for the future habitability of Bikini Atoll. Currently the significant residual radionuclides from nuclear tests that remain in the soil and the surroundings of the atoll are ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am. These are found to varying degrees in both terrestrial and marine environments. The

unique composition of coral soil, which is primarily calcium carbonate with no clay, produces a pattern of availability to plants of ^{137}Cs and ^{90}Sr very different from that for which most data (which relate to aluminium silicate clay soils of the Americas and Europe) are reported in the literature [R17].

308. Bikini Island, the primary island for habitation at Bikini Atoll, has the highest concentrations of ^{137}Cs per unit mass of soil and vegetation in the atoll. The average ^{137}Cs concentration varies over a considerable range among the atoll's islands. The average ^{137}Cs concentration in soil and vegetation on Eneu Island, the other main island of residence, is about 10–13% of that on Bikini Island. The ^{137}Cs concentrations in soil on Nam Island and Enidrik Island (the two other islands large enough for possible residence) are about 70% and 15%, respectively, of that on Bikini Island.

309. Concentrations of transuranic radionuclides ($^{239+240}$Pu and ^{241}Am), and their ratios to concentrations of ^{137}Cs and ^{90}Sr, vary around the atoll, reflecting differences in the design of the nuclear devices detonated near the various islands. In general, radionuclide concentrations decrease rapidly with depth in the soil column, although there are exceptions in parts of some islands. The activities of radionuclides per unit dry weight of soil on Bikini Island are shown in table 38. The concentration of ^{137}Cs in coconut reaches values up to 6,000 Bq/kg. Some other fruits, such as pandanus and breadfruit, have average ^{137}Cs concentrations of about 4 and 400 Bq/kg, respectively. The ^{90}Sr activities are less than 10% of the respective ^{137}Cs activities in the relevant foodstuffs. The activities of $^{239+240}$Pu and ^{241}Am are even lower than the ^{90}Sr activities [R17]. The results from resuspension studies show that the average resuspension of surface soil is very low, with resuspension factors ranging from 10^{-10} to 10^{-11} m^{-1}. On the basis of the measured activity concentrations in soil, the concentrations of $^{239+240}$Pu and ^{241}Am in air are expected to be very low, and consequently the expected contribution to doses due to radiation exposure via inhalation pathways is judged to be insignificant.

310. The residual radionuclides, ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am, are present in the atoll's lagoon, mainly in sediments but also in water and biota. Caesium-137 is found in very low concentrations in lagoon sediment, water and fish. Caesium compounds are generally highly soluble, and the major part of the original inventory of ^{137}Cs in the lagoon has long since dissolved and become mixed into the world's oceans. Strontium-90, which is chemically similar to calcium (a major component of the coral soils as calcium carbonate), competes with the very large quantities of calcium available for uptake by and distribution in marine species. It is also chemically bound in the growing coral and coral sediment, and remains in the lagoon environment primarily in the carbonate matrix. Consequently, ^{90}Sr is relatively unavailable to marine life.

311. The best estimate for the total inventory of $^{239+240}$Pu and ^{241}Am in Bikini Atoll sediments is 103 ± 25 TBq and 93 ± 10 TBq, respectively. On Bikini Island the absorbed dose rate in air measured at 1 m above the ground varied from about 0.01 to 5 mGy/a in studies conducted in August 1978. The values decay-corrected to 1999 would be about 60% of the 1978 values, i.e. from 0.006 to 3 mGy/a. Other potential routes by which exposure could occur (such as swimming or diving in the lagoon) have been analysed. The contributions to dose via these pathways were found to be so small that they could be neglected in the general dose assessment.

312. Assessments performed to evaluate the potential committed doses to the population that might in future live on Bikini Island have estimated the average annual effective dose due to external gamma radiation, based on typical local occupancy habits and decay-corrected to 1999, as 0.4 mSv. The overall annual individual dose was predicted to be about 8.0 mSv for a low-calorie diet. For a high-calorie diet assumed to consist of both imported and locally derived foods, a value of 4.0 mSv was estimated, and for a diet consisting of only locally derived foodstuffs, the overall annual dose was estimated as 15 mSv. In practice, doses resulting from a diet of locally derived foodstuffs are unlikely to be incurred under the current conditions, as the present Marshallese diet contains (and would in the near future presumably continue to contain) a substantial proportion of imported food, which is assumed to be free of residual radionuclides. The uptake of ^{137}Cs into terrestrial foodstuffs accounted for the largest fraction of the total estimated dose (table 39) [B34].

313. Transuranic radionuclides in the lagoon remain an important potential source of radiation. There is evidence that plutonium is indeed transferred from sediments into the aquatic ecosystem in small but measurable concentrations through the action of biogeochemical processes. However, the observed transfer of these radionuclides through the marine food chain to human foodstuffs is very low. The available information further indicates that actions of severe storms and hurricanes in the area over the past 40 years do not appear to have mobilized or transported the transuranic radionuclides to any significant extent [I9].

(iv) Semipalatinsk, Kazakhstan

314. Emphasis in this assessment is given to residual radioactivity from nuclear testing. As such, the main tests of interest are those that resulted in local fallout. These include the surface tests, excavation experiments and three underground tests in which an unplanned venting of radioactive material to the atmosphere occurred. In most areas outside the nuclear test site, external radiation dose rates and activity concentrations in soil are similar to typical levels in other regions and countries where no nuclear weapons testing has been carried out. The estimated annual effective dose to persons outside the nuclear test site due to residual radionuclides is 0.1 mSv at most. Actual exposures are more likely to be of the order of a few microsieverts per year, a dose rate very close to the global average due to fallout [I10].

315. Over most of the test site there is little or no residual radioactivity. However, the Ground Zero and the Lake Balapan areas are exceptions and are heavily contaminated. The only on-site inhabitants during the testing programme were in the town of Kurchatov and in the small settlements of Akzhar and Moldari along the northern edge of the site. Recently there has been limited resettlement within the area, mostly by semi-nomadic farmers and herders. There is some evidence that they have grazed animals in both the Ground Zero and the Lake Balapan areas. It is not known if there are any settlements close to the other cratering test sites.

316. Activity concentrations in soil are available for the most radiologically important radionuclides at most occupied locations off-site, but for few locations on site. Outside the nuclear test site, the results of ^{137}Cs measurements from IAEA missions in 1993 and 1994 all fell within the range 5–100 Bq/kg. Most results were at the lower end of this range, which is typical of global average fallout levels. Results for plutonium in soil fell within the range 0.2–7 Bq/kg, measured in 1991 and 1992. (For perspective, concentrations of ^{239}Pu in surface soil in south-central England as a result of weapons fallout are in the range 0.5–1.7 Bq/kg.) An exception to this is in the village of Dolon, where much higher plutonium levels (by a factor of up to 100) have been recorded.

317. The absorbed dose rates due to terrestrial sources outside the nuclear test site have been extensively measured and are shown in table 40. Taken together, the values represent the results of a survey conducted between 1991 and 1994 of approximately 600 locations around the entire nuclear test site perimeter. All nearby centres of population are believed to have been included. The values measured outside the test site are almost entirely within the range of dose rates due to natural sources measured in different countries and reported by UNSCEAR (0.024–0.160 µGy/h).

318. Measurements of activity from inside the nuclear test site are scarce in comparison with the data available for outside. The gamma spectrometry aerial survey undertaken in 1990 indicated that the absorbed dose rate over the entire test site was within the range 0.07–1 µGy/h. Measurements made at Ground Zero with survey meters indicated that the dose rate changed rapidly with increasing distance from the epicentre, such that values close to normal background levels were indicated at distances of a few hundred metres. Similar variations were observed in and around the Lake Balapan crater. High levels of actinides and fission products are present close to Ground Zero and Lake Balapan.

319. Low concentrations of artificial radionuclides in soil from the vicinity of the main settlements suggest, however, that the local food chain is unlikely to be a significant pathway of exposure. A limited food-sampling programme supports this [I10]. Drinking water samples taken from local wells outside the test site and one inside the test site indicated that ^{137}Cs and ^{90}Sr concentrations were not significant. The possible future contamination of groundwater owing to the leaching of radionuclides from underground tests must be considered, however. Air sampling carried out during 1991–1992 inside and around the test site by the former Soviet Union indicated negligible airborne levels of ^{137}Cs and $^{239+240}$Pu in Dolon and other villages.

320. External radiation exposure has been assessed from measurements of absorbed dose rates. Internal radiation exposure from inhalation has been assessed on the basis of activity concentrations in soil and assumptions regarding the levels of resuspended dust. The ingestion pathway has been modelled using environmental transfer factors (representing transfer from soil to the food chain) and a typical local diet. The ingestion of soil has also been assessed. The estimated doses to adults, assuming continuous habitation of the area, are given in table 41. The exposure of children has also been estimated, and in all cases the total annual doses are lower than those for adults. The annual dose estimated to persons living in settlements outside the test site is 0.06 mSv, with a higher value of 0.14 mSv for Dolon. Because of the conservative assumptions made in the assessment, these values are likely to be overestimates; a more realistic estimate of the dose to an average person living in the settlements is likely to be about one tenth of these estimates.

321. Two exposure scenarios were considered for the nuclear test site. The first assumes a group of visitors that stay at the highly contaminated areas for one hour per day and keep animals that take 10% of their feed from these areas. The values in table 41 indicate the level of dose that a small number of frequent visitors might receive. The external exposure pathway dominated the doses to visitors to these areas. The second scenario considered potential future settlement. The most pessimistic future scenario is one in which persons permanently inhabited the Ground Zero or Lake Balapan areas and derived all their crops and animal products from within these areas. The estimated potential future doses to permanent inhabitants are also given in table 41. External exposure would be the main exposure pathway for persons who might in the future permanently inhabit these two areas, but ingestion would also make a significant contribution, owing to the production of food in the contaminated areas. The estimated annual doses to permanent residents due to residual radioactivity on the site are about 140 mSv [I10].

322. Recent surveys at the Semipalatinsk test site highlighted the high degree of variability in the radiostrontium contamination. The highest values measured were associated with leakage from tunnels in the Degelen area, where 239 underground tests were performed, including one as part of the programme on peaceful nuclear explosions. It was also suggested that some ^{90}Sr may be in a highly mobile form and that ^{90}Sr ingestion is a comparatively important pathway of exposure compared with other radionuclide exposures at the test site and in the surrounding areas [H25].

(v) Novaya Zemlya, Russian Federation

323. Current dose rates in the Novaya Zemlya islands generally vary from 0.08 to 0.12 μGy/h, which is similar to the range observed in adjacent areas not used for testing and which essentially corresponds to natural background levels, although in small areas much higher dose rates can be detected. The internal dose rate due to ^{137}Cs (and to a lesser extent due to ^{90}Sr) for reindeer herders is estimated to have been about 1 mSv/a since the early 1960s; dose rates to urban residents were estimated to have been about 100 times lower [S22].

(vi) Nevada, United States

324. Four areas in Nevada have been used under the United States nuclear test programme: the NTS, the Tonopah Test Range, Project Shoal and the Central Nevada Test Area. The NTS encompasses 3,496 km^2 of land under the jurisdiction of the United States Department of Energy (USDOE). The Tonopah Test Range was withdrawn from public use for military use in the 1940s. Since 1956, the Tonopah Test Range has been managed by the USDOE and encompasses 1,606 km^2 of land used for defence and related research, design and testing activities. The Project Shoal Area was withdrawn from public use for purposes of underground nuclear testing. The Project Shoal underground nuclear test took place on 1963. The area is currently used by the United States Navy for testing and training for tactical manoeuvring and air support. Subsequent to an underground test in 1968, the withdrawal of public lands for the Central Nevada Test Area has remained unchanged and the area remains under the control of the USDOE. Cattle grazing and recreation are the main uses of the area around this site.

325. Radioactive waste management and disposal operations began at the NTS in the early 1960s, and low-level, transuranic mixed and classified low-level wastes have been disposed of in selected pits, trenches, landfills and boreholes on the NTS. The NTS currently serves as a disposal site for low-level waste generated by USDOE-approved operators and also as a storage site for a limited amount of transuranic mixed waste. The topography of the NTS has been altered by historic USDOE actions, particularly underground nuclear testing. The principal effect of testing has been the creation of numerous craters in Yucca Flat and on Pahute and Rainier Mesas. Underground nuclear testing has resulted in impacts on the physical environment in terms of ground motion, disruption of the geological media, surface subsidence, and contamination of the subsurface geological media and superficial soils. Waste disposal operations have also resulted in surface disturbance and the placement of material having long-term impacts on the environment. Table 42 summarizes the baseline information on the residual radionuclide inventory at the NTS.

326. Most of the areas considered in the NTS are located within the Great Basin, an area from which no surface water leaves except by evaporation. Streams in the area are ephemeral. Although precipitation is very low in the region, during extreme precipitation events there is some risk of flooding along arroyos and around playa lakes. Throughout the region, springs are the only natural sources of perennial surface water, but they are not used for human consumption. A considerable volume of groundwater, estimated at 2.7×10^9 m^3, is held in recoverable storage beneath the NTS and the surrounding region.

327. Radioactive contamination of surface areas at the NTS resulted primarily from the atmospheric testing of nuclear weapons between 1951 and 1962. Additionally, safety tests conducted at the surface between 1954 and 1963 resulted in radioactive contamination of the soil. More than 200 areas that are controlled because of radioactive contamination have been identified and mapped on the NTS.

328. More than 800 underground nuclear tests have been conducted at the NTS. Underground testing has resulted in unavoidable adverse impacts to portions of the land and the geological and groundwater resources, making them unusable for most purposes. Pockets of radioactive contamination surround each underground test location. From data on the number and dates of the underground tests at the NTS, the total activity of radionuclides remaining underground is estimated to be 1.1×10^{19} Bq. Much of this radioactive material remains captured in the original cavity and thus is not available to leach into the groundwater. The impacts of conducting subcritical experiments underground would be much less than those of nuclear testing, since no self-sustaining fission chain reactions occur and much less radioactive material is deposited in the geological environment. As in the case of nuclear testing, the radioactive material is captured underground.

329. Underground nuclear testing has resulted in the contamination of groundwater in the immediate vicinity of a number of tests. The quality of the groundwater has been impaired, but only in these limited areas. No radioactive contamination attributable to USDOE activities has been detected in monitoring wells outside the NTS. Detection of significant contamination is limited to underground testing areas on the NTS. Tritium-contaminated groundwater exists in the subsurface as a result of past underground testing of nuclear weapons performed within the NTS and at two off-site locations, the Project Shoal Area and the Central Nevada Test Area. On the basis of the combined results of studies performed by various authors, the estimated range of peak tritium concentrations at the area of uncontrolled use closest to the NTS varies from 0.02 Bq/L at 150 years after the beginning of migration to 1.4×10^5 Bq/L in 25–94 years. The migration of tritium-contaminated groundwater from the test location at the Project Shoal Area could result in peak concentrations ranging from 1×10^4 to 2.7×10^7 Bq/L at the boundary of the controlled area between 71 and 206 years after the test. No public water well currently exists at this location.

330. The environmental impacts related to the waste management programme are minor compared with those of the other programmes. Underground nuclear detonations create underground cavities into which the soil and rock above the cavity then collapse. The final result is a crater on the surface. Low-level waste at the Area 3 Radioactive Waste Management Site is disposed of in subsidence craters formed from past underground nuclear tests. Waste management programme operations in Area 5 are more diverse and include facilities for hazardous and mixed-waste management in addition to low-level-waste management facilities. After 30 years of waste disposal operations, the USDOE has not detected any contamination in groundwater monitoring wells recently completed near this area.

(vii) Reganne and In Ecker, Algeria

331. Though the Reganne site is at present not sealed off, access to the area of the test sites has been and continues to be restricted by military control. There are practically no roads leading to the Algerian test sites, making access very difficult. A survey has recently been performed at the nuclear test sites [I32]. External dose rate measurements were made at 76 locations. A total of 25 environmental samples were collected. While the number of dose rate measurements was considered adequate, the number of samples collected and analysed was somewhat small, in view of the size of the areas. Most of the areas at the test sites have little residual radioactive material except: *(a)* the ground zero locations of the Gerboise Blanche and Gerboise Bleue atmospheric tests at the Reganne test site, where the areas that have elevated external dose rates are only a very small part of the tracts surveyed and are confined to distances of a few hundred metres from the four individual ground zero points; and *(b)* at Taourirt Tan Afella in the vicinity of the E2 tunnel, where at the opening of one of the partially confined underground tests an accidental release of fission products mixed with molten rock took place and formed a large bed of hardened lava.

332. Despite the preliminary nature of the sampling and investigation programme, all conclusions indicate that present-day exposure rates do not justify a requirement for intervention, in view of the current state of development of the region. However, if the economic conditions change in the area, the requirement for intervention at the Gerboise Bleue, Gerboise Blanche and E2 tunnel sites should be reconsidered. At Reganne, for occasional visitors to the site, exposures to external radiation due to residual radionuclides from the tests are likely to be low, i.e. less than a few microsieverts per day, while the area at Taourirt Tan Afella has been protected from public intrusion by a security fence.

333. In addition to the above-mentioned sites, at the Adrar Tikertine experimental site, at In Ecker, plutonium in fine particulate form was spread over a wide area. The concentration of plutonium in sand was determined from a small number of samples that were not sufficient to be representative of the area and which therefore could not be used for a detailed or precise evaluation of the inventory or specific distribution of activity in the Adrar Tikertine area. Nevertheless, the activity concentration of anthropogenic radionuclides in those samples was generally below laboratory detection limits. Thus it is expected that the residual surface contamination from the plutonium dispersion experiments is unlikely to give rise to doses to nomadic herders or their families exceeding 1 mSv/a [I32].

(viii) Lop Nor, China

334. Lop Nor, located in central Asia in a vast desert region in western China, was the location for 34 nuclear weapons tests conducted between 1964 and 1988; of these, 22 were atmospheric tests and 12 were underground. Little information is publicly available on doses received by the public or by test personnel in China. It is known, however, that the trajectory of the cloud carrying radioactive debris was determined for each test. The Ministry of Public Health set up a nationwide monitoring network for environmental radioactivity in the early 1960s, but the Lop Nor test site has never been opened to Western scientists and no information could be located on present levels of contamination and public exposure, although available information indicates that the site was made a reserve for the highly endangered Bactrian camel [S22].

(ix) Amchitka, United States

335. Following a report stating that there was radioactive leakage from the test site to terrestrial and freshwater environments, recent surveys determined tritium concentrations in surface water in the range 0.41–0.74 Bq/L at the sites sampled, which included the reported leakage sites. Only at the Long Shot test site, where leakage of radioactive gases to the near surface occurred in 1965, were higher ^{3}H levels (5.8 Bq/L) still observed in 1997. The mean ^{240}Pu/^{239}Pu value for all of the Amchitka samples was 0.1991, with values ranging from 0.1824 to 0.2431.

336. The measured ^{3}H levels and ^{240}Pu/^{239}Pu ratios in freshwater moss and sediments at Amchitka provide no evidence of leakage occurring at the sites. Deviations from the mean ^{240}Pu/^{239}Pu ratios for global fallout were observed in marine algae, sediment and pooled Amchitka samples, and may suggest another source of plutonium release to the marine environment; however, uncertainties in analyses and environmental processes need to be fully assessed before any firm conclusions can be drawn. These results do not necessarily mean that leakage from the Amchitka underground nuclear tests is not occurring or will not occur into the North Pacific Ocean or the Bering Sea. Hydrogeological modelling predicts that leakage of ^{3}H from the test sites into the marine water might be seen beginning 20 to 3,000 years from now [D2].

(b) Sites contaminated by non-nuclear tests

(i) War sites contaminated with depleted uranium

337. During the enrichment process for natural uranium, the ^{235}U fraction is increased from its natural level (0.72% by mass) to 2% or more. The uranium that remains after the enriched fraction has been removed has reduced concentrations of ^{235}U and ^{234}U. This by-product is known as depleted uranium (DU). The ^{235}U content in DU is depleted to 0.2–0.3%, about one third of its original natural fraction [U17]. Since ^{234}U is a lighter isotope, its concentration is correspondingly higher in fuel uranium and lower in DU compared with natural uranium. The fact that DU has lower concentrations of ^{235}U and ^{234}U than natural uranium also means that DU is less radioactive than natural uranium. Only traces of isotopes beyond ^{234}Th and ^{231}Th in the decay chain are present in DU, as the other decay products have not had time to build up in significant quantities in the time since the DU was originally produced. The total specific activity of natural uranium is 25.4 Bq/mg, while that of DU is 14.2 Bq/mg. Table 43 gives the main physical properties of the three isotopes of uranium and compares their relative abundance by mass and activity in natural uranium and DU [U17].

338. DU has been used for both civilian and military purposes for many years. The civilian applications include uses in radiation shielding or as counterweights in aircraft. DU is also used for heavy tank armour. Armour made of DU is much more resistant to penetration by anti-armour munitions than conventional hard rolled steel armour plate. Also, owing to its high density, its high melting point and its property of becoming “sharper” as it penetrates armour plating, DU is used in anti-tank munitions. DU is pyrophoric; on impact against its target, a DU penetrator will ignite, breaking up into fragments and forming an aerosol of particles (“DU dust”) that can ignite spontaneously in air [I24].

339. Both tanks and aircraft can fire DU munitions, with tanks firing larger-calibre rounds (105 and 120 mm) and aircraft firing smaller-calibre rounds (25 and 30 mm). Typically the DU round fired by A-10 aircraft has a conical DU penetrator, 95 mm in length and with a diameter at the base of 16 mm, fixed inside an aluminium jacket. The weight of one penetrator is approximately 300 g [U20]. When the penetrator hits an armoured vehicle, the penetrator continues through the armouring while the jacket usually remains outside.

340. A typical burst of fire by an A-10 aircraft occurs for 2–3 s and involves 120 to 195 rounds. These hit the ground in a straight line, 1–3 m apart, depending on the angle of the approach. Penetrators that either hit non-armoured targets or miss targets will generally remain intact and become buried in the ground. The depth depends on the angle of the approach, the speed of the plane, the type of target and the nature of the ground surface. In clay soils, penetrators used by A-10 attack aircraft may reach a depth of more than 2 m. Conversely, penetrators hitting hard objects such as rocks and stones may ricochet and be found lying on the surface some distance from the targeted area [U20].

341. Normally 10–35% (maximum 70%) of the round becomes aerosol on impact with armour. Most of the dust particles are less than 5 µm in diameter and can be dispersed in the environment, spreading according to wind direction. The amount of dust produced is actually small, because the vast majority of DU munitions miss their targets or hit soft targets and remain intact. The dispersion of the DU dust leads to resuspended activity in the air and subsequent deposition on the ground. However, such radioactive material should be limited to within about 100 m of the target. In a combat situation, the main radiological hazard associated with DU munitions is inhalation of the aerosols created when DU munitions hit an armoured target [U20].

342. Small penetrator fragments and DU dust are gradually transported into the upper soil layer by weathering processes. Wind, rainwater or surface water flow may also redistribute the dust. Mobilization of DU through the soil profile and the possible migration of DU into groundwater will depend on a number of factors, such as the chemistry and structure of the surrounding soil, rainfall and hydrology [U20].

343. The alpha particles emitted by DU are very energetic but have a very limited range in tissue. They can barely penetrate the external layer of the skin and hence do not pose a hazard in terms of external irradiation, but internal irradiation is an important consideration. Uranium is not generally transferred effectively through food chains; therefore, in environmental assessments, inhalation is the exposure pathway that usually merits primary attention. Processes such as migration through the soil, deposition of resuspended material on to crops and transfer to groundwater may, however, be of interest in the longer term [I24].

344. The only exposure of concern may arise from external beta radiation to the skin if a penetrator is placed in a pocket or is used as an ornament worn on a neck chain. This could result in quite high localized radiation doses after some weeks of continuous exposure. Although there will not be any radiation skin burns, erythema may occur. The resulting gamma radiation exposure will be insignificant, of the same order of magnitude as natural radiation, at most [U17].

345. Although it has been suggested that DU from munitions remaining in Kosovo or other locations may migrate to groundwater, the uranium concentration arising from this source would be undetectable compared with naturally occurring concentrations in water. Oeh et al. [O3] measured water samples and the urinary excretion of uranium in a region of Kosovo where DU munitions were deployed. More than 1,300 urine samples from peacekeeping personnel and unexposed controls of different genders and ages were analysed. The urine measurements for 113 unexposed subjects had a uranium excretion rate of 13.9 ng/d (geometric standard deviation (GSD) = 2.17). The analysis of 1,228 urine

samples from the peacekeeping personnel resulted in a geometric mean of 12.8 ng/d (GSD = 2.60). No DU could be found in any water samples, and there was no difference between urine samples from persons potentially exposed and controls.

346. Metallic DU reacts chemically in the same way as metallic uranium, which is considered to be a reactive material. Studies carried out on penetrators collected in Kosovo, Serbia and Montenegro showed that ground impact caused numerous fine cracks in penetrators. This favours subsequent corrosion and dissolution [U17]. Corrosion occurs relatively quickly when the penetrator remains in the ground and is surrounded by soil. A penetrator can be completely corroded in the 25–35 years following impact. The corrosion products may in turn dissolve and disperse in water. However, the rate of corrosion depends on the composition of the soil. If the penetrator is lying on the ground surface, the corrosion rate is significantly lower. However, the corroded uranium is loosely attached and easily removable. Consequently, if such a penetrator is picked up, it could easily contaminate the skin and clothing of anyone handling it. Buried penetrators and jackets may inadvertently be brought to the surface in the future through digging as part of soil removal or construction work. The corresponding exposures would then be the same as for penetrators and jackets currently lying on the surface.

347. There have been reports that the DU in munitions contained small amounts of other radionuclides, such as isotopes of americium and plutonium as well as ^{236}U. The presence of these man-made radionuclides indicated that some of the DU had been obtained from uranium that had been irradiated in nuclear reactors and subsequently reprocessed, or resulted from contamination of equipment in the processing plant during the reprocessing of spent nuclear fuel [I24].

348. Doses to members of the public living in areas where they could be exposed to DU munitions are very low [I24]. There are several possible pathways through which populations in these areas may be exposed to radiation emitted by DU munitions. The most significant pathway is inhalation of DU particles that have been resuspended either by the wind or by human activities such as ploughing. Fragments of DU can be brought to the surface during the construction of houses, roads, etc. Lumps of DU lying on the ground surface (either complete penetrators or penetrator fragments) can be picked up by members of the public. Consequently, there is a possibility of people being exposed to external beta and gamma radiation and to internal radiation if dust from corroded DU or DU fragments enter the body. The surface radiation from DU includes beta and gamma radiation from its decay product, ^{234}Th. The external dose due to direct contact with DU fragments has been estimated to be 2.3 mSv/h [F7, I24, U17, U20].

349. As mentioned above, the jacket is the non-DU part of a weapon projectile that encases the DU penetrator. The projectile is designed so that the jacket stops upon impact against a hard surface while the penetrator enters the target. Potential exposures arising from jackets are far lower than from penetrators, because the jackets are made of aluminium rather than DU, of which they have only very low levels [U17].

350. It has been confirmed that DU munitions have been used in several recent military conflicts, including the Gulf War in 1991, the conflicts in Bosnia Herzegovina in 1994 and in Kosovo in 1999. It was probably also used in the 2003 Iraq war. Available estimates of the total munitions used in each conflict are presented in table 44.

351. *Kuwait.* The 1991 Gulf War was the first conflict in which DU munitions were used extensively. The total number of rounds expended in the Gulf War is estimated to be about 860,600, representing a total weight of DU of about 286 t [I24]. Of the 3,700 Iraqi army tanks destroyed during the Gulf War, DU munitions accounted for only around 500.

352. A large number of DU munitions were stockpiled on the United States military base of Camp Doha when a fire broke out on 11 July 1991. After the immediate clean-up operations, approximately 300 DU penetrators (corresponding to a total of 1,500 kg of DU) were found to be missing. The area was fenced and access to it restricted. In 2001, remediation actions were conducted. There was evidence of the presence of DU in environmental samples, but the concentrations of ^{238}U were more than two orders of magnitude lower than the values observed in the soil prior to remediation. A person spending several hours each day working on the site could receive a dose of 7.7 μSv over the course of a year, mainly from inhalation of resuspended material. Individuals using the area for recreational purposes would receive doses of about one sixth of this. Access to the area remains restricted, and actual doses due to DU to people working or spending time nearby would be lower still [U24].

353. At the Military Hospital storage site, adjacent to the area where contaminated tanks had been stored, some DU was present in the top 5 cm soil layer. However, the highest concentrations of ^{238}U observed were only about two to four times the value expected from the natural background levels across Kuwait. A person who worked on this part of the site could receive an annual dose due to DU of about 3.3 μSv, almost entirely via inhalation of resuspended material. Annual doses to members of the public using the area for recreation would be less than 1 μSv. Doses to members of the public making use of nearby facilities would be lower still [U24].

354. The site of Um Al Kwaty is used to store several thousand Iraqi military vehicles destroyed during the war, among them 105 tanks contaminated with DU. It is estimated that the tanks stored at the site have a total of about 1 t of DU associated with them. The site also contains 366 heaps of contaminated soil from Al Doha that contain ash from the fire at Camp Doha, fragments of munitions and other

metallic debris. The debris is estimated to contain about 1.5 t of DU. Access to the site is currently restricted [U24].

355. DU rounds were used in an attack on a convoy of Iraqi vehicles at Al Mutlaa, a major and expanding urban area with a population of about 50,000. Vehicles destroyed in the attack have been removed and the road has been completely resurfaced. None of the samples of either soil or vegetation contained detectable amounts of DU, and the concentrations of ^{238}U in the soil samples were consistent with the values expected generally in soil in Kuwait.

356. The Manageesh oilfields cover a very large area southwest of Kuwait City. During the Gulf War they were subjected to repeated air raids involving DU munitions. The area as a whole is thought still to contain several hundred unexploded landmines and cluster bombs. Access to this area is also restricted.

357. Overall, it cannot be excluded that fragments of DU penetrators or entire munitions might still be found and collected by members of the public at locations in Kuwait where DU munitions were used in the 1991 Gulf War. Prolonged skin contact with these DU residues is the only possible exposure pathway that could result in exposures of radiological significance. As long as access to the areas remains restricted, the likelihood that members of the public could pick up or otherwise come into contact with these residues is low [U24].

358. *Bosnia and Herzegovina.* There are 15 target sites confirmed by the North Atlantic Treaty Organization (NATO) in Bosnia and Herzegovina where DU munitions were used, of which one is inaccessible because of the presence of mines. There are also six NATO target sites in the vicinity of Sarajevo for which the coordinates are still missing. These sites could therefore not be investigated. Three of the 14 sites investigated by the United Nations Environment Programme (UNEP) clearly showed DU contamination, confirming the earlier use of DU ordnance. No DU contamination was found at the other 11 sites investigated. None of these sites showed signs of widespread contamination of the ground surface. Ground surface DU contamination was typically limited to areas within 1–2 m of penetrators and localized points of contamination caused by penetrator impacts. Almost 300 contamination points were identified during the mission, but most of them were only slightly contaminated. Given that several thousand DU rounds were reportedly fired against the target sites investigated, the number found is low. It is possible that the majority of the penetrators are buried deep in the ground [U18].

359. DU could be clearly identified in one of the drinking water samples. A second drinking water sample from a well showed traces of DU contamination, which were detectable only through the use of mass spectrometric measurements. DU was found in lichen samples at the three sites mentioned above. There are no reasons to expect the presence of any DU in food, owing to the low dispersion rate in the ground and the low uptake factor in food. DU contamination in air was found at two sites where DU use had been confirmed. The concentrations were very low, and the resulting radiation doses were minor and insignificant. At distances of over 100 m from contaminated areas, no DU could be detected in the air [U18].

360. *Kosovo.* During the Kosovo conflict in 1999, DU weapons were fired from NATO aircraft; it has been reported that over 30,000 rounds of DU were used. Because of the risks posed by mines and unexploded ordnance, the sites investigated by UNEP in 2000 were limited compared with the total area potentially affected by the use of DU in Kosovo and represented some 12% of all sites attacked using DU munitions during the Kosovo conflict [U20].

361. No significant widespread contamination of ground surfaces or soil was found in Kosovo, although localized points of concentrated contamination close to penetrator impact sites or penetrator holes exist. The levels of DU detected decreased rapidly with distance from impact points, the maximum distance at which levels were still measurable being 10–50 m. When a penetrator or a jacket was found on the surface of the ground, the soil below the penetrator normally had measurable levels of DU. The area of the impact point was normally small, i.e. less than 0.04 m^2, but the relative concentration of DU at such a point could be high. The absolute concentration of DU in soil varied from a few milligrams of DU per kilogram of soil to about 18 g of DU per kilogram of soil, which corresponded to about 6% of the weight of a penetrator.

362. The depth of soil beneath impact points with measurable DU levels was normally in the range 10–20 cm, with the activity concentration decreasing with increasing depth. This vertical distribution probably resulted from the dissolution and dispersion of DU following the initial surface contamination or from the penetrator lying on the surface. However, the amount of DU at the impact points was very low and the corresponding exposures insignificant.

363. The surface of penetrators was probably subject to oxidation, as part of the radioactive material was easily removed from the oxidized surface. However, the amount was very low, about 10^{-5} of the mass of the penetrator, i.e. a few milligrams. As in the case of the penetrators, the soil beneath a jacket had measurable activity to a depth of 15–20 cm. The potential exposure to radiation arising from the jackets is much lower than from the penetrators, because the jackets are not made of DU and are only slightly contaminated [U20].

364. It is probable that many penetrators and jackets remain hidden at some metres depth in the ground. No measurable levels of DU were found in houses, vehicles or other objects. Results on the levels in botanical material were not conclusive except for lichen (and possibly bark). No measurable levels of DU were found in milk samples taken from cows grazing in fields that potentially might have elevated levels of DU [U20].

365. *Serbia and Montenegro.* In Serbia, significant levels of DU were found at localized points in the immediate vicinity of penetrators lying on the ground and around penetrator impact marks/holes. The levels of DU detected decreased rapidly with distance from such points, and beyond a distance of one metre were no longer detectable by field measurements. Laboratory analyses of soil samples, however, enabled activity levels to be traced for several metres further from the points. More detailed laboratory analyses of soil samples revealed widespread low levels of DU at five of the six study sites [U17].

366. Localized points of increased activity can occur at sites of penetrator impacts or close to a penetrator that has remained on the surface and been subject to corrosion. The concentration of DU can be very high at these points, but the extent of the increased activity is very limited, normally within a radius of 1 m, and the total amount varies widely, being in the range 0.01–10 g of DU per kilogram soil. Beneath these points, the activity levels are measurable in soil down to a depth of 10–20 cm or more, with the activity concentration decreasing with increasing depth [U20]. The penetrators recovered had decreased in mass by 10–15% because of corrosion. This has important implications for decontamination approaches as well as for possible future migration into groundwater. DU was not present in any of the groundwater or drinking water samples [U17].

367. Airborne DU particles were detected at two of the six sites. While these particles may have become airborne from on-site digging operations, the finding highlighted the possibility of exposure pathways associated with soil disturbance at DU sites. The overall exposure to DU decreases with time as the exposure via airborne contamination from resuspension of DU dust on the ground surface decreases with time. On the other hand, the probability of DU migration in soil increases with time, owing to the corrosion of DU penetrators [U17]. Many penetrators were found to be heavily corroded, and given a similar rate of corrosion, those penetrators still on the surface may have more or less disappeared from the environment (as solid objects) within 10–20 years. What happens in the case of penetrators buried deep in the ground is not yet known.

368. Uranium concentrations were within the normal range for uranium concentration in drinking water. The concentrations of uranium in air samples were also varied within the normal range, even though they were in the upper part of that range. The UNEP mission to Kosovo in 2000 found that lichen appears to be a bioindicator of airborne DU contamination.

369. *Iraq.* At the time of writing, there were no conclusive results publicly available from assessments of DU levels in the environment in Iraq. Also, the amount of DU munitions used and the sites of impact in the 2003 conflict are unknown. No conclusions on the current situation regarding public exposure due to DU in Iraq can be drawn at present. Preliminary surveys of “hot spots” in Iraq have not detected environmental contamination with DU, but contamination is still anticipated to be found, as many of the destroyed Iraqi tanks and armoured personnel carriers were hit by DU rounds, normally 2–7 times per armoured vehicle. These vehicles are therefore expected to have extensive DU contamination in the form of dust and large fragments [U19]. Urine analysis in United States personnel who served in the conflict has been inconclusive regarding exposure to DU [M24].

(ii) Contaminated sites in the Russian Federation

370. The Russian Federation inherited from the former Soviet Union several thousand square kilometres of radionuclide-contaminated land and some tens of petabecquerels of radioactive waste. Environmental contamination began and was particularly intensive in the early years of the “Atomic Project” activities initiated in the mid-1940s [V10]. At present in the Russian Federation, about 650 million cubic metres of liquid and solid radioactive waste with a total activity of approximately 7.4×10^{19} Bq (2 billion curies) have been accumulated. In addition, approximately 12,000 t of spent nuclear fuel, with a total activity of about 3×10^{20} Bq (8.2 billion curies), are kept at the sites of Minatom and other agencies in the Russian Federation [L2].

371. The total land area contaminated with radionuclides as a result of activities of the Minatom enterprises is about 480 km^2. About 15% of the total area contaminated with radionuclides has gamma radiation exposure rates of above 2 μGy/h [L2]. More than 90% of this land, i.e. 65.7 km^2, was contaminated as a result of the accident at the Mayak complex in 1957 [V10]. The main sites and contaminated areas are described in table 45. An area of about 0.26 km^2 was restored in the period 1996–1999, and rehabilitation of 13.5 km^2 of contaminated land is planned for the period 2001–2010 [L2].

372. At uranium ore mining and milling enterprises, more than 300 million tonnes of solid waste (in dumps of barren rocks and unspecified ores, etc.) and about 60 million cubic metres of liquid waste (in tailings dumps) have accumulated up to the present time. Their total activity (due to radionuclides of uranium and its decay products) is about 7×10^{15} Bq. The total area occupied by the dumps is 9.871 km^2 [L2].

373. Chemical and metallurgical enterprises for nuclear material and fuel element production have accumulated more than 600,000 m^3 of liquid radioactive waste and about 5 million tonnes of solid radioactive waste, containing radionuclides of uranium, thorium and their decay products with total activity of over 1.6×10^{14} Bq (4,200 Ci). The area of land contaminated with radionuclides is 1.868 km^2, including 0.464 km^2 with exposure rates in the range 2–10 μGy/h (200–1000 μR/h).

374. In 1999 there were 50 operating nuclear research reactors and critical or subcritical assemblies in the Russian Federation, 53 facilities whose operation had been suspended

or that were in the process of decommissioning, and 6 facilities under construction. Spent nuclear fuel from the research facilities was concentrated mainly at the following sites: the Russian Research Centre Kurchatov Institute; the Institute of Physics and Power Engineering; the Research Institute of Atomic Reactors; the Sverdlovsk Branch of the Research and Development Institute of Power Engineering; the St. Petersburg Institute of Nuclear Physics of the Russian Academy of Sciences; and the Karpov Physical and Chemical Research Institute's branch in Obninsk. The interim storage facilities for spent nuclear fuel are 80% filled on average [L2].

375. At the Mayak Industrial Association, studies were carried out on Karachai Lake, which is being filled with soil. Beginning in 1951, the lake was used for the discharge of medium- and high-level liquid radioactive waste. Stage-by-stage remediation of the water reservoir was started in 1988. At present, as a result of the remediation actions, the average area of Karachai Lake has been reduced by a factor of over 3 (to 100,000 m^2), which has significantly reduced the emanation of radioactive aerosols from the water surface and shoreline and their subsequent transport by wind. This work is soon to be completed [L2].

376. At the Mining and Chemical Complex, two of the three uranium–graphite production reactors have already been shut down. Many years of reactor operation led to the accumulation of radioactive silts in cooling and storage ponds, and also caused contamination of the Yenisei River flood plain. Contamination levels in the Yenisei flood plain began to decline when the reactors with once-through cooling were shut down. Dose rates in the range 0.08–0.4 μSv/h have been measured in populated areas along the Yenisei River. As a result of the shutdown of these once-through reactors, radionuclide discharges into the Yenisei River have decreased by a factor of over 10, and the present exposure rate at the water surface does not exceed allowable values, even at the discharge point [L2].

377. Up to 2000, the Russian Navy had withdrawn 184 nuclear submarines from service. Of these, 108 were in the north-west part of the country (the Murmansk and Archangel regions) and 76 were in the Far East (Primorsk and the Kamchatka region). Spent nuclear fuel was not unloaded from most of the submarines. A number of the nuclear submarines were withdrawn from service over 10–15 years ago, and defects in the vessels' structures have appeared during this long period afloat. The nuclear submarines with spent nuclear fuel on board represent a serious potential radiation hazard to the environment [L2, V10].

(iii) Contaminated sites in the United States

378. The main contaminated sites in the United States are usually related to the mining of uranium and of other products that have uranium associated with the ore (such as phosphate rocks), to the processing of monazite, to industries dealing with radium, to fuel preparation for nuclear power plants and to research institutions associated with defence programmes.

379. The United States Environmental Protection Agency (EPA) coordinates a project aimed at identifying and cleaning up contaminated areas throughout the country. It has listed 84 sites contaminated with radionuclides; of these, 61 are currently on the EPA's National Priority List. Of these, 14 sites are directly linked with United States nuclear military programme operations (i.e. USDOE sites): Brookhaven National Laboratory, New York state; Feed Material Production Center, Ohio; Hanford Areas 100, 200 and 300, Washington state; Idaho National Engineering Laboratory, Idaho; Lawrence Livermore National Laboratories, California; Monticello Mill Tailings, Utah; Mound Plant, Ohio; Oak River Reservation, Tennessee; Paducah Gaseous Diffusion Plant, Kentucky; Rocky Flats Plant, Colorado; Savannah River Site, South Carolina; and Weldon Spring, Missouri. Four sites are related to the production of radium devices and products, and eight sites are related to NORM, mainly phosphate ore processing and heavy-metal smelting. About 25 sites have been contaminated by improper waste disposal or by the use of waste as landfill; some of these sites are inside military installations. The main concern for such sites is related to the public exposure due to possible contamination of groundwater. For the other sites, the origin of the radioactive contamination is not clear, except for one site, reported to have been contaminated as a result of radiopharmaceutical manufacture [E5]. A large national programme called the Superfund targets the clean-up of hazardous contaminated sites and is conducting recovery operations at most of the sites listed; for some of them remedial operations have already been completed.

(iv) Contaminated sites in the European Union

380. The Dounreay nuclear site, located on the north coast of Scotland, United Kingdom, was responsible for the release of an unknown quantity of approximately sand-sized fragments of irradiated nuclear fuel during the late 1950s, 1960s and 1970s. The first Dounreay hot particle to be formally identified was recovered from the Dounreay foreshore in 1983. A further single particle was recovered from Sandside Beach the following year. Particles have been detected and removed from the Dounreay foreshore regularly since 1984 and from the offshore sediments since 1997. Over 1,200 individual particles have since been found in the littoral (intertidal) and marine environments in the vicinity of Dounreay, including Sandside Beach (1 km west of Dounreay), the Dounreay foreshore, Dunnet Beach and Murkle Beach (both approximately 25 km east of Dounreay), and in marine sediments adjacent to the Dounreay site. In addition, 86 particles have been found on the Dounreay site itself (table 46).

381. Particles are detected in the environment by their ^{137}Cs gamma activity, but the total activity is dominated by the beta emitters ^{90}Sr and its associated ^{90}Y. The particles were

produced during the reprocessing of fuel at Dounreay during the late 1950s, 1960s and 1970s. Two main types of particle, produced from Materials Test Reactor and Dounreay Fast Reactor fuel, have been identified. Materials Test Reactor particles, which make up ~80% of the total recovered, were produced as a result of fault conditions during milling and cropping operations, prior to reprocessing. These milling activities stopped at Dounreay in 1973. Dounreay Fast Reactor particles were most likely produced during combustion incidents in the dissolution cycle during reprocessing. Several such incidents are known to have occurred between 1969 and 1972. Very few particles are found on publicly accessible beaches, and those which are found are small and are promptly removed. Although the risks to members of the public from the presence of particles in the environment are small, they are a problem of public concern [D5, T8].

382. No information has been found on sites in other countries of the European Union contaminated as a result of military activities, except for those related to former uranium mining activities.

(v) Dumping of radioactive waste in the sea

383. Radioactive waste has been dumped in the Arctic Sea, the North Atlantic, the North Pacific and the West Pacific (figure XXX). At present, the total activity of waste dumped in these regions is estimated to have decreased to a total of about 4 × 10^{13} Bq. This information is contained in the relevant IAEA database [I11]. Doses to critical population groups in coastal areas of the Arctic, North Atlantic and Far East regions of the Russian Federation due to the consumption of seafood products containing radionuclides were shown not to exceed 10^{-4}–10^{-3} of natural radiation background exposure [L2].

384. *Kara Sea* [I11]. In 1992, it was reported that the former Soviet Union had dumped radioactive waste in the shallow waters of the Arctic Seas for over three decades (figure XXXI). The International Arctic Seas Assessment Project (IASAP) was launched by the IAEA in 1993 with the objectives of assessing the current environmental situation associated with the radioactive waste dumped in the Kara and Barents Seas and examining possible remedial actions.

385. The total amount of radioactive waste dumped in the Arctic seas was first estimated by the Russian Federation to be approximately 90 PBq at the time it was dumped. Items disposed at sea included: six nuclear submarine reactors containing spent fuel; the shielding assembly from an icebreaker reactor, which contained spent fuel; ten nuclear reactors without fuel; and solid and liquid low-level waste. Of the total inventory, 89 PBq came from high-level waste comprising reactors with and without spent fuel. Solid waste, including the above reactors, was dumped in the Kara Sea, mainly in the shallow fjords of Novaya Zemlya, where depths at dumping sites ranged from 12 to 135 m, and in the Novaya Zemlya Trough, at depths of up to 380 m. Liquid low-level waste was released into the open Barents and Kara Seas. On the basis of reactor operating histories and calculated neutron spectra, the estimate of the total radionuclide inventory of the high-level radioactive waste at the time it was dumped has been revised to 37 PBq. The corresponding inventory of high-level waste dumped at sea was estimated to be 4.7 PBq in 1994, of which 86% were fission products (main radionuclides ^{90}Sr and ^{137}Cs), 12% activation products (main radionuclide ^{63}Ni) and 2% actinides (main radionuclide ^{241}Pu).

386. The high-level radioactive waste dumped in the Kara Sea and adjoining fjords was in discrete packages, which are expected to leak at some time in the future. They therefore constitute a potential chronic exposure source where the concern relates to future increments of dose to exposed individuals. The open Kara Sea has relatively low levels of artificial radioactivity compared with some other marine areas. Measurements of environmental materials suggest that the annual individual doses due to artificial radionuclides in the Kara and Barents Seas are in the range 1–20 µSv.

387. In two fjords where both high- and low-level wastes were dumped, elevated levels of radionuclides were detected in sediments within a few metres of the low-level waste containers, suggesting that some had leaked. However, this leakage has not led to a measurable increase of radionuclides in the outer parts of the fjords.

388. Calculations of individual doses were undertaken for time periods covering the projected peak individual dose rates for three scenarios and for the following population groups: *(a)* groups living in the Ob and Yenisei estuaries and on the Taimyr and Yamal peninsulas, with habits typical of subsistence fishing communities in other countries with Arctic coastlines; *(b)* a hypothetical group of military personnel patrolling, for 100 hours in a year, the foreshores of the fjords containing dumped radioactive material; and *(c)* a group of seafood consumers considered representative of the northern Russian population situated on the Kola Peninsula. The calculated peak doses to members of these groups due to all sources are shown in table 47.

(vi) Accidental losses of radioactive material at sea

389. Besides the reported events of planned dumping of radioactive material in the sea, there were also several events that included the loss or the release of radioactive material in the sea. These events are summarized in table 7 of annex C of the UNSCEAR 2008 Report and include the following [I17]:

(i) Six nuclear submarines have been lost since 1963 at various sites in the Atlantic Ocean: two from the United States Navy—Thresher in 1963 (one nuclear reactor, 1.15 PBq) and Scorpion in 1968 (one nuclear reactor, 1.3 PBq, and two nuclear warheads); three from the Navy of the former Soviet Union—K-8 in

1970 (two nuclear reactors, 9.25 PBq, and a nuclear warhead, 30 GBq), K-219 in 1986 (two reactors, 9.25 PBq) and K-278 Komsomolets in 1989 (reactor core, 3.59 PBq); and one from the Russian Federation—K-141 Kursk in 2000 (two nuclear reactors, 1–2 PBq). With the exception of the accident involving the Russian submarine Kursk, the depth at the sites of the accidents, below 1,500 m, has not permitted the recovery of the submarines or their nuclear reactors.

(ii) Nuclear weapons have been designed to be carried on submarines, surface ships, aircraft and rockets. There are seven recorded accidents that have resulted in the confirmed loss of one or more nuclear weapons.

(iii) There have been four recorded accidental re-entries of nuclear powered satellites and one recorded accidental re-entry of a spacecraft. Four of these accidents resulted in the actual or potential release of radionuclides into the environment.

(iv) There have been two recorded incidents where radioisotope thermoelectric generators (RTGs) have been lost at sea, both occurring near the eastern coast of Sakhalin Island in the Sea of Okhotsk and both involving emergency disposals of the RTGs during transport by helicopter. In the first incident, which occurred in 1987, the RTG disposed of contained about 25.3 PBq of ^{90}Sr. The second RTG was disposed of in 1997 and contained about 1.3 PBq of ^{90}Sr.

390. Sealed radiation sources are widely used in the marine environment in association with oil and gas exploration and extraction. In some instances the well logging tool and drill string containing the sealed source become stuck in the drill hole and tool recovery is not feasible. The equipment is generally left in place and the hole is closed/sealed. This results in situations where radioactive material could enter the marine environment. In general, these losses have occurred deep in the sediment. The nature of the containment as well as the location of the loss are such that, in general, radionuclide release could occur only after a long period of time. The IAEA database on sealed radiation sources lost in the sea includes about 150 items [I17].

(vii) Other sources of public exposure

391. Since the start of the space age in 1957, radiation sources have been used on board spacecraft for power generation, for thermal control, and in subsystems and instruments (figure XXXII). While electricity for spacecraft has predominantly been produced by photovoltaic cells, there are occasions when, owing to mission criteria (e.g. high power requirements, insufficient solar energy flux in deep space or requirements for planetary landing), the use of solar power is impractical. In such cases, nuclear power sources have been used. To date, only the former Soviet Union, the Russian Federation and the United States have utilized nuclear power systems in Earth orbit or beyond [U44].

392. The United States launched one thermoelectric reactor in 1965. The reactor was shut down after 43 days of operation and placed in a long-term “storage” orbit (an orbit with an estimated orbital decay time of longer than 400 years). The former Soviet Union launched 31 thermoelectric reactors between 1970 and 1988. Their lifetimes ranged from 0.1 to 293 days. Two thermoionic reactors were launched by the former Soviet Union in the period 1987–1988. Their operational lifetimes were 142 and 343 days. It should be noted that no nuclear reactors have been launched since 1988. In addition to nuclear reactors, RTGs have been used as spacecraft power sources. The United States launched 25 missions using 43 RTGs as power sources, two of them using ^{210}Po and the others ^{238}Pu. The former Soviet Union launched two missions with RTGs using ^{210}Po and one mission with four RTG units using ^{238}Pu [U44].

393. Radioisotope heating units (RHUs) utilize radioactive decay to provide heat to surrounding satellite systems and instruments. RHUs have been used on board deep-space probes (i.e. space probes operating beyond the asteroid belt), such as the United States New Horizons probe to Pluto, launched in 2006, and on board planetary landing craft such as the Lunokhod lunar rovers of the former Soviet Union and the United States Mars Exploration Rovers. RHUs are usually small in size and typically produce approximately 1 W of thermal power. Depending on the size of the spacecraft, the number of RHUs used can vary.

394. The current status of these devices is shown in figure XXXIII. Radioactive sources have also been used on board satellites and launch vehicles in applications such as triggering launch vehicle flight termination systems, calibration of on-board instruments and scientific experiments. As an example, the Mars Exploration Rovers (launched in 2003 and still operational as of April 2008) each carry a Mössbauer spectrometer, which uses a small amount of ^{57}Co, and also an alpha particle X-ray spectroscope. Sources of this type are small, and their impact on the environment is considered minimal [U44].

395. In eight cases all or part of the nuclear system reentered the earth’s atmosphere, and there have been two situations where environmental contamination occurred. The first was in April 1964, when the United States SNAP 9A satellite burned up during re-entry. In August 1964, plutonium was detected in the stratosphere (at a height of 32 km), and in May 1965, it was detected at aircraft altitude. In November 1970, it was estimated that some 5% of the original plutonium was still in the earth’s atmosphere. Plutonium was eventually detected on all continents and at all altitudes—the concentration in the southern hemisphere was about four times higher than in the northern hemisphere. The second event was in 1978, when the Cosmos-954 satellite of the former Soviet Union came down over Canada, leading to a track of radioactive residues some 500 km long. Some

50 other objects have been recovered. Other satellites or parts of satellites have fallen into the oceans, and one was recovered intact [E1].

396. Reports of accidents involving unconventional orphan sources in the new States that resulted from the dissolution of the Soviet Union have caused particular security concerns. The new States, some of which were not even aware of the existence of such sources, exercised no control over them. Many orphan sources have also been found on former military bases. The resulting exposures are described in annex C. Notable cases of particular concern are abandoned thermoelectric generators containing powerful radioactive sources of ^{90}Sr, which were introduced in the 1970s for dual civilian and military use. RTGs were used in various civilian and military applications, for example to power navigational beacons and communications equipment in remote areas. They usually hold over 1.5 PBq of ^{90}Sr. RTGs were widely used in the former Soviet Union for such applications as generating electricity, heat and battery power for remote communication systems. These types of generator have also been built in the United States, and their radioactive content is more or less of the same order of magnitude. A large number of navigational beacons powered by these RTGs were operated in the Arctic area from Novaya Zemlya to the Barents Straits. In Alaska, United States, several generators were located in the Burmont area. Many RTGs are now being recovered and their sources are being recycled. The first abandoned RTG was found and recovered from the riverbed of the Ingury River in the Republic of Georgia. Two other RTGs were recovered by the IAEA in a remote forested area of north-west Georgia in 2001. RTGs were also found in Tajikistan, dumped in an abandoned building and completely unsecured. A number of RTGs have also been recovered in Belarus [G13, I35].

397. In the period of 2004–2005, a bilateral project between Norway and the Russian Federation decommissioned 96 RTGs from north-western Russia. It is estimated that about 760 RTGs primarily used as lighthouse energy sources still remain along the northern Russian coast. An analysis of radiation protection issues related to decommissioning RTGs has shown that a safe decommissioning practice is unlikely to result in significant radiation exposure of human populations, with a worst case scenario being direct contact with an exposed ^{90}Sr heat source [S34].

(c) Summary on public exposure due to military uses of atomic energy

398. Activities, practices and events involving military and defence uses of sources of radiation have led to releases of radioactive material into the environment with resulting exposures of human populations. The main contribution to the global collective dose resulting from man-made sources has come from the testing of nuclear weapons in the atmosphere. This practice occurred between 1945 and 1980. Each nuclear test resulted in an unconstrained release to the environment of substantial quantities of radioactive material. These were widely dispersed in the atmosphere and eventually deposited everywhere on the earth's surface.

399. Historically, the Committee has given special attention to the evaluation of exposures due to atmospheric nuclear weapons testing. Numerous measurements of the global deposition of ^{90}Sr and ^{137}Cs and the presence of these and other fallout radionuclides in the human diet and the human body have been made since the time tests took place. The worldwide collective dose resulting from this practice was evaluated in the UNSCEAR 1982 Report [U9], and a systematic listing of transfer coefficients for a number of fallout radionuclides was given in the UNSCEAR 1993 Report [U6].

400. Although the total explosive yields have been divulged for each test, information concerning the fission and fusion yields remains suppressed for the most part. Some general assumptions have been made to estimate the fission and fusion yields of each test in order to estimate the amounts of radionuclides produced in the explosions. The estimated total fission yields from all individual tests is in agreement with the estimate of global deposition of the main fission radionuclides ^{90}Sr and ^{137}Cs, as determined by worldwide monitoring networks [U3].

401. With improved estimates of the production of each radionuclide in individual tests and using an empirical atmospheric transport model, it has been possible to determine the time course of dispersion and deposition of radionuclides and to estimate the annual doses due to various pathways in each hemisphere. 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 (and now results mainly from residual levels of ^{14}C, ^{90}Sr and ^{137}Cs in the environment). The average annual doses are higher than the global average by 10% in the northern hemisphere (where most of the testing took place) and are much lower in the southern hemisphere. Although there was considerable concern at the time of testing, exposures in fact remained relatively low, reaching at most about 5% of the background level due to natural radiation sources.

402. Exposures of local populations living in areas around 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 local conditions and consideration of the potential for exposure were not great in the early years of the test programmes. However, dose reconstruction efforts are proceeding to clarify this issue and to document the local and regional exposures that occurred. Local and regional doses may have been very different from the exposure of global fallout. An example is shown in figure XXXIV, where results for ^{137}Cs deposition are presented for the tests in Nevada and for the contribution from global fallout [S23].

403. 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 between 1962 and 1990. Although it is the intention of most countries to agree to ban all further tests, both atmospheric and underground, the treaty to this effect has not yet come into force. Further underground testing occurred in 1998 in India and Pakistan, and in 2006 in the DPRK. Thus it cannot yet be stated that the practice has ceased. Underground testing resulted in a large global burden of radioactive material, and in particular of plutonium, albeit in underground environments. The contribution of this material to future population exposure is uncertain. Currently these residues are not expected to expose members of the public, because they are buried deep underground, and, because of the high temperature reached during the tests, they were fused within the matrix of host rock in an apparently stable and insoluble form.

404. At present there is great concern regarding the reuse of nuclear test areas, since some are being reoccupied. Residues in some environments, for example in localized areas at the Semipalatinsk test site, may be considerable, while in others, such as the Mururoa and Fangataufa Atolls, the residues will not contribute more than a fraction of the normal background exposure to a population eventually occupying the site. For other sites still, such as the Marshall Islands and Maralinga, exposures will be highly dependent on the habits of the populations occupying the area.

405. 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 the military nuclear installations. Since monitoring of releases was limited and there was little recognition of the potential risks, present evaluations of exposure must be based on dose reconstructions. Results are still being obtained that document this experience. Practices have greatly improved and arsenals are now being reduced.

406. The military use of DU has led to the contamination of large areas with residues from munitions in several locations, for example Kosovo, former Serbia-Montenegro, Bosnia and Herzegovina, Kuwait and Iraq. This fact has created serious concern that members of the public could be exposed to such residues. A large international effort to assess the consequences of this contamination has been performed, and the main conclusion is that, except for a few specific scenarios (such as the long-term handling of lumps of DU), exposures are expected to be low. It is very unlikely that the long-term behaviour of DU with regard to the leaching and transport of corroded DU lodged in the ground and its potential migration could cause any impact on underground water sources. An assessment of the DU residues in Iraq has not yet been performed.

E. Historical situations

407. Some experiments using atomic weapons were carried out that were not related to military activities. However, these operations would not be allowed today under current international conventions.

408. *Nuclear explosions for peaceful purposes.* Over a period of 24 years, 128 nuclear explosions for peaceful purposes were conducted at 115 sites in the former Soviet Union—in Russia, Kazakhstan, Uzbekistan, Turkmenistan and Ukraine. The first was in 1965 at the Semipalatinsk test site, in the Chagan River channel, to create a water reservoir, and the last was in 1988, near the town of Kotlas. The overall quantity of fission fragments was about 100 kg. Of 108 camouflet explosions,[3] 76 were fully contained. In 26 cases there was radioactive gas leakage (blasts showed pressure efflux), and one explosion, Kraton-3, resulted in the release of radioactive products. The explosion sites and their technical purposes are shown in figure XXXV. The total energy yield of peaceful nuclear explosions in Russia reached 0.75 Mt, or 2% of the value for all underground nuclear explosions in the former Soviet Union.

409. Radioactive traces and contamination of soil and vegetation cover are very rare. Some of these 128 events were single excavation explosions. Five of these, such as the Taiga test, led to the contamination of adjacent areas, requiring remediation. The Taiga test was an attempt to create a canal; this resulted in a radioactive trace 25 km in length. An accidental release from the Kraton-3 test caused the formation of a trace 31 km in length [V10]. The underground nuclear explosion Kristall took place in 1974. Its purpose was to construct a reservoir dam for diamond enrichment plant tailings. Explosions of this type are accompanied by the formation of craters and are characterized by significant releases of radioactive products into the environment. Because of the heavy radioactive contamination, all further work at the Kristall site was stopped. In 1990 a water-filled crater, 60 m in diameter and 6 m deep, still existed at the location of the explosion. During clean-up operations in 1992, the crater was filled with barren rock from the Udachnaya diamond field and was covered with an artificial mound about 100 m in diameter and 7–20 m in height [G5].

410. Kazakhstan's low population density, vast territories that are unsuitable for farming and considerable reserves of minerals made the country a convenient location for the development and production of defence technology and armaments. Apart from the Semipalatinsk test site, there are three other test sites in Kazakhstan where underground nuclear explosions were conducted for peaceful purposes. The radioecological situation at the three sites is not considered serious for the population or the environment. However, the radioecological situation at the Koshkar-Ata storage facility for waste is of major concern [C14].

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[3] Camouflet: a cavern caused by a subterranean explosion.

F. Exposure from accidents

411. Several accidents have included the release of nuclear or radioactive material to the environment, leading to exposure of members of the public. In the present report, the Chernobyl accident, which occurred in 1986, is described in annex D, “Health effects due to radiation from the Chernobyl accident”, and other accidents, such as the Kyshtym accident of 1957, the Windscale accident of 1957, the Three Mile Island accident of 1979 and the Tomsk accident of 1993, are described in annex C, “Radiation exposures in accidents”. There have also been accidents with orphan sources that involved exposures and fatalities among members of the public; these accidents are also described in annex C.

G. Summary on public exposure

412. Exposure to natural sources of radiation is an unavoidable fact of the human condition. The single main source of exposure is the inhalation of radon gas. The estimates of the global average per caput values of exposure to natural sources of radiation are essentially the same as in the UNSCEAR 2000 Report. The estimated value of worldwide average annual exposure to natural radiation sources remains at 2.4 mSv. The normal range of exposures to the various components is presented in table 12. As described earlier in this annex, the dose distribution worldwide is expected to follow approximately a log-normal distribution, and most exposures would be expected to fall in the range 1–13 mSv/a.

413. The interest in exposures to NORM is increasing as new situations are identified and corresponding dose assessments are performed for specific scenarios. Doses of up to a few millisieverts per year may be expected for some specific scenarios, such as the use of sludges from water treatment as fertilizers, or the use of wastes and other materials as landfill or building materials. There is not yet a consistent approach to characterize inventories of sources and to estimate potential and actual exposures in order to extrapolate to a worldwide dose assessment. The Committee encourages the continued development of inventories and methodologies for dose assessment in order to make possible a broader view of the scenarios in a global context.

414. Residues due to conventional mining operations also lead to huge amounts of material with enhanced levels of NORM, and these represent a challenge regarding both the disposal of the residues and site restoration. The large diversity of ores containing low levels of nuclides from the uranium and thorium families, which may be concentrated in products, by-products and wastes, complicates the problem. The detailed picture of worldwide exposure is far from complete. As with other contaminated sites, the main radioactive materials are still under the control of operators, and most situations pose mainly potential exposure for members of the public. Although the public exposure is not expected to be high, some areas with enhanced levels of NORM may involve the low-level exposure of large numbers of people. A large effort is needed to reach an international consensus on ways of addressing this situation to keep the public exposures under control at levels compatible with exposures to other sources.

415. One continuing practice is the generation of electrical energy by nuclear power reactors. During the routine operation of nuclear installations, releases of radionuclides are low and radiation exposures must be estimated using environmental transfer models. For all fuel cycle operations (mining and milling, reactor operation and fuel reprocessing), the local and regional exposures are estimated to be 0.72 man Sv/(GW a). For the present world nuclear energy generation of 278 GW a, the collective dose per year of practice is of the order of 200 man Sv. The assumed representative global value for the local and regional populations of nuclear installations is about 250 million persons, and the annual per caput dose to this population is less than 1 µSv. The collective doses due to globally dispersed radionuclides are delivered over very long periods and are expressed for the projected maximum future population of the world. If the practice of nuclear power production were to be limited to 100 years at the present capacity, the maximum annual per caput effective dose to the global population would be less than 0.2 µSv. This dose rate is minute compared with that due to natural background radiation.

416. Releases of isotopes produced and used in industrial and medical practices have been discussed and appear to be associated with rather insignificant levels of exposure of the general public. Except in the case of accidents, in which more localized areas can be contaminated to significant levels, there are no practices that result in important exposures as a result of radionuclides released to the environment.

417. While doses due to nuclear power production have been extensively described and reported, this is not the case for military uses and activities. Furthermore, some historical estimates assigned doses to nuclear power production (such as those due to the generation of radioactive waste and to uranium mill tailings, among others) that were in part also related to military activities.

418. The main contribution to the global collective dose due to man-made sources has come from the testing of nuclear weapons in the atmosphere. This practice occurred between 1945 and 1980. These tests have led to local, regional and global exposure because of the worldwide dispersion of radioactive material in the atmosphere, material that was subsequently deposited everywhere on the earth’s surface. It has been estimated that the worldwide average annual per caput effective dose reached a peak of 110 µSv in 1963 and has since decreased to about 5 µSv (mainly due to residual levels of ^{14}C, ^{90}Sr and ^{137}Cs in the environment). The average annual doses are higher than the global average by 10% in the northern hemisphere, where most of the testing took place, and are much lower in the southern hemisphere.

The underground testing also left an environmental legacy of plutonium in the subterranean environment of all the sites involved in such tests. Although currently any exposure to these sources is low, exposure scenarios for the distant future are very uncertain.

419. Besides areas related to atomic bomb production and testing, early uses of radiation also left a legacy of numerous small contaminated sites around the world. Efforts to decontaminate these sites and return them to public use have been a focus of attention in many countries. Several types of contamination are involved, many related to industrial uses of naturally occurring radionuclides or to old mining areas. Exposures and collective doses are site-specific; once the areas are defined, exposures can be constrained. There is a general tendency for exposures to fall with time because of clean-up procedures, although for some sites there will be a need for long-term follow-up because of the long half-lives of the radionuclides involved. In the United States alone, just over 5,000 remediation projects have been completed to date at various USDOE facilities, and another 5,400 remain. Some 1,186 sites are currently under decommissioning. As site release criteria are usually developed with a focus on critical group exposure, real doses to the public will depend on whether released sites are actually occupied. In general, individual doses estimated for a hypothetical critical group are in the range 0.3–1.0 mSv. Regional average individual doses will be at least one order of magnitude lower, and the contribution to the worldwide population doses will most probably be negligible.

420. The enrichment process for natural uranium generates a large amount of by-products containing DU. Owing to the properties of this dense metal, it has found civilian and military uses. Military use led to pockets of contamination over large battlefield areas on the territory of the former Yugoslavia and in Kuwait. This has led to great public concern, and consequently considerable work has been done to assess current and potential exposures due to these residues in the environment. Although most areas were cleaned up before release to public access, uncertainties remain on the long-term exposures to specific individuals. This is because of the possibility of penetrators presently buried underground being found following human actions such as digging or ploughing, and of the enhanced corrosion rates observed for penetrators, which could ultimately lead to migration of DU into underground water. However, no significant collective doses are expected to result from either of these pathways.

421. Historically contaminated sites related to the peaceful uses of atomic energy are primarily related to the radium industry. These areas, mainly located in the United States, the European Union and Canada, have already been identified, and most of them have been isolated from the public or have been the subject of decommissioning programmes. Residual exposures are thereby constrained to levels that are compatible with current operational practices. There are also a large number of sites with mining residues associated with nuclear power production worldwide. Large environmental restoration programmes are being undertaken in order to bring the level of exposure in these areas within the range of those considered acceptable for ongoing practices.

422. Possible future practices (such as weapons dismantling, decommissioning of installations and waste management projects) can be reviewed as experience is acquired, but these are all expected to involve little or no release of radionuclides and consequently little or no exposure.

423. A large number of smaller accidents have also resulted in the exposure of members of the public, and many have led to fatalities. Annex C of the UNSCEAR 2008 Report, “Radiation exposures in accidents”, discusses this subject in more detail. Most of these accidents resulted in the exposure of small groups of people to radiation from industrial and medical sources that had left institutional control. These accidents have mostly involved relatively small numbers of persons, usually family, close friends or neighbours, but individual doses were in some cases very high.

424. There were also a few situations where this type of accident led to more widespread environmental contamination and to the exposure of larger numbers of people. These include: the Goiânia accident in 1987, with the dispersion within an urban area of a medical ^{137}Cs source; the accident in Mexico in 1983, where a cobalt source for medical purposes found its way into the production of steel used in building material and other objects; and the accident in Taiwan, China, where several residential buildings used material with contamination from a cobalt source. Such accidents led to widespread exposures, and although the collective doses resulting from such events are not high, those individuals who personally manipulated the sources were subject to doses that led in some cases to deterministic effects or even death.

425. Exposure of members of the public to the various sources discussed in this annex has a very wide variability in actual doses and in the contribution of different sources to the overall exposure. As an example, figure XXXVI shows the estimated contribution of different sources to the population exposure of different countries. In describing exposure from different sources, there is no standard pattern followed by different countries. For example, most countries do not have specific data on exposures from consumer products, and therefore such data are not included on their overall assessments. Also, exposures to sources have different time trends in different countries. For example, while in United Kingdom it has been verified that the contribution from various sources has not changed significantly since the 1970s, with natural sources dominating public exposure, in the United States, the average annual per caput dose from medical exposure has increased from 0.54 mSv in 1982 to about 3 mSv in 2006, making medical exposure the largest source of radiation exposure to United States population [J5, M23].

426. A better understanding of the components of the total exposure from different sources on a geographical basis

could change the current exposure assessment and lead to more precise estimates of the distribution of exposures worldwide. Up to now, only the variability associated with exposures to individual sources has been taken into account in worldwide dose estimates. There are, however, circumstances in which the distribution of doses due to one source affects the overall distribution of doses due to other sources. This can be the case, for example, for certain locations where there are high levels of natural radionuclides in the environment and where higher doses due to radon inhalation may be correlated with high doses due to external exposure or food ingestion. Another possible situation is the uneven distribution of nuclear power plants worldwide, which is broadly correlated with the distribution of population.

427. An example of different dose distributions affecting public exposure is given in figure XXXVII, which shows several maps related to different sources of exposure of the public in the United States. It can be seen that concentrations of uranium and thorium are closely correlated with each other and also with external dose rates and radon concentrations. Also, the distributions of nuclear installations and of population density appear to be correlated. The distribution of collective dose contributions may be very different from current estimated distributions, considering specific distributions among the individual quantities involved. This could indicate a need for future revision of the methodology for estimating averages and ranges of population doses worldwide.

III. OCCUPATIONAL RADIATION EXPOSURE

428. The International Labour Organization (ILO) [I62] and the International Basic Safety Standards [I7] define occupational exposure as “all exposure of workers incurred in the course of their work, with the exception of exposure excluded from the Standards and exposures from practices or sources exempted by the Standards” [I62].

429. Various national authorities or institutions have used different methods to measure, record and report the occupational data included in this annex [I25]. The main features of the method used by each country that responded to the UNSCEAR Global Survey of Occupational Radiation Exposures are summarized in table A-15. The procedures for the recording and inclusion of doses differ from practice to practice and from country to country. It must be recognized that differences in monitoring and reporting practices do exist, and these differences may, in particular cases, lead to spurious conclusions being drawn from comparisons between reported data.

430. The criteria applied in different countries to select workers who should be monitored differ considerably. Some countries monitor only the exposed workers, while others also include non-exposed workers in their individual monitoring programmes for various reasons. This can lead to spurious results when attempting to compare levels of exposure in different countries and practices. Moreover, the exposure due to radon is often underreported, since many countries record the dose only when radon concentrations of above 1,000 Bq/m^3 in air are found. There are likely to exist workplaces where radon exposure can deliver significant doses but which have not yet been identified [F15].

431. Occupational radiation exposures have been evaluated by the Committee [U3, U6, U7, U9, U10] for six broad categories of practice: practices involving elevated levels of exposure to natural sources of radiation, the nuclear fuel cycle, medical uses of radiation, industrial uses, military activities and miscellaneous uses (which includes educational and veterinary uses of radiation). The Committee has evaluated five-year average exposures beginning in 1975. The data presented in this annex are for the periods 1995–1999 and 2000–2002. The data from the previous periods are provided for comparison. Table 48 presents the practices for which the occupational exposure has been evaluated.

432. The data in this annex were obtained in much the same way as the data for the UNSCEAR 2000 Report [U3], i.e. by means of a questionnaire, the UNSCEAR Global Survey of Occupational Radiation Exposures. For the current period, a new questionnaire (requesting more detailed information for the period 1995–2002) was distributed to Member States of the United Nations by the UNSCEAR Secretariat. The data have been supplemented by other (usually published) sources of information. For the nuclear power industry, for example, a principal source is the joint databank of the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) and the IAEA—the Information System on Occupational Exposure (ISOE) [O14, O19, O20], which serves as a main source of data on occupational exposure resulting from reactor operations for the period 1995–2002. Table A-15 presents the complementary information provided by those States that responded to the UNSCEAR survey.

433. Differences may exist in the procedures used in various countries to categorize workers according to their occupations. This 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 between countries can be made 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 the dose assigned when dosimeters are lost. The approaches used in measuring and reporting

occupational exposures in each of the countries for which data were reported are summarized in table A-15. Where important differences in approach are apparent, caution should be exercised in making direct comparisons between data.

434. In the UNSCEAR 2000 Report, the Committee evaluated occupational exposure for each practice in each country using average values for all workers over five-year periods. The purpose of this annex is to provide more detailed information on occupational exposure related to the different practices, for example to identify job functions and categories of work within each practice that lead to more significant exposures, to identify the contributions of external versus internal exposure to the total effective dose, and to obtain information about the reliability of measurements associated with the accreditation or authorization of monitoring services.

435. About 70% of the countries that reported data have their external dosimetry services accredited or authorized by some national or international regulatory authority. The situation is the very different for internal dosimetry, for which about 25% of the countries have reported that their services are accredited or authorized.

A. Assessment methodology

1. Dose recording

436. In most countries, dose recording and reporting practices are governed by regulations and may differ for various categories of workers depending on the anticipated levels of exposure. The IAEA, in its publications [I7, I13, I14, I16, I27], has provided guidelines on how monitoring data and results should be reported, what dose levels should be recorded, and what documents and records of radiation exposure should be maintained. Although there are guidelines for dose recording, there may be variations from country to country that may significantly affect the reported values of collective dose. The most important differences arise because of the following factors:

- The recording of dose values less than the MDL;
- The technique used for measurement of external radiation exposure, for example thermoluminescent dosimeter (TLD), film, electronic dosimeter, optically stimulated dosimeter or glass dosimeter;
- The assignment of dose values to fill missing periods in the records;
- The evaluation of anomalous results, such as unexpectedly high or low dose values;
- The subtraction of background radiation doses;
- The protocol for determining who in the workforce should be monitored and for whom doses should be recorded in particular categories;
- Whether or not internal exposures are included or are treated separately;
- The reliability of the individual monitoring data.

437. In order to ensure the reliability of dose assessments, some countries have implemented systems to authorize monitoring services based on a set of requirements established by the national regulatory authority, while others apply criteria based on the quality management system for accrediting individual monitoring services [M19].

2. Characteristics of dose distributions

438. The dose distributions presented in this annex follow the same approach as the one described in the UNSCEAR 2000 Report [U3]. The Committee is interested in comparing dose distributions and in evaluating trends. For these purposes, four characteristics of the dose distributions are identified as being particularly useful:

- The average annual effective dose (i.e. the sum of the annual dose due to external irradiation and the committed dose due to intakes in that year), E;
- The annual collective effective dose (i.e. the sum of the annual collective dose due to external irradiation and the committed collective dose due to intakes in that year), S;
- The “collective dose distribution ratio”, SR_E (for values of E of 15, 10, 5 and 1 mSv), provides an indication of the fraction of the collective dose received by workers exposed at various levels of individual dose;
- The “distribution ratio for the number of exposed workers”, NR_E (for values of E of 15, 10, 5 and 1 mSv), provides an indication of the fraction of the total number of workers exposed at various levels of individual dose.

439. 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, 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. Similarly, 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 that exceed E mSv.

440. Depending on the nature of the data reported and subject to the objectives of the evaluation (or the topic of interest), the “number of workers” may be those monitored, those who work in workplaces classified as controlled areas, those measurably exposed, the total workforce or some subset thereof. Therefore these derived quantities 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.

3. Estimation of worldwide exposures

441. Inevitably, the data provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures were insufficient for estimating worldwide levels of dose. Procedures were therefore developed by the Committee to derive estimates of 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. For the occupational groups involved in practices other than the nuclear fuel cycle, the approach to derive estimates of worldwide doses used in the UNSCEAR 2000 Report is no longer used here. This is because the available data for the last two periods, 1995–1999 and 2000–2002, are not sufficient to derive a reliable number that reflects the worldwide level of exposure. For medical exposure, the number of workers was estimated on the basis of the information from the UNSCEAR Survey of Medical Radiation Usage and Exposures. The Committee has decided to evaluate the worldwide level of occupational exposure for the different practices in the industrial and miscellaneous fields on the basis of the trends in the countries for each practice. The worldwide level of exposure was estimated on the basis of the quantile regression using the median estimated values of the data reported by the countries [K15].

442. 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. Hence the degree of extrapolation from reported to worldwide doses is less, and this extrapolation can be carried out more reliably than for other occupational categories. Moreover, worldwide statistics are generally available on the 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, due to a given stage of the nuclear fuel cycle (e.g. uranium mining, fuel fabrication or reactor operation) is estimated from the total of the annual collective effective doses reported by countries multiplied by the reciprocal of the fraction, f, of the 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 arising in country c and n is the number of countries for which occupational exposure data have been reported. The fraction of the 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 the country, c, and in the world, w, respectively.

443. The number of monitored workers worldwide, N_w, in a given year 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 for each year. Values of these quantities have then been averaged over five-year periods, except for the last period (2000–2002), which included only three years, and the average annual values are reported in this annex. The Committee has also made projections for exposures for the period 2002–2006 based on extrapolating the trends for each practice over the six periods previously analysed.

B. Natural sources of radiation

444. Enhanced levels of natural background radiation are encountered in many occupational settings, especially in underground mines. Mining involves a large number of workers, and although the data are more limited than those for occupational exposures to man-made sources, the annual collective effective dose has been estimated to be approximately twice as large [U6]. Until implementation of the International Basic Safety Standards [I7], most countries had not been particularly concerned with assessing occupational exposure to natural sources of radiation. Over the last few years, exposures to enhanced levels of natural radiation have become a focus of attention in the field of radiation protection. Title VII of the European Basic Safety Standards [E11] and related guidance [E14] cover those work activities where the presence of natural radiation sources that lead to a significant increase in the exposure of workers and members of the public cannot be disregarded. Besides the European Union countries, others have already implemented radiation protection legislation for NORM.

445. The great majority of the workers exposed to natural sources of radiation are not individually monitored. They include aircrew, workers involved in mineral extraction and processing, and workers exposed to radon in workplaces other than mines. The doses of aircrew are estimated from measurements in the aircraft and also by numerical simulation with computer codes. The occupational exposure of aircrew is controlled through limiting their time in flight [U41]. The workers involved in mineral extraction and processing represent by far the largest occupational group exposed to sources of ionizing radiation. Only a few countries have monitored these workers on a routine basis. Besides mines, there are several other workplaces where workers may receive very high doses due to radon exposure; this has been highlighted in the results of survey programmes conducted in some of these workplaces. Since for many countries these data are not routinely recorded, an extensive review of the literature has been conducted in order to present a more comprehensive picture of occupational exposure to natural sources.

1. Cosmic ray exposures of aircrew and space crew

(a) Aircrew

446. Exposure to cosmic radiation is influenced by many factors, as was discussed in section II.A.1 of this annex. The International Commission on Radiological Protection (ICRP), in its Publication 60 [I47], has identified airline flight crews as an occupationally exposed group. By the early 1990s, the European Commission had agreed that a comprehensive survey should be undertaken of the radiation environment produced by cosmic rays at aviation altitudes, and an extensive programme of experimental and theoretical studies was supported [E9, S31]. The European Union has established standards for the protection of workers exposed to natural radiation [E10]. These standards explicitly include flight personnel, who could receive an annual dose due to cosmic rays of over 1 mSv. Since 2002, the European Union countries have recorded the associated doses in an occupational exposure database on a regular basis.

447. In recent years, new experimental studies have been conducted of the monitoring methodology for estimating the low- and high-linear-energy-transfer (LET) components of the radiation field on board aircraft [B5, S10, S11, S31]. The tissue equivalent proportional counter (TEPC) is the only direct-reading dosimeter that measures both absorbed dose to tissue and radiation quality in terms of linear energy [L14, T1]. Several studies have been carried out to compare the dose estimated on the basis of the results of on-board measurements with the ones estimated by calculations using the computer codes. Good agreement has been observed between the measured values and the calculated ones [B15, B17, B44, F6, L8, L15, O2, S32].

448. A number of computer codes have been developed to estimate aircrew doses according to specific parameters related to the flight routes. A new version of the Civil Aerospace Medical Institute (United States Federal Aviation Administration) computer program CARI-6M calculates, on the basis of an anthropomorphic phantom, the effective dose of galactic cosmic radiation received by an individual on an aircraft flying a user-specified route [N3]. The European Program Package for the Calculation of Aviation Route Doses (EPCARD) is a tool to calculate the effective dose or the ambient dose equivalent and to determine the contribution of the different field components [M8]. The Predictive Code for Aircrew Radiation Exposure (PCAIRE) estimates values for the total ambient dose equivalent or the effective dose. The PCAIRE program is based on experimental results from measurements on board aircraft, and its predictions should agree with the associated measurement results [L6]. SIEVERT, a computerized system for the assessment of exposure to cosmic radiation in air transport, is also a very useful tool [B42, B44].

449. The different programs have been used to calculate route doses for 28 different flights that took place during the period from May 1992 until September 2001. Calculations were performed for both effective dose and ambient dose equivalent. There are relatively larger differences (up to 30%) between the results of the different transport codes for effective dose than between the results for ambient dose equivalent. For the latter quantity, the agreement is within 10–15%. This can be explained by the different assumptions about the galactic proton distribution and the use of a proton radiation weighting factor of 5 in the calculation of effective dose, whereas the corresponding mean quality factor is 1.5 in the calculation of ambient dose equivalent [L15].

450. Since August 2003, 45 airline companies in Germany have routinely assessed the exposure of their personnel by application of computer codes. For the first year of dose registration, from August 2003 to July 2004, the national dose registry for occupational exposure includes data on a total of 31,000 crew members. The collective dose to the group of 60 man Sv contributes more than 50% to the total of the collective dose of all workers in Germany. About the same proportion of collective dose to aircrew is reported by the Netherlands [V3]. As seen in table 49, Germany and the United Kingdom report the largest number of flight personnel among the European Union countries. The average annual dose of the flight personnel varies from 1.3 to 2.5 mSv. None of the reported annual dose values exceeded 6 mSv. The frequency distribution of the individual dose values is bimodal; however, the dose distribution observed for the other categories of work is characterized by an exponential decrease in the number of observations with increasing values of the dose. Table 50 presents the dose estimates for specific flight routes leaving Frankfurt [S38].

451. The number of flight personnel in the United States is approximately 150,000 [U27]. Radiation doses due to individual commercial flight segments typically range from 0.3 to >60 μSv per flight, depending on latitude, altitude and duration. Annual doses range from 0.2 to 5 mSv, depending on flight routes and number of hours flown per year [W4, W5].

452. There are a large number of females in the workforce. Female flight attendants flying both a large number of hours during pregnancy (e.g. 100 hours per month) and only the routes with the highest dose rates (e.g. 0.006 mSv per block hour) would exceed 0.5 mSv to the embryo/foetus (excluding natural background and medical exposures) [W4].

453. Data on the occupational exposure of crew members are presented in the first part of table A-16 and also in table 49. Most of the limited number of data refer to the year 2002. The number of reported monitored workers is 90,540. The reported collective effective dose is 165 man Sv. The reported average effective dose is about 1.8 mSv. The reported average effective dose data are in agreement with the data presented in table 49. In this table, information is provided for the United States, with a workforce of approximately 150,000 [U27]. No changes in terms of the total number of crew in the worldwide workforce have occurred since the UNSCEAR 2000 Report. Assuming that the countries reported in tables 49 and A-16 represent about 80% of the worldwide workforce, the total would be 300,000 workers. The average effective dose for the European countries is about 2 mSv. The average annual flying time is estimated as 600 hours for aircrew in European countries and about 50% more for aircrew in the United States. On the basis of these values, it is assumed that 50% of the workforce is exposed to 2 mSv/a and 50% is exposed to 3 mSv/a. Under these assumptions, the estimated collective effective dose is about 900 man Sv. This value for the collective dose is about the same as that estimated in the UNSCEAR 2000 Report, 800 man Sv [U3]. These doses could be slightly underestimated, if it is assumed that the crew members are also frequent flyers, since most of them receive free air tickets for travel with their airlines. Couriers represent a separate group; they may spend greater total times in flight in the course of a year, but even so are unlikely to incur a dose exceeding 10 mSv in a year.

(b) Space crew

454. At altitudes of between 200 and 600 km and at low inclinations, the major contribution to the absorbed dose is delivered inside the South Atlantic Anomaly (SAA) by the geomagnetically trapped protons and electrons of the radiation belt. The SAA is an area where the radiation belt comes closest to the earth's surface owing to a displacement of the magnetic dipole axes from the earth's centre. In this region, fluxes vary extremely rapidly with altitude, because of interactions of the charged particles with the nuclei of the atoms of the upper atmosphere. The flux in the SAA is anisotropic, with most of the flux arriving perpendicular to the magnetic field lines [R8].

455. The dose measurements for the on-board crew of various missions (first United States Spacelab mission (SL1), Dedicated German Spacelab missions (D-1 and D-2), International Microgravity Laboratories (IML-1 and IML-2), German Mir-92 flight to the Russian space station) show that the doses were in the range 1.9 mSv to around 27 mSv, depending on the mission, as shown in table 51. The main contribution to the dose came from the protons of the SAA; its value increases with altitude and decreases with increasing solar activity and mass shielding [R6, R7, R8].

456. The fraction of the dose on the Mir space station due to the SAA on an orbit inclined at 51.6° and at an altitude of about 400 km was determined during the Euromir '95 mission. The measurement was performed using an hourly measuring period for 170 h. It was found that the maximum dose due to crossing the SAA was equal to 0.055 mGy. Averaging all the measurements, it was calculated that the mean dose rate inside Mir varied from 0.012 to 0.014 mGy/h, and that half of this value was due to the SAA [D4].

457. Measurements of the cosmic radiation dose inside the Mir space station and the additional dose to two astronauts in the course of their extravehicular activity (EVA) were performed. During an EVA lasting 6 h, the ratio of dose rates inside and outside Mir was measured. During the EVA, Mir crossed the SAA three times. Taking into account the influence of these three crossings, the mean outside/inside dose rate ratio was 3.2. The absorbed dose rate inside Mir was 0.023 mGy/h, while the mean absorbed dose rate during the EVA was 0.073 mGy/h [D12].

458. The dose assessments for various space missions of the former Soviet Union and the United States show that the daily absorbed dose varied between 0.32 and 0.57 mGy, and the daily dose equivalent between 0.62 and 1 mSv. The dose assessment was based on data from dosimeters placed in different locations in the space station. The value for the radiation weighting factor was about 3 at high latitude and decreased to about 1.5 near the equator. This effect is due to the greater geomagnetic protection at low latitudes, where only high-energy particles penetrate the atmosphere. Nearer the poles, there is a higher particle flux with lower mean energy. Variations could be explained by differences in the mass shielding properties at the locations of these detectors [B41].

459. The second flight of IML-2 on Space Shuttle flight STS-65, which was launched on 8 July 1994, was sustained in a 28.45º by 296 km orbit for a duration of 14 days, 17 hours and 55 minutes. The crew doses varied from 0.94 to 1.2 mGy. A reasonable agreement was found between the galactic cosmic ray dose, dose equivalent and LET spectra measured using the TEPC flown in the payload bay and those calculated using models [B3].

460. The Mir-18 mission began in March 1995 [B4]. The absorbed dose measurements for the Mir-18 crew showed that the dose depended on the tasks the crew performed. Estimates were 3.76 ± 0.18 mGy, 2.87 ± 0.15 mGy and 3.53 ± 0.24 mGy for the commander, flight engineer and flight researcher, respectively. Dosimeters were worn at least 80% of the time. The dose values are not corrected for the loss of high-LET particles. The Mir space station was in a 51.65º inclination orbit from 1986 to 2001.

461. Evaluation of individual doses using cytogenetic dosimetry techniques has shown that the yields of dicentrics and centric rings scored after long-term space flights are considerably higher than those scored prior to the flights. In this study, a total of 22 cosmonauts were examined. Some of them were examined after repeated flights. The missions lasted for 4–6 months on average. Individual doses measured using biodosimetry to cosmonauts who showed a reliable increase in the yields of chromosomal-type aberrations after their first flights were estimated to be from 0.02 to 0.28 Gy [F3].

2. Exposures in extractive and processing industries

462. The extraction and processing of radioactive ores are carried out in a number of countries throughout the world. The extractive industries include all forms of mining. Minerals and other natural materials that are not normally regarded as being radioactive may nevertheless contain significant levels of natural radionuclides from the uranium and thorium decay chains. These raw materials, their by-products from processing and the end products produced may lead to exposures in workplaces where there is often no perception, let alone appreciation, among workers of the various relevant radiation protection problems. The main source of exposure in most mining operations is radon. Exposure due to long-lived radionuclides in mineral dusts can, however, be important in certain mining and other situations.

463. Mining is an extensive industry. Employment in the mining industry is changing in several ways for a variety of interrelated reasons: commercial, political, technological, demographic and social. The net effect, however, has been a steady fall in the number of people employed in mining. According to the International Labour Organization, since the early 1990s, when about 25 million people were estimated to be employed in mining (including some 10 million in coal mining), the decline in employment has ranged from steady to more rapid at different times in different regions. By the year 2000, a decline in the number of workers in mining ranging from 32% to about 45% was estimated to have occurred, which would give an estimate of about 6.8 million workers involved in coal mining operations [I39]. The estimated number of underground coal mine workers in China is about 6.05 million [L20]. Mining is still a male-dominated industry. Although more women are now working in all aspects of mining in some countries, any increase in female employment is generally from a very low base.

464. By far the largest category of workers exposed to ionizing radiation are those employed in the extractive and processing industries. A rough estimate of the total number of workers potentially exposed to internal radiation in non-nuclear industry in the European Union is 5,000–10,000. Exposure situations for workers in these industries differ considerably with respect to the type of industry, the conditions in the workplace, the radionuclides involved, and the chemical and physical forms of the matrices in which the radionuclides are incorporated [V1].

465. The main potential sources of occupational exposure in the extractive industries are the natural radionuclides arising from the radioactive decay of the ^{238}U and ^{232}Th series. Exposures may arise via three main routes: *(a)* the inhalation of radon, thoron and their respective progenies; *(b)* the inhalation and ingestion of ore dust; *(c)* external irradiation with gamma rays.

466. Radon is the main source of radiation exposure in most underground mining operations. While several isotopes of radon exist in nature, one (^{222}Rn) dominates in terms of dose to workers. Under some circumstances, ^{220}Rn (thoron, a decay product of the ^{232}Th chain) may also be important. For convenience, unless stated otherwise, "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 referenced [C13].

467. Continuous radon and thoron gas measurements along with several particle size distribution measurements were made at 20 locations in a rare earth (monazite) pilot processing plant near Bangkok, Thailand. The measurements were conducted from February 2001 to November 2006. A miniature alpha track detector combining both radon and thoron measurements was used. The radon and thoron concentrations ranged from 15 to 100 Bq/m^3 and 150 to 1,550 Bq/m^3, respectively. The measured thoron range was large at any single location. Near a monazite digesting tank, for example, the thoron concentration in air ranged from 80 to 1,500 Bq/m^3 over the five-year period. The UNSCEAR 2000 Report's conversion factors of 9 nSv/(Bq h m^{-3}) for effective dose from radon and 40 nSv/(Bq h m^{-3}) for effective dose from thoron were used. Several studies document the equilibrium fraction, F_{eq}, for thoron indoors, as 0.02–0.03. The value 0.02 was used in the thoron dose calculation. The F_{eq} used for radon indoors was 0.4. The calculated bronchial dose for individuals who worked in the same location in the rare earth processing facility for 2,000 hours in a year could lead to a calculated annual lung dose of up to 0.7 mSv due to radon and 2.4 mSv due to thoron. The particle size distributions taken over intervals of 1 to 2 months with a miniature integrating particle size sampler showed four peaks, at 5, 150, 400 and 5,000 nm, with 50% of the activity associated with the 150 nm mode [H6]. The results of the SMOPIE project (Strategies and Methods for Optimization of Internal Exposures) indicate that rare earth processing may give rise to annual doses of over 20 mSv [V1].

468. The natural radionuclides involved in any processing technology for natural raw material end up either in the finished products or in the liquid, solid or gaseous waste generated. Depending on their chemical properties, the radionuclides are concentrated or distributed in the end products and in the waste [B19, S20]. The grinding of raw materials may generate fine particles of dust and also make it easier for radon to escape into the workplace air. Processing materials rich in uranium or thorium decay products at high temperatures (e.g. coal combustion) could enrich airborne

dust in some radionuclides of the uranium and thorium series, e.g. ^{210}Po and ^{210}Pb. At very high temperatures (3,000ºC or greater), other radionuclides of the uranium or thorium series may also sublimate. For example, ^{228}Ac may sublimate during welding from welding rods doped with ^{232}Th [B19, I18, I26].

469. In a survey programme involving six underground coal mines in Baluchistan, Pakistan, radon measurements were carried out to estimate the workers' doses due to radon exposure. Radon concentrations varied from 121 to 408 Bq/m^3 in the mines under study. The dose estimate was based on the conversion factor of 5 mSv/WLM on the assumption that the occupancy time in the mines is 4,000–4,500 h/a. Consequently the annual doses for workers were within the range 2.1–7.0 mSv [Q10]. An evaluation of occupational exposure in three underground coal mines in Turkey (Kozlu, Karadon and Üzülmez) indicated average annual effective doses of 4.9 mSv. The total workforce was 12,510 and the collective effective dose was estimated to be 61.5 man Sv [F10]. Evaluation of occupational exposure due to intakes of long-lived radionuclides from the radon decay series by workers in coal mines in Brazil indicated average annual committed effective doses of less than 1 mSv [L17]. In an assessment of occupational radiation exposure carried out in Polish coal mines in 1997, it was estimated that the maximum value of the dose equivalent received by any miner during the period of an entire year of work under such conditions would not exceed 3.5 mSv [I18, S24]. In a survey programme carried out in three underground coal mines in Western Australia employing 297 workers, the estimated average annual effective dose was 2.9 ± 1.5 mSv [H22].

470. An occupational exposure assessment of some 80 coal mines in China was carried out during the period 2002–2004. The results indicated that the average annual dose to the staff of the underground mines is 2.4 mSv, with the largest dose being over 10 mSv [C12]. The effective doses for Chinese coal mine workers seem to have a decreasing trend; the average value was reported as 4.8 mSv for 1999 [T4]. Of the 6 million underground coal miners countrywide, 1 million are working in large coal mines, 1 million in medium-sized coal mines, 4 million in small coal mines and 50,000 in bone-coal mines. Bone-coal is an impure coal that contains much clay or other fine-grained detrital mineral matter; it is hard and compact. On this basis, the collective dose is estimated to be about 14,600 man Sv (table 52). Most of the occupational exposure is due to radon and its progeny [C12].

471. In the Islamic Republic of Iran, there are about 150 underground mines, of which 60% are coal mines and 40% metal mines. To assess the possible presence of high radon levels in these mines, a radon survey programme of non-uranium mines was started in early 2000. The evaluation of occupational exposure in the ten mines gave the following results: 35 workers incurred an average effective dose of 8.3 mSv, and 235 workers an average effective dose of 0.06 mSv in the two manganese mines; 235 workers in the lead mine received an average effective dose of 1.2 mSv; and 8,772 workers in the seven coal mines received an average effective dose of 2 mSv [G9].

472. An assessment was undertaken of occupational exposure in 27 underground non-uranium mines in Western Australia. These mines employed 2,173 workers, which represented nearly 80% of the underground workforce at the time of the survey. The average annual effective dose across all mines was estimated to be 1.4 mSv, ranging from 0.4 mSv for a nickel mine to 4.2 mSv for a coal mine. Radon progeny exposure contributed approximately 70% of the total effective dose [H22].

473. The average annual effective dose to workers in four metal ore mines in Poland was 2.5 mSv (maximum value 9.6 mSv). Annual doses for workers in two lead and zinc mines were estimated at about 4 mSv (maximum value 8.7 mSv), and for workers in two copper mines at about 2.8 mSv (maximum value 7.0 mSv); these doses were also due to radon exposure [I18]. Workers at a commercial underground lead and zinc mine in Ireland have been monitored for radon exposure; 11 workers received annual doses due to radon inhalation in the range 1–6 mSv [C25].

474. The estimated average annual doses received by underground gold mine workers in South Africa were 6.3 mSv in 1997, 4.9 mSv in 1998, 5.4 mSv in 1999 and 7.0 mSv in 2000. The data are presented in table 53. A survey programme carried out in the gold mines during 1993–1994 found that 71% of the dose was due to inhalation of radon gas and its short-lived progeny, 25% due to external gamma exposure and the remaining 4% due to inhalation of dust [I18, W17].

475. An evaluation of the occupational radiation exposure to NORM in surface and underground mining operations in a gold mine in the Ashanti Region of Ghana showed that the annual effective dose is about 0.26 ± 0.11 mSv for surface mining and 1.83 ± 0.56 mSv for the underground mines. The total number of workers was 4,439 [D1].

476. A dose assessment for 45 workers in five different areas of the largest underground phosphate mine in Egypt, the Abu-Tartor phosphate mine, was conducted taking into account measurements of radon, its short-lived decay products, thoron and external dose (using TLDs). The calculated effective dose due to airborne radionuclides was the main contributor to the occupational exposure and exceeded 20 mSv/a, especially at locations in the side tunnels (where levels were higher by a factor of up to 4 because of inadequate ventilation). The average annual effective dose was 11.66 mSv. The mean value of external dose as measured by TLDs was 8.97 mSv/a. These results are presented in table 54. The dose estimate calculated from workplace measurements underestimates the annual dose by around 25% [K11]. The average annual effective dose (due to radon, radon progeny and thoron progeny) in other Egyptian phosphate mines was 70.2 mSv, with a range of 12.2–136.9 mSv

[H31]. More recent evaluation has been conducted in three phosphate mines in Egypt, located in the Eastern Desert about 500 km south of Cairo. The average annual effective doses for workers from the mines, due to inhaled radon progeny, are in the range 107–182 mSv [E3].

477. The estimated annual doses for workers in surface copper mines in Poland were about 1 mSv resulting from internal exposure due to radium and about 0.5 mSv from external exposure [I18]. The exposure of surface workers in gold mines in South Africa is generally very low, except for workers in acid plants, where the radium originating from the pyritic ore can become very highly concentrated during the formation of scales and give rise to substantial external gamma and dust inhalation exposures. A survey of occupational exposure carried out in 1999 in South African mines and mineral processing facilities (other than those associated with gold production) showed that around 98% of the 9,955 workers received doses of less than 5 mSv. The workers with the highest exposures are in copper mining [W17].

478. Another group of exposed workers are those in diamond mines in Africa. Security measures are implemented to reduce diamond thefts. These measures are explicitly authorized through national regulations and cover a large spectrum, from access control to the use of special equipment to prevent the employees having direct contact with the diamonds. Personal searching, including searching by hand and X-ray searching, which is practised in some conditions in some countries, is one of the security measures. Personal searching has two main functions: to recover diamonds that have been concealed with the intention to steal, and to deter and prevent theft. The radiation dose is about 5 µSv per scan in screening workers to detect if they have swallowed or hidden diamonds in their bodies. There is no estimate of the number of workers involved in these diamond mines and of how often they are exposed [I6].

479. A fluorspar mine that operated in St. Lawrence, Newfoundland, Canada, from the early 1930s until 1978 was estimated to have radon progeny concentrations of 2–130 WL. The source of radon was eventually identified as the water that poured into the mines [D3]; the radon itself apparently originated from the host granite. Mechanical ventilation was introduced in all levels of the mine that were still operating, and the radon daughter levels subsequently fell below the suggested limit of 1 WL in 1960 [M31]. The last fluorspar mine was closed in St. Lawrence in 1978. The average annual internal and external effective doses received by workers in the phosphate fertilizer plant were 0.75 mSv and 0.88 mSv, respectively [B39].

480. In most of the extractive and processing industries in Brazil, average annual effective doses were somewhat greater, above 1 mSv [L17]. An evaluation of internal exposure of workers at a thorium purification plant in Brazil showed that the annual effective dose ranged from 0.12 to 1 mSv. In this facility, thorium sulphate is converted in the purification process into concentrated thorium nitrate, $Th(NO_3)_4$, which is then used in gas mantle production [C2]. The average annual effective dose of workers in an electrothermal plant in the Netherlands for producing elemental phosphorus is about 1 mSv [E4]. A radiological survey was conducted and a radiation protection system implemented during the site remediation and decommissioning of an old and abandoned Greek phosphate fertilizer industry. The initial estimate of the effective dose to workers involved in the decontamination process, for a worst-case scenario, was estimated to be up to 9 mSv [K17].

481. Various assessments of annual effective doses received by workers in zircon milling plants have been reported. The results of these assessments are summarized in table 55, from which it would appear that, in most zircon milling operations, workers do not receive annual doses exceeding about 1 mSv. Except for bagging operations, this is likely to be the case even if respiratory protection is not used [I41]. However, the results of the SMOPIE project indicate that zircon milling may give rise to annual doses of between 6 and 20 mSv, in workplaces where protection measures are poor or non-existent [V1].

482. Data from the UNSCEAR Global Survey of Occupational Radiation Exposures on the occupational exposure of workers involved in extractive and processing industries are included in table A-16. For coal mines, only the United Kingdom has reported data on occupational exposure. The workforce consists of 5,000 workers, who represent about 10% of the number reported in the previous period. The average annual effective dose has remained constant at 0.6 mSv. For other mineral mines, five countries have reported data, representing about 1,300 workers. The average effective dose is 1.2 mSv.

483. The level of exposure depends on a number of factors, including the type of mine, the geology and the working conditions, particularly the ventilation. In general, the occupational exposure is distinguished by the type of mine (underground versus above ground). The range of typical values of annual effective dose for underground coal mines is 0.5–4 mSv. The typical average effective dose for coal mining operations is considered to be 2.4 mSv. The range of typical values of annual effective dose for other mineral mining is 1.3–5.0 mSv. The typical average effective dose for other mining operation is considered to be 3.0 mSv. In order to have a rough estimate of the worldwide level of exposure due to the extractive mining industry, it is assumed that the total workforce comprises about 11.5 million workers, that 60% of this workforce (i.e. 6.9 million workers) receive an average annual effective dose of 2.4 mSv, and that 40% of the workforce (i.e. 4.6 million workers) receive an average annual effective dose of 3.0 mSv. This results in an estimate for the annual collective effective dose of about 16,560 man Sv for coal mines and 13,800 man Sv for other mines. This makes a total of some 30,360 man Sv annually for the mining industry as a whole. It has been very difficult to distinguish the level of exposure and the numbers of workers engaged in mining and mineral extraction. In this annex, the

collective dose estimated for workers involved in mineral extraction includes those involved in mineral processing. The level of exposure to radon may be underestimated, since the doses for workers in workplaces where the radon concentration is below 1,000 Bq/m^3 may not be reported. The number of workers, the average effective doses and the collective effective doses are presented in table 57.

484. The UNSCEAR 1988 Report [U7] estimated the collective doses for coal mining as 2,000 man Sv. This was based solely on exposures in mines in the United Kingdom and on the worldwide production of coal. The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,600 man Sv, which was about 16% of the current estimate of 16,560 man Sv. For non-coal mines, the collective dose estimate has also increased considerably. The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,000 man Sv, which is about 14% of the current estimate of 13,800 man Sv. The overall estimate for mining activities is 30,360 man Sv, which is about seven times higher than the previous estimate [U3].

3. Gas and oil extraction

485. Naturally occurring radioactive material (NORM) found in the earth's crust, largely in the form of ^{226}Ra and ^{228}Ra and their associated radionuclides, is brought to the surface during gas and oil production processes. The NORM represents a potential internal radiation exposure hazard to both workers and members of the public through the inhalation and ingestion of radionuclides. In addition, a gamma exposure rate higher than normal background has been observed in the oil and gas industry.

486. The mixed stream of oil, gas and water associated with the production process also carries the noble gas ^{222}Rn, generated in the reservoir rock through the decay of ^{226}Ra. This radioactive gas emanating from the production zone travels with the gas/water stream and then preferentially follows the dry export gases. As a consequence, equipment from gas treatment and transport facilities may accumulate ^{210}Pb formed from the short-lived progeny of ^{222}Rn, which plate out on to the inner surfaces of gas lines. These ^{210}Pb deposits are also encountered in liquefied natural gas processing plants [G7].

487. NORM in the oil and gas industry has the potential to give rise to external exposure during production owing to the accumulation of gamma-emitting radionuclides. Moreover, it can give rise to internal exposure to workers and other persons through the inhalation or ingestion of radionuclides, particularly during maintenance, the transport of waste and contaminated equipment, the decontamination of equipment and the processing of waste. The short-lived progeny of the radium isotopes, in particular of ^{226}Ra, emit gamma radiation capable of penetrating the walls of internally contaminated pipes and vessels. Therefore the deposition of contaminated scales and sludge inside these components produces enhanced dose rates outside them as well. The values depend on the amount and activity concentrations of radionuclides present inside the components and the degree of shielding provided by the pipe or vessel walls. Maximum dose rates usually range up to a few microsieverts per hour, but in a few cases dose rates of up to 100 μSv/h (about 1,000 times greater than the normal background values due to cosmic and terrestrial radiation) have been reported outside production equipment [M14, T2, W9].

488. At the Omar oilfield in Syria, the highest equivalent dose rates were 30 μSv/h on the surface of the well-head and 25 μSv/h on the surface of some piping containing scale deposits, especially in valve and bend areas. In the Gulf of Suez oilfield in Egypt, the maximum equivalent dose rate measured at the surfaces of separator tanks and piping, and due to scale precipitate, was 33 μSv/h [A9]. Dose rates observed in oil production and processing facilities vary from 0.1 μSv/h to 300 μSv/h [I23].

489. The IAEA has published information concerning concentrations of NORM in oil, gas and by-products that may result in occupational radiation exposure. The concentrations of ^{226}Ra, ^{228}Ra and ^{224}Ra in scales and sludge range from less than 0.1 Bq/g to 15,000 Bq/g. The activity concentrations of radium isotopes are lower in sludge than in scales. The opposite applies to ^{210}Pb, which usually has a relatively low concentration in hard scales but may reach a concentration of over 1,000 Bq/g in lead deposits and sludge. Although thorium isotopes are not mobilized from the reservoir, the decay product ^{228}Th grows in from the decay of ^{228}Ra after deposition of the latter. As a result, when scales containing ^{228}Ra age, the concentration of ^{228}Th increases to about 1.5 times the concentration of ^{228}Ra still present [I23].

490. An assessment of the occupational exposure *t* due to petroleum pipe scales has been performed for three oilfields. Four radiation exposure pathways were investigated: inhalation of pipe scale dust generated during pipe rattling; incidental ingestion of the pipe scale dust; external exposure resulting from uncleaned pipes; and external exposure resulting from pipe scale dispersed on the ground. The estimated annual effective dose for the operator and the assistant was 0.11–0.45 mSv for inhalation and 0.02–0.1 mSv for sporadic ingestion. The annual effective dose due to external exposure from uncleaned pipes ranged from 0 to 0.28 mSv. The annual effective dose due to external exposure from pipe scale dispersed on the ground was estimated to be 2.8 mSv for the operator and 4.1 mSv for the assistant [H5].

491. According to an estimate based on assuming the inhalation of 5 μm AMAD (activity median aerodynamic diameter) particles incorporating ^{226}Ra (with its complete decay chain in equilibrium), ^{228}Ra and ^{224}Ra (also with its complete decay chain in equilibrium), each at a concentration of 10 Bq/g, a committed effective dose per unit intake of about 0.1–1 mSv/g would be delivered. The exact value depends on the extent of ingrowth of ^{228}Th from the decay of ^{228}Ra and on the lung absorption types assumed. For 1 μm AMAD

particles, the committed effective dose per unit intake would be 25–30% higher [I23].

492. Available data from the UNSCEAR Global Survey of Occupational Radiation Exposures for gas and oil extraction are included in table A-16. The data have been presented for only two countries. The total number of monitored workers was 500 for the period 1995–1999 and 600 for 2000–2002, and the average effective dose was 1.3 mSv for both periods. It is difficult to estimate the collective dose for this practice since the total number of workers exposed to ionizing radiation is not known.

4. Radon exposure in workplaces other than mines

493. The levels of radon in workplaces are exceptionally variable, and high doses to workers can arise in places other than uranium mines. Regulatory authorities have recognized the importance of controlling radon exposure in workplaces other than mines. The European Guideline 96/29/Euratom [E10], which formulated basic safety standards for the protection of the health of workers and members of the general public against the hazards of ionizing radiation, included consideration of areas where the presence of natural radiation sources would increase exposures to employees or members of the public to levels that could not be ignored from the standpoint of radiation protection. ICRP Publication 65 [I48, I61] indicated a planning value in the range 500–1,500 Bq/m^3, above which radiation protection measures are required; orientation values are available for application to health protection.

494. The radiation protection regulations applied in Switzerland since the promulgation of 1994/SSS-94 [S33] established a radon concentration limit of 3,000 Bq/m^3 for industrial areas. Orientation values of 200 Bq/m^3 and 400 Bq/m^3 were indicated for new buildings and for the renovation of buildings, respectively. These workplaces are varied in nature. They include industries (food industries, breweries, laundries, etc.), waterworks, shops, public buildings and offices, schools, subways, spas, caves and closed mines open to visitors, underground restaurants and shopping centres, tunnels (construction and maintenance) and sewage facilities [I21, S39, S41].

495. An occupational exposure survey in over 500 of the 2,600 water supply facilities in Bavaria showed that, in all geological regions, exposure levels giving rise to over 6 mSv/a can occur. About 2% of the staff is subjected to exposure levels that give rise to over 20 mSv/a [S40, T9, T10]. A survey of occupational exposure was conducted in ten drinking water supply plants in Slovenia. The annual doses were found to be below 0.5 mSv at six of the workplaces and in the range 0.6–3.0 mSv at the other four [V16].

496. Occupational exposure in radon therapy rooms is related to the different treatment procedures, which affect the temporal variation of radon and its progeny. An evaluation of occupational exposure due to radon and its progeny in the treatment facilities of the radon spa Bad Gastein in Austria produced different dose ranges for each of the four treatment rooms monitored. The estimated annual effective doses were 9.4–32 mSv, 1.8–2.4 mSv, 1.3–1.7 mSv and 0.2–0.3 mSv [L7]. The annual individual effective doses to the employees of a therapeutic dry carbon dioxide spa in Hungary, due to inhalation of ^{222}Rn, ranged from 0.9 to 4.2 mSv. The highest dose to a staff member was received by an attendant who spent much of his time in the treatment room watching over the patients in the “pit” [C30]. The results of the dose assessment for a therapeutic cave in Hungary showed that staff received doses of up to 20 mSv/a when working 4 hours per day in the cave [K6]. Annual effective doses of between 1 and 44 mSv were estimated for workers in Spanish spas [S29]. Bath attendants were the working group subject to the highest doses. In Slovenia, a dose assessment was performed in five spas; the radon concentration in indoor air rarely exceeded 200 Bq/m^3 [V13].

497. In Slovenia, there are more than 3,000 caves located in the Karst regions. Some 50 professional guides and other workers are employed in the Postojna and Skocijanske caves, and many volunteers from local cave associations work or serve as guides for visitors in about 20 other caves. Annual doses, estimated on the basis of various lung models, ranged from 10 to 85 mSv [J7]. A survey carried out in 2002 of occupational exposure in three Irish caves showed that 13 workers received annual doses due to radon inhalation in the range 1–6 mSv, and one worker received an estimated annual dose of 12 mSv [C25]. A dose assessment was carried out in 2004–2005 in the Lantian Xishui karst cave of Shaanxi, China. The average annual effective dose to tour guides was found to vary between 1.2 mSv and 4.9 mSv [L23].

498. A radiation survey of seven archaeological sites inside Egyptian pyramids or tombs, conducted in the Saggara area, obtained measurements of radon (^{222}Rn) and its short-lived decay products, thoron (^{220}Rn) progeny and gamma radiation. In seven of the pyramids and tombs, workers could receive annual doses ranging from 2 to 13 mSv; in the others, annual doses were less than 1 mSv [B26]. The dose assessment for the workers at two archaeological sites in Alexandria, Egypt, has shown that the effective doses are in the range 0.05–5 mSv/a at both sites [H2]. The estimated average annual effective dose to tour guides at the great pyramid of Cheops was 0.05 mSv, and estimates for the pyramid guards varied from 0.19 to 0.36 mSv [H1].

499. A programme of radon measurements in Irish schools has been conducted since 1998. A total of 45,000 individual radon measurements were made in 3,444 primary and post-primary schools. The average radon concentration was 93 Bq/m^3, comparable with the 89 Bq/m^3 observed for homes; the highest concentration measured was 4,948 Bq/m^3. In 74% of the schools, no classrooms had radon concentrations of greater than 200 Bq/m^3, while in 9% of the schools, the radon concentration in at least one classroom exceeded 400 Bq/m^3. A total of 591 schools (17% of those

measured) had radon concentrations of between 200 and 400 Bq/m^3. A total of 898 schools (26% of those measured) will require some degree of remediation to reduce indoor radon concentrations [C25]. The radiation survey performed in 25 classrooms in the capital city of Kuwait between September 2003 and March 2004 showed that the annual dose was about 1 mSv [M1]. In a radon survey in a school with elevated levels of radon in Slovenia, the annual effective doses received by the staff were estimated to range from 1.3 to 12.6 mSv [V15]. Another radiation survey, in schools on the territory of an abandoned uranium mine in Slovenia, found that the annual doses for the staff ranged from 0.07 to 0.27 mSv [V14]. An extensive radon survey was performed in 890 schools in Slovenia, and radon concentrations with an arithmetic mean of 168 Bq/m^3 and a geometric mean of 82 Bq/m^3 were found. In 67% of the schools, indoor radon concentrations were below 100 Bq/m^3, while in 8.7% of them the concentration exceeded 400 Bq/m^3. The average value of the gamma dose rate measurements was 102 nGy/h and the geometric mean was 95 nGy/h [V11, V12].

500. The average annual effective dose to the workers in 94 offices in Hong Kong has been estimated to be 0.35 mSv [Y3]. In the United Kingdom, a study was undertaken throughout British Telecom underground workplaces during 1993–1994 to assess occupational exposure due to radon. The study concluded that no British Telecom staff received an annual radiation dose of greater than 5 mSv [W13]. In Venezuela (Bolivarian Republic of), the average effective dose received by the employees of the Caracas subway system has been estimated as about 1 mSv/a [L9] A radiation survey in 201 rooms of 26 major hospitals in Slovenia gave an estimate of the annual effective doses for 966 staff (94.2%) of less than 1 mSv, but for 10 workers the doses were between 2.1 and 7.3 mSv [V17].

501. Available data from the UNSCEAR Global Survey of Occupational Radiation Exposures for radon in workplaces other than mines are included in the last part of table A-16. Five countries have reported data for the period 2000–2002. These data show considerable variation for the average effective dose, from 0.7 to 5 mSv. Germany has reported separate data for spas, waterworks and tourist caves. The average effective dose for people working in spas, 4 mSv, is twice that in the other workplaces, 2 mSv, as shown in table 56.

502. Elevated levels of radon have been found in a number of countries, but the levels of exposure vary considerably according to the workplace. So far the UNSCEAR reports have performed only crude estimates of the worldwide levels of exposure, owing to a lack of information. Although the number of data available for the last two periods has increased compared with the previous periods, the sample sizes are still very small and the levels of exposure depend on factors that vary from country to country, such as geology, building materials and regulatory regimes. There are clearly very few data on which to base an accurate estimate of worldwide exposure. Since the scenario of exposure throughout the world has not changed dramatically since the UNSCEAR 2000 Report, the number of exposed workers is estimated as 1.250 million, the collective effective dose as about 6,000 man Sv and the average effective dose as 4.8 mSv (table 57). The level of exposure is the same as estimated in the UNSCEAR 2000 Report [U3]. Clearly this estimate is very crude.

5. Conclusions on occupational exposure to natural sources of radiation

503. After the implementation of the International Basic Safety Standards [I7] and subsequently the implementation of the European Union standards for the protection of workers exposed to natural radiation (European Union Directive 96/29/Euratom) [E10], data on levels of occupational exposure to natural sources of radiation have become available, mainly in the European Union countries. Other qualifying data are needed on specific issues for each category of exposure in order to be able to derive an accurate estimate for the worldwide average levels of exposure to natural sources of radiation. The highest level of occupational exposure comes from exposure to natural sources of radiation.

504. Data have indicated that aircrew are one of the most highly exposed occupational groups. In Germany, the collective dose to this group, 60 man Sv, contributes more than 50% of the total collective dose to all workers in the country. The estimated worldwide collective effective dose to aircrew is about 900 man Sv. This value is about the same as that estimated in the UNSCEAR 2000 Report, 800 man Sv [U3].

505. Work activities with materials containing NORM can involve significant exposure of workers through internal contamination by inhalation. However, there can be considerable differences in workplace conditions, the radionuclides involved and the physical and chemical matrices in which the radionuclides are incorporated.

506. The level of exposure in mines depends on a number of factors, including the type of mine, the geology and the working conditions, particularly the ventilation. The UNSCEAR 1988 Report [U7] estimated the global collective dose for coal mining as 2,000 man Sv. The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,600 man Sv, which is about 16% of the present estimate of 16,560 man Sv. For coal mines, the estimated number of workers is 6.9 million and the average effective dose is 2.4 mSv. The increase is due to taking into consideration the contribution of the coal miners in China. The current estimate of the exposure levels for coal miners seems to be more realistic than the previous ones, since it is based on data obtained from a comprehensive survey performed in China, which represents the great majority of the global workforce. On the basis of the survey programme carried out in China, the level of exposure appears to be declining, since the annual effective dose fell from 4.8 mSv in 1999 to 2.4 mSv in 2000–2002 [C12, T4]. For non-coal mines, the collective dose estimate has also increased considerably.

The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,000 man Sv, which is about 14% of the current estimate of 13,800 man Sv. The estimated number of workers in non-coal mines is about 4.6 million, and the average effective dose is 3.0 mSv. However, for non-coal miners the worldwide estimate is still only rough, since the data need to be qualified with regard to their completeness, in particular for the number of workers engaged in underground and above-ground mines. The overall estimate for mining activities is 30,360 man Sv, which is about seven times higher than the previous estimate [U3].

507. The SMOPIE project, which dealt with occupational internal exposures from practices and work activities in NORM industries in European countries, covered a broad variety of practical issues, including: the generation of and exposure to dust; whether the exposure is continuous or discontinuous; whether the exposure is worker-induced or process-induced; and the variation of doses between workers. Several studies have been reviewed, but they do not provide the information required for a scientifically sound evaluation of the problem. The results of the project have revealed that there still is a severe lack of information on the number of exposed workers in NORM industries and on the associated occupational doses. The number of 85,000 exposed workers, as derived in this project, warrants more research. The largest group of exposed workers (70,000) appears to be welders using thoriated welding electrodes. The available data suggest that the grinding of welding rods may give rise to annual doses of between 6 and 20 mSv [S4, V1]. There is some evidence that alternative (non-radioactive) welding rods are increasingly being used. This means that the number of exposed workers should decrease in the future. A survey programme in Denmark has shown that the annual committed effective dose from the inhalation of ^{232}Th, ^{230}Th, ^{228}Th and ^{228}Ra, for a full-time TIG (tungsten inert gas) welder, is below 0.3 mSv in a realistic case and around 1 mSv or lower with conservative assumptions. The contribution from grinding electrodes was lower, 0.010 mSv or less [G2]. Again, precise details on this trend were not available.

508. According to the SMOPIE project, the second largest group of exposed workers (10,000) are those trading or using phosphate fertilizers (The data originate from only one country.). The results indicate that, like the grinding of thoriated welding rods, zircon milling may also give rise to annual doses of between 6 and 20 mSv in workplaces where protection measures are poor or non-existent. Rare earth processing may even give rise to annual doses of greater than 20 mSv. In both industries, the number of exposed workers is small [V1].

509. The results of the occupational exposure survey performed in nine European Union countries from 1996 to 2000 have shown that the average annual effective dose declined from 6 to 3 mSv during that period. The annual collective dose fell from 70 to 39 man Sv; therefore the mean value may be influenced by the increasing number of monitored workers. The reduction of 71% in the number of workers receiving annual doses of over 20 mSv is the largest for all work sectors. There was a substantial change in the dose distribution towards lower values in almost all dose bands. However, substantial differences exist between the countries where monitoring was undertaken. There are some uncertainties in this evaluation, since the registered doses may include uranium miners as well as non-uranium miners or workers in tourist caves and at drinking water facilities, i.e. they include external exposures as well as doses from radon inhalation. The recommendations of ICRP Publication 65 [I48] changed the dose calculation substantially by introducing conversion factors and detriment coefficients, as a consequence of which the values of the calculated doses fell considerably. However, the declining values of the annual doses may also be a result of modified work management and workplace conditions [F15]. In conclusion, a declining level in reported occupational exposures to natural sources of radiation in European countries has been seen, although substantial differences exist between the countries where monitoring is undertaken [F15].

510. Elevated levels of radon have been found in a number of countries, but the levels of exposure vary considerably depending on the workplace. The level of exposure to radon may be underreported, since the doses for workers in workplaces where the radon concentration is below 1,000 Bq/m^3 may not be reported. So far the UNSCEAR reports have performed only crude estimates of the worldwide levels of exposure, owing to a lack of information. Although the number of data available for the last two assessment periods has increased compared with the previous periods, the sample sizes are still very small and the levels of exposure depend on many factors that vary from country to country, such as geology, building materials and regulatory regimes. There are clearly very few data on which to base an accurate estimate of worldwide exposure. Since the scenario of exposure throughout the world has not changed dramatically since the UNSCEAR 2000 Report, the same value for the worldwide annual collective effective dose of 6,000 man Sv is assumed. As in the UNSCEAR 2000 Report [U3], the number of workers is estimated to be 1.250 million and the average effective dose to be 4.8 mSv. These estimates are clearly very crude.

511. The worldwide level of exposure for workers exposed to natural sources of radiation has increased considerably compared with the UNSCEAR 2000 Report [U3]. The estimated number of workers is about 13 million. The estimated average effective dose is 2.9 mSv and the estimated collective effective dose is 37,260 man Sv.

C. Man-made sources for peaceful purposes

1. Nuclear power production

512. 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 [U11], 1977 [U10], 1982 [U9], 1988 [U7], 1993 [U6] and 2000 [U3] Reports, with comprehensive treatment in the UNSCEAR 1977, 1982 and 2000 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. Because 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 due to waste disposal are not expected to add a significant amount to the collective exposure of workers to radiation due to the other stages in the fuel cycle.

513. Each stage in the fuel cycle involves different types of workers and work activities. In some cases, for example for reactor operation, the data are well segregated, while in others the available data span several activities, e.g. uranium mining and 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 Global Survey of Occupational Radiation Exposures [U3, U6, U7, U9, U10] but also from other sources, particularly the joint OECD/NEA and IAEA Information System on Occupational Exposure (ISOE) [O14, O19, O20], which serves as a main source of occupational exposure data for reactor operations in the period 1995–2002.

514. For each stage of the fuel cycle, this annex provides estimates of the magnitude of and temporal trends in the annual collective and per caput effective doses, the numbers of monitored workers and the “distribution ratios”. The collective doses are also expressed in normalized terms, i.e. 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, i.e. the amounts of mined uranium, the separation work during enrichment and the amount of fuel required to generate a unit of electrical energy in various reactor types, are given in section II.C of this annex. 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 for each reactor type and per unit electrical energy generated.

515. 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 of fuel fabricated or reprocessed, corresponding to a unit of energy subsequently generated in the reactor), which is the principal measure of output of the nuclear power industry. This form of normalization is both valid and useful when treating data averaged 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 are averaged over five-year periods.

516. 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 Global Survey of Occupational Radiation Exposures are summarized in table A-15. Data collected under ISOE are provided by participants according to standardized reporting formats, although the details requested have increased over time, and not all countries report to the same level of detail. Additionally, the data provided under ISOE are based on operational data collected from the participating utilities, and may differ slightly from official dose records. The reported collective doses and the collective dose distribution ratios are largely insensitive to the differences identified in table A-15, 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 the decisions and practices concerning which workers in a particular workforce are to be monitored. Differences in these areas could not be discerned from responses to the UNSCEAR Global Survey of Occupational Radiation Exposures, and they therefore cannot be discerned from table A-15. 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 among reported data. As mentioned before, the criteria applied in different countries to select workers who should be monitored differ considerably. Some countries monitor only the exposed workers, while others also include the non-exposed workers in their individual monitoring programme for various reasons.

(a) Uranium mining and milling

517. Most natural uranium is mined for energy production in fission reactors, but it is also used in nuclear research reactors and in military activities. Commercial uranium use is primarily determined by the fuel consumption requirements

of power reactors and continues to increase steadily, while the requirements for research reactors remain modest by comparison.

518. 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 performed at a location relatively close to the mine. The milling process involves the crushing and grinding of raw ores, followed by chemical leaching, the separation of uranium from the leachate and precipitation of yellowcake [K14], and the drying and packaging of the final product for shipment.

519. Uranium mining has been conducted in 24 countries (see table 14 for annual uranium production worldwide and section II.C of this annex) over the period 1998–2003. This practice has ended in some countries. Between 1990 and 1997, 34 countries were involved in uranium mining, and over the whole nuclear era, some 37 countries [U3]. The major producer is Canada, which is responsible for about 30% of the world production, followed by Australia with about 14%, and Niger with about 10%. About 93% of the world's production comes from only ten countries: Australia, Canada, Kazakhstan, Namibia, Niger, the Russian Federation, South Africa, Ukraine, United States and Uzbekistan.

520. In the mining and milling of uranium ores, the workers incur both internal and external radiation exposures. Mining operations such as drilling, blasting, loose-dressing, mucking, crushing, boulder-breaking, loading and dumping, etc., generate ore dusts of different particle sizes, which become dispersed in the mine environment and give rise to an inhalation hazard. Concentrations of these ore dusts are quite variable with time and location. Extremely high values can be reached during blasting and ore dumping. In general, these workplaces are very dusty, and consequently there is a potential risk for inhalation of aerosol particles containing radionuclides from the ^{238}U decay chain. The internal dose depends on workplace conditions, which vary considerably according to the type of mine (underground or above ground), 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 resulting from this source would be expected in the milling of the ores and the production of yellowcake. Internal exposure makes by far the greatest contribution to the total exposures resulting from underground mining.

521. Exposure data for the mining and the milling of uranium ores from the UNSCEAR Global Survey of Occupational Radiation Exposures for 1995–2002 are given in tables A-17 and A-18, respectively, and trends for the six periods 1975–1979, 1980–1984, 1985–1989, 1990–1994, 1995–1999 and 2000–2002 are given in figure XXXVIII.

522. Over the four previous five-year periods (1975–1994), the average annual amounts of uranium mined worldwide were 52, 64, 59 and 39 kt. For the periods 1995–1999 and 2000–2002, the average annual amounts mined were 34 kt. This represents a reasonably constant level of production for the first three periods and a reduction by about one third for the last three periods. The average annual amount of uranium mined remained constant over the last three periods.

523. Germany has ceased mining operations; its reported doses relate to the decommissioning of mines. Other countries, e.g. France and Spain, are in the same situation. Still other countries, e.g. Argentina, Belgium, Gabon and Hungary, have completely stopped their uranium production in the last several years (see table 14).

524. The estimate of worldwide levels of exposure resulting from uranium mining has been derived by scaling up to the total world uranium production from the 36% of production for which data were reported. For the reported data, Canada dominates, accounting for about 30% of the world uranium production. On this basis, the average annual number of monitored workers worldwide has decreased dramatically over time: 240,000, 310,000, 260,000, 69,000 in the first four periods (1975–1979, 1980–1984, 1985–1989 and 1990–1994), compared with 22,000 and 12,000 in the last two periods (1995–1999 and 2000–2002). These reductions by a factor of 3 and 6 in the last two periods are also seen in the values for average annual collective effective doses. For the first four periods the worldwide estimates were 1,300, 1,600, 1,100 and 310 man Sv, but for 1995–1999 and 2000–2002 the values fell to 85 and 22 man Sv, respectively. Similarly, the average collective dose per unit mass of uranium extracted was 26, 23, 20 and 8 man Sv/kt for the first four periods and declined to 2 and 1 man Sv/kt for 1995–1999 and 2000–2002, respectively. However, the estimated average annual effective doses have been high over the years, even though they started to decrease in the last two periods: they decreased from 4.5 mSv in 1990–1994 to 3.9 mSv in 1995–1999 and to 1.9 mSv in 2000–2002. The average effective dose for measurably exposed workers has decreased significantly as well. The data are consistent with a worldwide reduction in underground mining activity coupled with more efficient mining operations. The trends are presented in table 58 and are represented graphically in figure XXXVIII.

525. In order to evaluate the occupational exposure in underground and above-ground mines, a new questionnaire was distributed requesting the data to be provided separately. Canada and Germany have reported data separately for above-ground and underground mines. The data are presented in table 59. The effective doses were in the range 0.3–1.3 mSv for above-ground mines and 1.0–3.1 mSv for

underground mines. Effective doses for the workers in the underground mines are at least twice as high as those in the above-ground mines. The data reported by Germany for underground mines are related to the decommissioning of mining facilities. The doses reported by Canada show a decreasing number of monitored workers and decreasing collective dose and average effective dose for underground miners. The major reason for the reduction in the level of occupational exposure in Canada is that uranium mining moved from the conventional cut-and-fill method used to mine ore grades of around 0.1% U in northern Ontario to the more advanced, non-entry type of method used to mine the higher-grade ores (some exceeding 20% U) in northern Saskatchewan. These non-entry mining methods significantly reduced gamma radiation exposures and greatly restricted exposure to radon progeny and uranium ore dust.

526. The contribution of internal and external exposure to the total effective dose has been analysed in this annex on the basis of data provided by Canada, the Czech Republic and Germany for each type of mine. The percentage dose contributions from radon and ore dust inhalation and from external exposure are given in table 60. The contribution of each source varies according to the type of mine and the ore grade. However, internal exposure is the main contributor to the total effective dose, independent of the type of mine, and its overall contribution is about 70%.

527. According to the Canadian Occupational Radiation Exposures reports [H9, H10, H11, H12, H13, H14], radiation exposure is significantly higher for underground mining workers than for surface mining workers. It also differs considerably according to job function. The contribution of radon exposure to the total effective dose is about 60%, independent of the type of mine. As shown in table 61, the annual effective dose to the more exposed miner job category in Canada, averaged over the period 1995–2001, fell from 11 mSv to 2 mSv for underground mines and rose from 1 mSv to 2 mSv for above-ground mines.

528. For the period 1996–2000, the average annual doses received by workers at three underground uranium mines in India were around 8 mSv. The main contribution to the effective dose came from inhalation of ^{222}Rn and its short-lived progeny [K10].

529. The assessment of exposure of miners to the long-lived α-emitting radionuclides associated with respirable ore dusts in the Jaduguda uranium mine in India, where the U_3O_8 concentration is less than 1%, has shown that the inhalation of ore particles has contributed only about 5% of the annual effective dose limit, indicating that in this mine it is not a significant source of exposure [J3]. At ore grades of up to about 3% U_3O_8, limitation of airborne silica will usually place a stricter constraint upon dust concentration than does radioactivity. However, at ore grades in excess of 3% U_3O_8, and when the ore is not high in silica, radiation exposure resulting from inhalation of ore dust could become important.

530. Data on exposure of workers due to uranium milling are presented in table A-18. The Committee assumes that the amount of uranium milled is equal to the amount mined. The estimated worldwide level of exposure has decreased over the six periods: *(a)* the average annual number of monitored workers was 3,000 for the periods 1995–1999 and 2000–2002, which is substantially fewer than in the previous four periods: 12,000, 23,000, 18,000 and 6,000; *(b)* the average annual collective effective dose was 4 man Sv and 3 man Sv for 1995–1999 and 2000–2002, respectively, compared with 124, 117, 116 and 20 man Sv for the previous four periods; *(c)* the average annual effective dose was 1.6 mSv and 1.1 mSv for 1995–1999 and 2000–2002, respectively, compared with 10.1, 5.1, 6.3 and 3.3 mSv for the previous four periods. The data are presented in table 62 and figure XXXIX.

(b) Uranium conversion and enrichment

531. 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. Some reactors use fuel slightly enriched in ^{235}U (generally about 3% enrichment, in contrast to natural uranium, which contains about 0.7% ^{235}U). The U_3O_8 from the milling process is converted to UO_2 by a reduction reaction with H_2. The UO_2 is converted to UF_4 by the addition of hydrofluoric acid (HF) and then to UF_6 using fluorine (F_2). The gaseous product, uranium hexafluoride (UF_6), is then enriched in ^{235}U. Most of this is performed by the gas diffusion process, but gas centrifuge techniques are being used increasingly. Once the enrichment process has been completed, the UF_6 gas is reconverted into UO_2 for fuel fabrication [U3].

532. In 2003 there were 29 uranium conversion/recovery facilities and 21 uranium enrichment facilities in operation. The enrichment capacity of these facilities and a few other small producers is presented in section II.C of this annex. The greater part of the enrichment services came from five suppliers: the United States Department of Energy, Eurodif (France), Techsnabexport (Russian Federation), Urenco (Germany, Netherlands and United Kingdom) and China [X1]. Most thermal reactors use enriched uranium with typically a 3% level of enrichment. Four types of uranium fuel will be considered: unenriched metal fuel, used in Magnox reactors; low-enriched oxide fuel, used in AGRs and LWRs; unenriched metal fuel, used in HWRs; and mixed oxide fuel, used in FBRs. Mixed oxide (uranium–plutonium) fuels are increasingly being developed for use in LWRs.

533. Exposure data for this practice are given in table A-19. The average annual number of monitored workers increased from 12,600 in 1990–1994 to about 18,000 in 2000–2002. The average annual collective dose has increased from 1.28 to 1.70 man Sv. The average annual effective dose to monitored workers was low, 0.1 mSv, in 1995–2002, and has not changed since 1985–1989. The absence of data from the Russian Federation would suggest that these figures are

underestimates. Even taking this into account, the individual and collective doses arising from enrichment are low. The trends in this practice are presented in table 64 and figure XL.

534. Occupational exposure occurs during the enrichment and conversion stages of the fuel cycle. External radiation exposure is more important than internal radiation exposure, but workers may be exposed to internal radiation, particularly during maintenance work or in the event of leaks. The workers may be exposed to UF_6, classified as a soluble compound and assigned as Type F for lung retention, according to the ICRP [I51, I57]. In these situations, the occupational exposure to daily intakes of these uranium compounds of any isotopic composition would be limited by considerations of chemical toxicity rather than radiation dose [I55, S40]. A new questionnaire was distributed to Member States to obtain information about the contribution of internal exposure to the total effective dose. Data from China show that 64% of the dose is due to external exposure. The contribution of each source varies according to the level of exposure. The data provided by China show that, for effective doses lower than 1 mSv, the contributions of internal and external exposure are about the same. For effective doses higher than 1 mSv (1–5 mSv), the contribution of internal and external exposure is about 17% and 83%, respectively.

(c) Fuel fabrication

535. 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 3–5% ^{235}U). The main exceptions are the gas-cooled Magnox reactors and the HWRs, which use natural uranium. Some older research reactors use high-enriched uranium (up to 98%); however, for security reasons this material is being used ever less frequently. The principal source of exposure during fuel fabrication is uranium (after milling, enrichment and conversion, most decay products have been removed).

536. Exposure data for fuel fabrication are given in table A-20. The average annual number of monitored workers has been reasonably constant over the six 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 has been approximately 10,000, about half the number of monitored workers. The estimated average annual collective dose showed a decline, from 36 to 21 man Sv, between the first two five-year periods, showed little change over the next two periods, with the value for 1990–1994 being approximately 22 man Sv, and then increased to about 30 man Sv for the last two periods. The average annual effective dose to monitored workers showed an initial decline, from 1.8 to 1.0 mSv, between the first two periods, and the value for 1990–1994, 1.0 mSv, is very similar to that for 1980–1984. For the last two periods the average effective dose increased by about 60%. The trends in occupational exposure are presented in table 65 and figure XLI.

537. The increase in the average effective dose may have two possible reasons: the inclusion of new countries that contributed higher levels of exposure in these last two periods, and the fact that some countries began to include the dose due to internal exposure in their dose records. There are two main sources of exposure in the fabrication of nuclear fuels: external exposure to gamma radiation and internal exposure resulting from the inhalation of airborne material. China has provided information that the doses below 1 mSv are entirely due to external exposure. However, for the doses above 1 mSv, there is an important contribution from internal exposure (between 30% and 80%). According to an NRC report on fuel fabrication facilities, internal exposure contributes most of the total effective dose, up to about 99% of the total dose [U29, U30, U31, U32, U33, U34, U36, U37]. However, the internal dose component depends on the type of nuclear fuel. The occupational exposure in the production of nuclear fuel is expected to be lower for fuel that involves only natural uranium than for fuels that involve enriched uranium or plutonium. In conclusion, the type of dose that is recorded in the national databases can be a source of discrepancy among countries. Some countries record only the doses from external exposure and others record the doses due to both internal and external exposure. Some countries also include in their individual monitoring programme workers who do not work in controlled areas. The variation in types of nuclear fuel also influences the comparison of doses between countries.

(d) Reactor operation

538. 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); pressurized 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) at present make only a minor contribution to energy production. Between 1990 and 1994, the number of operating reactors remained relatively stable, increasing slightly from 413 to 432 by the end of the period. A listing of nuclear reactors in operation during the period 1990–1997, the installed capacities and the electrical energy generated is given in annex C of the UNSCEAR 2000 Report [U3], “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 GW(e) (net gigawatts of electrical power) [I8]. For the period 1998–2002, the number of nuclear reactors in operation, the installed capacities and the electrical energy generated are given in section II.C.1 of this annex. The average number of power reactors operating in the world over the period 1998–2002 was 444, with an average capacity of about 278 GW(e).

539. In addition to data provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures, data on exposures of workers at nuclear power reactors are also available from the ISOE database [O14, O19, O20]. The ISOE occupational exposure database includes information on occupational exposure levels and trends for 401 operating reactors in 29 countries, covering about 91% of the world's operating commercial reactors [O22]. The ISOE data on occupational exposures at nuclear power reactors for 1990–2002 [O19, O20] and data from the UNSCEAR Global Survey of Occupational Radiation Exposures combined with information provided in the UNSCEAR 2000 Report [U3] for the various types of reactor are given in table A-21.

540. 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 and GCRs (which include older Magnox reactors), as well as a newer generation of reactors, AGRs, HWRs and LWGRs. Within each category, there is much diversity in design and in refuelling schedule, which may contribute to differences in occupational exposure. 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 discussed in this section.

541. The type of reactor is only one of the factors influencing the doses received by workers. 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. 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 incur some additional external exposure due to ^{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 due to tritium, which is a pure beta emitter.

542. Throughout the world, occupational exposures at commercial nuclear power plants have been steadily decreasing over the past decade, and this trend is reflected in the data for 1995–2002. Regulatory pressure (particularly after the issue of ICRP Publication 60 [I47] in 1991), technological advances, improved plant designs, installation of plant upgrades, improved water chemistry, improved plant operational procedures and training, the involvement of staff in the control of their own doses, and international sharing of ALARA data and experience have all contributed to this decreasing trend. Globally, ISOE includes the world's largest database on occupational exposures at nuclear power plants and provides an international forum for radiation protection experts from both utilities and national regulatory authorities to discuss, promote and coordinate international cooperative undertakings in the area of worker protection at nuclear power plants [O5, O6, O7, O8, O9, O10, O11, O12, O13, O14, O15, O18, O19, O20].

543. Data on occupational exposures for reactors of each type are detailed by country in table A-21, and a worldwide summary by reactor type is given in table 66. Worldwide levels of exposure have been estimated from the data provided; the extrapolations are based on the total energy generated in countries providing data. Very little extrapolation was needed, as the data provided were substantially complete (about 96% for PWRs, 99% for BWRs, 63% for HWRs, 100% for GCRs and 13% for LWGRs). Data provided through ISOE for 1995–2002 are included as provided by ISOE participants. With a few exceptions, the ISO programme includes essentially all reactors worldwide. The annual data reported in response to the UNSCEAR Global Survey of Occupational Radiation Exposures have been averaged over five-year periods, which provide the average effective dose and the number of monitored workers. The ISOE data provided from 1995 to 2002 are given as averages over the periods 1995–1999 (five years) and 2000–2002 (three years), and provide estimates for the collective effective dose. Figures XLII and XLIII illustrate some of the trends. Previous UNSCEAR reports treated FBRs and high-temperature graphite reactors (HTGRs) separately. No data were provided on these in either the ISOE database or the responses to the UNSCEAR Global Survey of Occupational Radiation Exposures, and in the main these types of facility are no longer operational. The UNSCEAR 1993 and 1988 Reports [U6, U7] concluded that they make a negligible contribution to occupational exposure, and therefore they are not considered further.

544. The UNSCEAR 1993 Report [U6] identified the need for more data on measurably exposed workers, as these provide a better basis for the comparison of average doses to individuals than is possible using the monitored worker data. The UNSCEAR Global Survey of Occupational Radiation Exposures now provides good data on measurably exposed workers for PWRs, BWRs and HWRs (see table A-21). 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) [H8].

545. The procedures for the recording and inclusion of doses incurred by transient or contract workers may differ from utility to utility and country to country, and this may influence the statistics in different ways. In some cases, transient workers may appear in the statistics for a given reactor

several times in one year (whereas they should rather appear only once, with the summed dose being recorded). If appropriate corrections are not made, the statistics so compiled will inevitably overestimate the size of the exposed workforce and will underestimate the average individual dose, as well as the fraction of the workforce receiving doses above the prescribed levels and the fraction of the collective dose arising from these doses. This will only be important where extensive use is made of transient workers and where no centralized reporting database is used.

546. Countries also differ in how they present information on 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. Other countries provide data for utility employees only, whereas still others present the collective dose for the total workforce but individual doses for the utility employees only. Where necessary and practicable, the data provided have been adjusted to allow them to be fairly compared with other data; these adjustments are indicated in the respective tables.

(i) Light-water reactors

547. PWRs constitute the majority of the installed nuclear generating capacity for the period 1998–2002, followed by BWRs. Averaged over the whole period, about 91% of the total energy was generated in LWRs (of this, about 67% was from PWRs and 24% from BWRs), with contributions of about 4.5% for HWRs, 1% for GCRs and 3.5% for LWGRs. FBRs contribute only about 0.1% of the total energy generated. Experience has shown that there are significant differences between occupational exposures at PWRs and those at BWRs. Each type of reactor is therefore considered separately.

548. *PWRs.* External gamma radiation is the main source of occupational exposure at PWRs. Since in general only a small contribution comes from internal exposure, the latter 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 resulting 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 that is associated with significant dose is the replacement of steam generators. Data on the collective doses associated with maintenance have been collected by the OECD/NEA [O9] and are given in table 67.

549. The average number of PWRs worldwide increased from 78 in 1975–1979 to 266 in 2000–2002. The corresponding increase in average annual energy generated has been somewhat greater, from 27 to 191 GW a. The number of monitored workers at PWRs increased from about 63,000 in 1975–1979 to 283,000 in 2000–2002 (see figure XLII and table 66). Between the first two periods, the average annual 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, followed by a reduction to 415 man Sv in the fourth period. The dose increased again to 506 man Sv and finally decreased to 415 man Sv. Although the number of reactors increased by a factor of around 2 between 1980 and the last period, the collective dose has remained between 400 and 500 man Sv. To see the underlying trend in the efficiency of radiological protection measures in both design and operational procedures, it is more instructive to look at the normalized annual collective dose. Per reactor this increased from 2.8 to 3.3 man Sv over the first two periods but has since dropped to about 2.0 in the last four periods (2.3, 1.7, 2.0 and 1.6 man Sv). The corresponding values for collective effective dose divided by the energy generated are (in chronological order to 2002) 8.1, 8.0, 4.3, and 2.8, 3.0 and 2.2 man Sv/(GW a).

550. The average annual effective dose to monitored workers fell consistently over the first four periods, being 3.5, 3.1, 2.2 and 1.3 mSv, and then increased to 1.9 and 1.7 mSv in the last two periods, an overall reduction of about one half. Overall, the average annual effective dose to measurably exposed workers was about 2.7 mSv for 2000–2002. The dose distribution data also parallel the downward trend in doses, with both NR_{15} and SR_{15} consistently dropping to <0.01 and 0.06, respectively, for the period 2000–2002.

551. There is considerable variation in the worldwide average values with respect to both the trends and the 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 annual reports [O5, O6, O7, O8, O9, O10, O11, O12, O13, O15, O18, O20].

552. *BWRs.* External radiation 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 numbers of BWRs are located in the United States and Japan.

553. Worldwide, the average number of BWRs increased from about 50 in 1975–1979 to about 90 in 2000–2002; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 15 to 67 GW a. Overall, 40% of this energy was generated by BWRs in the United States, 25% in Japan, 16% in Germany and Sweden, and the remaining 19% in other countries. On the basis of the UNSCEAR Global Survey of Occupational

Radiation Exposures, the number of monitored workers at BWRs worldwide increased from about 59,000 to about 160,000 at the end of period four, and then decreased to 144,000 and 113,000 in the last two periods (see figure XLII and table 66). 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. For the last two periods the values were 237 and 160 man Sv. 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 to 2.7 man Sv in the next two periods, remained constant at about 2.6 man Sv in 1995–1999, then finally decreased to 1.8 man Sv per reactor. The corresponding values normalized to the energy generated were 18, 18, 7.9, 4.8, 3.8 and 2.4 man Sv/(GW a). Both sets of values indicate significant reductions over the six periods.

554. The average annual effective dose to monitored workers over the six periods has consistently fallen: 4.7, 4.5, 2.4, 1.6, 1.7 and 1.4 mSv. There has been a reduction by a factor of about 3 overall. The worldwide average annual effective dose to measurably exposed workers, 2.1 mSv, is about 50% 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 delivered at individual dose levels of above 15 mSv having been 0.09 in 2000–2002.

555. There is considerable variation in the worldwide average values with respect to both the trends and the levels of dose in individual countries. However, the differences seem to be decreasing over time, and for the vast majority of countries reporting, a downward trend is apparent.

(ii) Heavy-water reactors

556. The worldwide average number of HWRs increased from 12 in 1975–1979 to 39 in 2000–2002. The corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 3 to 13 GW a. The number of monitored workers in HWRs worldwide increased from about 7,000 to about 20,000 over the first four periods, and remained about the same over the last two periods, as shown in figure XLII and table 66. The average annual collective effective dose increased from about 32 man Sv in the first five-year period to about 46 and 60 man Sv in the second and third periods. In the fourth and fifth periods, however, it decreased significantly, to 35 and 29 man Sv, before increasing again to 38 man Sv in the period 2000–2002. The normalized average annual collective effective dose per reactor decreased slightly, from 2.6 to 2.3 man Sv, over the first three periods, and then dropped to 1.1 man Sv and remained constant. The corresponding values normalized by the energy generated fell by a factor of almost 4, from 11 to 2.9 man Sv/(GW a), over the six periods. Both sets of values indicate significant reductions over the six periods.

557. The average annual effective dose to monitored workers fell from 4.8 to 3.2 mSv over the first two periods but remained about the same for the third period. For the fourth period it fell significantly to 1.7 mSv, and became steady again in the last two periods at 1.6 mSv. As before, the reduction overall was by a factor of about 2. The doses due to the intake of tritium (as tritiated water) may have provided an important contribution, around 20%, to the total effective dose [H15].

(iii) Gas-cooled reactors

558. There are two main types of GCR: Magnox reactors, including those with steel pressure vessels and those with prestressed concrete pressure vessels; and AGRs. Another type, HTGRs, reported previously [U7], 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, in terms of both installed capacity and energy generated, became more important. The relative importance of AGRs will increase as Magnox reactors are decommissioned.

559. The UNSCEAR 1993 Report [U6] investigated the differences in occupational exposures between Magnox reactors and AGRs. These arise mainly from the use of concrete (as opposed to steel) pressure vessels in the AGRs (and the later generation of Magnox reactors) and from the increased shielding they provide against external irradiation, the dominant source of occupational exposure. The UNSCEAR 1993 Report identified significant differences between the various types, with the average annual effective dose in first-generation Magnox reactors steel pressure vessels remaining uniform at about 8 mSv, whereas the values for Magnox reactors with concrete pressure vessels and for AGRs were less than 0.2 mSv. During the 1990–1994 period, significant dose reductions were made at the Magnox reactors, with further reductions during the last two periods. More detailed information can be found in the reviews of radiation exposures in the United Kingdom [H26, H27]. In this annex no distinction has been made in table 66 between the various types of GCR.

560. The worldwide number of GCRs averaged over five-year periods has decreased significantly from 40 in 1975–1979 to 23 in the last period (2000–2002). Some reactors have been shut down. The number of monitored workers as provided by the UNSCEAR Global Survey of Occupational Radiation Exposures increased overall, from 13,000 in the first period to 30,000 in the fourth, and then decreased to 21,000 and 18,000 in the last two periods, as shown in figure XLII and table 66. The average annual collective effective dose dropped over the six periods, being 36, 34, 24, 16, 7 and 4 man Sv. The normalized collective dose per reactor also decreased over this period, from 0.9 to 0.2 man Sv. The corresponding values for energy generation decreased in the

first five periods from 6.6 to 0.7 man Sv/(GW a) and then increased to 2.6 man Sv/(GW a). The worldwide average annual effective dose to monitored workers, averaged over five-year periods, fell progressively from 2.8 mSv in the first period to 0.2 mSv in 2000–2002. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv has been small, falling from 0.02 by a factor of over 100. Between 1992 and 1994 there was only one instance of a worker at a United Kingdom GCR incurring a dose of over 15 mSv in a year, and only ten workers received doses of over 10 mSv in a year [H27].

(iv) Light-water-cooled, graphite-moderated reactors

561. LWGRs were developed in the former Soviet Union and have only been installed in what are now the Russian Federation, Ukraine and Lithuania. Only data equivalent to 13% of the total energy generated by LWGRs were provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures, ISOE [O19] and other sources [R22].

562. There is no information available to estimate the worldwide level of exposure. The overall number of LWGRs increased from 12 in the first period to 20 during 1990–1994. The corresponding average annual energy generation increased from 4.4 to 9 GW a. The number of monitored workers increased over the first three periods from about 5,000 to 13,000, but no data are available for the last three periods. The average annual collective effective dose increased significantly, being 36, 62, 173 and 190 man Sv for the four periods from 1978 to 1994. The value for the occupational exposure given here corresponds to the period from 1978 to 1994. There are insufficient data for reliable extrapolation to subsequent periods.

563. It was suggested in the UNSCEAR 1993 Report [U6] 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 occupational exposure.

(v) Summary

564. Data on occupational exposure at reactors worldwide are summarized in table 66. The worldwide number of power reactors averaged over the six periods increased from about 190 in the first period to 444 in 2000–2002. The corresponding increase in average annual energy generation was from 55 to 278 GW a. Averaged over the whole period, about 91% of the total energy was generated in LWRs (of this, about 67% was from PWRs and 24% from BWRs), with contributions of about 4.5% for HWRs, 1% for GCRs and 3.5% for LWGRs. The number of monitored workers increased from about 150,000 to 530,000 in the fourth period and decreased to about 440,000 in the last period. The period 1990–1994 is the first for which a reasonably robust estimate of the number of measurably exposed workers, some 290,000, is available; this value dropped to 170,000 for the period 1995–2002.

565. The annual collective effective dose averaged for each of the six periods increased over the first three periods (600, 1,000 and 1,100 man Sv) but fell back to 900, 800 and 600 man Sv in the last three periods. The trends in annual values are shown in table 66 and figure XLIII. About 93% of the collective dose was received by workers at LWRs. Averaged over all the periods, the contribution from workers at HWRs was 6%, at GCRs 1% and at LWGRs about 13%. LWGRs were not considered in this evaluation.

566. The normalized collective effective dose per reactor averaged over all reactors rose over the first two periods, from 3.1 to 3.7 man Sv, but dropped to 2.8, 2.1, 1.5 and 1.1 man Sv over the remaining periods. The corresponding figures per unit energy generated are 10.9, 10.4, 5.7, 3.9, 2.5 and 2.5 man Sv/(GW a) for the six periods. 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 first four periods.

567. The annual effective dose to monitored workers averaged over all reactors fell steadily, from 4.1 to 1.0 mSv. This number may be an underestimate, since the data for LWGRs are not included in the dose estimate of the last periods. 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.

568. 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 A-21. 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 0.02 in 2000–2002. The corresponding fraction of the collective dose arising from doses in excess of 15 mSv decreased from 0.60 to 0.13.

569. Information on doses according to job category has been provided through the ISOE programme (table 67). To account for some inhomogeneity in the statistical recording systems, these data have been aggregated into five broad categories: refuelling, maintenance, inspection, servicing and a fifth category covering all other tasks. The data available at the job level in the ISOE database cover European reactors, as well as those in China, South Africa and Brazil.

570. In general, the annual doses associated with most jobs, regardless of reactor type, decreased from the 1995–1999 period (five years) to the 2000–2002 period (three years).

For PWRs, the standardized annual dose due to refuelling showed a 20% decrease. Decreases in doses due to maintenance jobs and servicing jobs of 30% and 10%, respectively, were also observed. A 38% increase in the annual dose due to inspection for all countries over the period 2000–2002 resulted partially from an increase in the number and frequency of controls in France and Germany. For BWRs, doses associated with annual maintenance, inspection and servicing decreased by about 30%, while the annual dose due to refuelling (which is more standardized) remained stable or even showed a small increase.

571. The evolution of doses due to maintenance and servicing for both PWRs and BWRs is the consequence of many factors, including reductions in the duration of refuelling outages and in the number of tasks performed, the implementation of ALARA programmes and better job preparation.

(e) Decommissioning

572. Some nuclear power plants are already in a phase of decommissioning. The workers involved in this process may receive internal and external exposures. When nuclear reactor facilities are dismantled as part of decommissioning a nuclear power station, radioactive dust is generated. This radioactive dust is likely to diffuse in the working environment, resulting in internal exposure. However, most of the dose comes from external exposure. There are few published data available on doses due to decommissioning. Data from 13 nuclear power plants in the United States show that about 2,000 workers were involved in this process in the period 1995–2002. The average annual effective dose for the measurably exposed workers was around 2 mSv and the average annual collective dose was around 4 man Sv. These data are presented in table 68. The available data are not sufficient for evaluating the worldwide level of exposure.

(f) Fuel reprocessing

573. The principal reason for reprocessing has been to recover unused uranium and plutonium in the spent fuel elements. A secondary reason is to reduce the volume of material to be disposed of as high-level waste. In addition, the level of radioactivity in such "light" waste after about 100 years falls much more rapidly than in spent fuel itself. The practice is conducted in only a few countries: France and the United Kingdom have with commercial-scale facilities, Japan and India have experimental facilities, and the Russian Federation has been reprocessing fuel for reactors developed in that country [U3]. In the last decade, interest has grown in separating ("partitioning") individual radionuclides both to reduce long-lived radionuclides in residual waste and to be able to transmute separated long-lived radionuclides into shorter-lived ones. Reprocessing to recover uranium and plutonium avoids wasting a valuable resource, because most of the spent fuel (uranium at less than 1% ^{235}U and a little plutonium) can be recycled as fresh fuel, saving some 30% of the natural uranium that would otherwise be required. It also avoids leaving the plutonium in the spent fuel, where in a century or two the radiological hazard from other components will have diminished significantly, possibly allowing the plutonium to be recovered for use in weapons.

574. Spent fuel assemblies removed from a reactor are highly radioactive and produce heat. They are therefore put into large tanks or "ponds" of water, which cools them and, with three metres of water over the assemblies, shields the radiation they emit. They remain for a number of years either at the reactor site or at the reprocessing plant, and the level of radioactivity decreases considerably with time. For most types of fuel, reprocessing occurs at any time from 5 to 25 years after the fuel is unloaded from the reactor.

575. The exposure data for 1995–1999 and 2000–2002 are given in table A-22. In the earlier period, the contribution of 33.9 man Sv from the Russian Federation accounted for over 50% of the worldwide average annual collective effective dose.

576. The estimate for the worldwide level of exposure was based on the trends in the data from the reporting countries. The number of monitored workers has increased over the six periods, from 8,000 in the first period to 76,000 in the last. The collective effective dose dropped from 53 man Sv in 1975–1979 to 36 man Sv in 1985–1989, increased to 67 man Sv in the following period, and remained steady in the last two periods. The effective dose has decreased progressively, from 7.1 mSv in the first period to 0.9 mSv in the last period. The trends are presented in table 69 and figure XLIV. The increase in collective dose is associated with increased numbers of workers.

(g) Research related to the nuclear fuel cycle

577. It is difficult to estimate the levels of occupational exposure that can unequivocally be attributed to research and development related to the commercial nuclear fuel cycle. Few data are available separately for this category; even when they are, uncertainties remain as to their proper interpretation.

578. Occupational exposures arising in nuclear research are presented in table A-23. 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 estimate for the worldwide level of exposure was based on the trends in the data from the reporting countries. In the last three periods, the number of monitored workers decreased by about 25%, from 120,000 in 1990–1994 to about 90,000 in 2000–2002. The annual collective effective dose dropped by a factor of 4 over the six periods, from 170 man Sv in 1975–1979 to 36 man Sv in 2000–2002. This fall is a consequence of the reduction in the

effective dose, which fell from 1.4 to 0.4 mSv from the first period to the last. The trends are presented in table 70 and figure XLV.

(h) Waste

579. Radioactive waste arises at all stages of the nuclear fuel cycle in the process of producing electricity from nuclear material. The cycle comprises the mining and milling of the uranium ore, its processing and fabrication into nuclear fuel, its use in the reactor, the treatment of the spent fuel taken from the reactor after use and finally the disposal of the waste. Radioactive waste is classified as low-level, intermediate-level and high-level waste: *(a)* low-level waste is generated by hospitals, laboratories and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, clothing, filters, etc., which contain small amounts of mostly short-lived radioactive material. In order to reduce its volume, it is often compacted or incinerated (in a closed container) before disposal. Worldwide it makes up 90% of the volume but only 1% of the radioactivity of all radioactive waste; *(b)* intermediate-level waste contains higher amounts of radioactive material and may require special shielding. It typically includes resins, chemical sludges and reactor components, as well as contaminated materials from reactor decommissioning. Worldwide it makes up 7% of the volume and 4% of the radioactivity of all radioactive waste; *(c)* high-level waste may be the spent fuel itself or the principal waste from its reprocessing. While making up only 3% of the volume of all radioactive waste, it contains 95% of the radioactive material. It includes the highly radioactive fission products and some heavy elements with long-lived radioactivity. It generates a considerable amount of heat and requires cooling, as well as special shielding during handling and transport. If the spent fuel is reprocessed, the separated waste is vitrified by incorporating it into borosilicate (Pyrex) glass which is sealed inside stainless steel canisters for eventual disposal deep underground. On the other hand, if spent reactor fuel is not reprocessed, all the highly radioactive isotopes remain in it, and so the whole fuel assemblies are treated as high-level waste. This spent fuel takes up about nine times the volume of the vitrified high-level waste that would result from reprocessing and encapsulating an equivalent amount of spent fuel, which is then ready for disposal.

580. The doses of the personnel managing radioactive waste depend on the scope of the activities performed. The average annual effective dose for the workers involved in the safe management of spent fuel is in the range 0.2–11 mSv. The level of exposure is lower for the workers involved in waste management (disposal facilities), where the average annual effective dose is in the range 0.2–3 mSv [I38, T4]. Some of these data are presented in table 71.

(i) Summary

581. The trends in worldwide occupational exposures arising from each stage of the commercial nuclear fuel cycle are summarized in table 72 and are illustrated in figures XLVI and XLVII. The data are annual averages over five-year periods, except for the last period, which covers only three years. During the first three periods, the number of monitored workers in the commercial nuclear fuel cycle rose, from about 560,000 to 880,000, but in 1990–1994 it started to fall. The figures for the last three periods are 800,000, 700,000 and 660,000 (figure XLVII). This decrease was largely due to the drastic reduction in the estimated number in the mining sector, from 260,000 to 12,000. For the three last periods, this may be an underestimate, owing to the limitations of the data set, but all other indicators support a significant reduction in this component of exposure of the monitored workforce. In the first five-year period, mining accounted for over 40% of the workforce, but over the subsequent periods, reactor operation became the dominant sector with respect to the number of monitored workers, and at 440,000 it now accounts for about 70% of the total.

582. The average collective effective dose, averaged over five-year periods, initially increased from 2,300 to 3,000 man Sv but in the last four periods decreased to 2,500, 1,400, 1,000 and 800 man Sv (figure XLVII).

583. The average annual effective dose received by monitored workers in the fuel cycle has fallen progressively over the course of the six periods: the values are 4.4, 3.7, 2.6, 1.8, 1.4 and 1.0 mSv. There is considerable variation in these averages for the different stages of the fuel cycle, but overall the downward trend is evident in all nuclear fuel cycle stages. The fraction of monitored workers receiving annual doses in excess of 15 mSv (NR_{15}) averaged over five-year periods has decreased from about 0.20 to about 0.02; the corresponding decrease in the fraction of the collective effective dose (SR_{15}) has been from about 0.63 to about 0.06.

2. Medical uses of radiation

584. Radiation is used in medicine for both diagnostic and therapeutic purposes. Irrespective of the level of health care system, medical uses of radiation increase yearly as the benefits of procedures become more widely disseminated. The medical use of ionizing radiation remains a rapidly changing field, stimulated in part by the high level of innovation by equipment supply companies. The wide range of applications and of procedures and techniques employed in the context of patient exposure are described in annex A, “Medical radiation exposures”, which also discusses changes in practice and current trends. Consideration here is limited to the occupational exposures that arise from the application of these medical procedures. The physicians, technicians, nurses and others involved constitute the largest single group of workers occupationally exposed to man-made sources of radiation. Occupational doses received by staff can be differentiated according to the source of exposure, thereby characterizing different occupational groups. There is a need to have an evaluation of these occupational doses according to the main procedures that cause them.

585. There exists a group of individuals who support or comfort patients undergoing radiation treatment or diagnostic procedures. Individuals in this group are generally considered as members of the public, though they can also be workers. The doses for this group of "comforters" are not considered in this annex.

586. The Committee has evaluated occupational exposure for each practice using average values for all workers over five-year periods, without having taken into account the influences of job function and medical procedure on staff exposure. One of the purposes of this annex is to provide significant information on occupational exposure related to the different practices. This will be done by: identifying the job functions and categories of work within each practice that give rise to the more significant exposures; evaluating the contribution of external and internal exposure to the total effective dose; and indicating extremity doses (equivalent doses in hands and lens of the eye).

587. Data from the UNSCEAR Global Survey of Occupational Radiation Exposures for workers involved in all medical uses of radiation are presented in table A-24. The estimation of the worldwide level of occupational exposure was based on the trends from the data reported by countries.

588. The doses used in this annex are those provided by the countries. For this analysis it was assumed that the dose had been estimated taking into account the design of any lead apron used, its thickness and the position of the dosimeter, in particular whether the dosimeter was worn outside the apron or under it, or whether one dosimeter was worn under the apron and a second worn outside it [N11].

(a) Diagnostic radiology

589. Diagnostic examinations with X-rays have been used in medicine for over a century, although with increasing sophistication and new techniques. Medical imaging has experienced a technological revolution resulting in the improved imaging of anatomy, physiology and metabolism [H21]. 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, even though alternative modalities for some diagnoses (such as ultrasound and endoscopy) are becoming increasingly available, particularly in developed countries. An increasingly wide range of equipment and techniques are employed to meet a diversity of diagnostic clinical purposes. Variations in occupational doses among six identified subgroups in diagnostic radiology (computed tomography technologists, general radiographers, fluoroscopy technologists, radiologists, nurses and radiologic technology interns) were evaluated. More than 80% of computed tomography (CT) technologists and general radiographers do not have measurable exposure [A8]. On the other hand, the average individual effective dose for interventional procedures is significantly higher than for conventional diagnostic radiology. Medical doctors performing interventional procedures are the most exposed occupational group in diagnostic radiation [K1]. On the basis of such findings, it is no longer appropriate, for example, to treat doses from diagnostic radiology and from interventional procedures together, as the dose average disguises significant differences between them.

(i) Conventional diagnostic radiology

590. Conventional X-ray examinations involve static imaging; the various techniques applied (radiography, CT, mammography and bone mineral densitometry) are described in annex A, "Medical radiation exposures". For radiography, which is the most widely used X-ray application, the average doses depend on the equipment used. For CT, occupational doses are very low and the technique does not represent a significant source of occupational exposure. For mammography, the doses are generally similar to those in CT. In general, the techniques used in conventional radiography do not represent a significant source of occupational exposure.

591. During radiography with fixed installations, the radiographer would normally stand in a control booth that typically is shielded as a secondary barrier against X-ray tube leakage and scattered radiation from the room and the 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. Mobile units, however, operate in an unshielded environment and are therefore of greater concern [N10].

592. Occupational exposure arising from the use of CT 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, CT does not represent a significant source of exposure.

(ii) Interventional procedures

593. The past four decades have witnessed immense technological advances in radiology. The introduction of image intensification led to the development of interventional radiology. Dotter and Judkins described the first percutaneous treatment of arteriosclerotic vascular obliterations in 1964 [D13], and the range of interventional procedures has dramatically increased since then. This has been accompanied by considerable equipment development. Because of the great advantages of interventional radiology, it is not surprising that both the number and the variety of interventional procedures have grown significantly over the years. Fluoroscopic guidance is frequently utilized in performing many interventional techniques, including precision diagnostic and therapeutic injection procedures. In 29 European countries, the number of coronary angiographies (CA) and PTCA (percutaneous transluminal coronary angioplasty) procedures increased by 264% and 416%, respectively, between

1992 and 2001 [T5, V20]. It is estimated that approximately 1–4 million interventional procedures are performed annually in the United States, with at least 50% performed under fluoroscopy [M5].

594. The development of CT equipment has made possible a variety of clinical applications. One example is CT fluoroscopy, which allows the observation of real-time CT images [K4]. In addition, biopsy examinations performed by CT fluoroscopy offer better accuracy and easier manipulation than conventional examinations. Although the beam for CT is narrow, the tube voltage and current are relatively high. Exposures are unavoidable for medical staff who carry out the examinations. Various surface doses for operating and assisting physicians are shown in table 73. Since examination times differed greatly from case to case, the doses were averaged per minute of fluoroscopy for each set of fluoroscopy conditions [N15].

595. These procedures require the surgeon and assisting personnel to remain close to the patient and thus close to the primary beam of radiation. The advent of complex and prolonged coronary interventional procedures has further increased levels of radiation exposure, although proper procedures and experience can decrease exposures per case. The use of digital imaging, although potentially capable of reducing radiation dose, requires additional constraints on input dosing, fluoroscopy and personnel exposure. Data on the occupational exposure of paediatric cardiologists are sparse, but suggest that technical limitations in working with the smaller patient may adversely affect radiation exposure to physicians and the medical personnel who assist them [K3, L10].

596. Occupational exposures of primary medical doctors involved in interventional procedures vary considerably according to the procedure used. Doses were assessed for different parts of the body according to the type of procedure; results are shown in table 74. The doses resulting from the coronariography procedure are about three times higher than those for angioplasty, arteriography and valvuloplasty. The average time of fluoroscopy can be lower that for the other procedures, but the number of frames is higher [S21].

597. A total of 1,000 consecutive patients with chronic pain undergoing interventional procedures performed by one physician were studied. Two fluoroscopy units were utilized and operated by two certified radiological technologists. The procedures performed included caudal and interlaminar epidural injections, facet joint nerve blocks, percutaneous adhesiolysis, intercostal nerve blocks, sympathetic blocks, transforaminal epidural injections and other procedures. The results showed that these 1,000 patients had undergone 1,729 procedures with an average duration of radiation exposure of 13.2 ± 0.33 seconds per patient and 7.7 ± 0.21 seconds per procedure. Dosimetry measurements indicated an effective dose of 13 mSv (1,345 mrem) outside the lead apron; the measurement inside the apron was below the detection limit. The levels of exposure were significantly below the annual limits recommended [M6].

598. The radiation exposures to three vascular surgeons performing 47 consecutive endovascular aortoiliac aneurysm (EAIA) procedures were determined over a one-year period. The total fluoroscopy time was 30.9 hours (mean of 39.4 minutes per case). The time spent using high-level fluoroscopy varied between 5% and 37%, although in one case it was 60%. The current ranged from 2.1 to 4.7 mA and the tube potential from 65 to 105 kV. Annual effective doses for the primary surgeon, first assistant and second assistant, respectively, were: 1.5, 1.6 and 0.9 mSv under the lead apron, and 13.8, 12.6 and 5.2 mSv outside it. The estimated equivalent doses to the eyes were 7.8, 5.7 and 2.0 mSv for the primary surgeon, first assistant and second assistant, respectively. The estimated equivalent doses to the hands were 18.7, 16.0 and 5.4 mSv for the primary surgeon, first assistant and second assistant, respectively [L16].

599. Occupational doses in interventional cardiology and radiology services at a university hospital are shown in table 75 for the period 1999–2001. According to the data presented in this table, the doses are about the same for all staff if protective measures are undertaken [V9].

600. An evaluation of the occupational exposure to personnel performing cardiac catheterization (dose per procedure) has shown that the range of effective doses for diagnostic catheterizations was 0.02–38 µSv, for percutaneous coronary interventions 0.17–31.2 µSv, for ablations 0.24–9.6 µSv and for pacemaker or intracardic defibrillator implantations 0.29–17.4 µSv. The authors have estimated a reduction in dose of a factor of 4 from 1971 to 2006 for the staff involved in diagnostic catheterizations. For percutaneous coronary interventions, an increasing pattern was observed over time, but this was not statistically significant. The higher radiation exposure for percutaneous coronary interventions was primarily due to the long fluoroscopy times. The contribution of fluoroscopy to the total dose was about 30% for diagnostic catheterizations and 60% for percutaneous coronary interventions [K13].

601. An evaluation of the typical occupational dose levels in interventional radiology and cardiology installations covered a sample of 83 procedures performed by ten specialists in six laboratories [V7]. The monitored staff wore nine thermoluminescent chips sited next to the eyes and on the forehead, neck, hands, left shoulder, left forearm and left arm during each individual procedure. Doses for interventional radiologists and cardiologists are presented in tables 76 and 77, respectively. Radiologists were occasionally out of the room controlling the image acquisition from the system console, and had the lowest dose values. For cardiologists, doses were divided into values measured with and without the use of a protective lead screen. The lowest values correspond to staff who made regular use of the protective screen. The mean dose values for interventional radiologists and interventional cardiologists are presented in figure XLVIII. A more homogeneous distribution was observed for vascular radiologists than for interventional cardiologists. This is because of the variable positions usually adopted by a radiologist with

respect to the patient, while for interventional cardiology procedures, doses are mainly received on the left side, which is closest to the scatter volume throughout the procedure [V7]. The main difference between radiology and cardiology is that, for the former, the X-ray tube is less likely to be rotated and moved during the procedure, and the position of the operator is more variable, depending on the procedure [R5]. There is exposure to scattered radiation not only in the upper part of the operator's body, but to the lower part as well, even though this exposure is at low levels [B33, M5, S21].

602. Different investigators have observed substantial differences in doses received for the same type of procedure. These differences may be as large as an order of magnitude. Many factors influence occupational radiation exposures during fluoroscopy use. No single standardized method has evolved to permit easy comparison of dosimetry results among studies [K13, P1, T11, T12]. The doses vary considerably according to the procedure, operator training and quality assurance. As shown in table 78, occupational doses related to interventional procedures are strongly dependent on several parameters, including: dose rate gradients in the vicinity of the patient; the technique selected (kV, mA or mA s per pulse); the different filtrations available in modern equipment; field size; TV monitor; intensifier size; operational modes (continuous or pulsed fluoroscopy); the number of frames; dose rates; locations inside the room; the typical interventions performed; patient weight and size; design and maintenance of the facility; and the existence and use of protective tools, especially spectacles and ceiling-suspended screens [C1, K3, M10, P12, S37, V8, W15, Z6].

603. National data on occupational exposures arising from X-ray diagnostic radiology over the six periods are presented in the first part of table A-24. Most of the countries have not distinguished between data from conventional and interventional procedures. There is a wide variation in the effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the variety of procedures performed by the medical staff and the protective measures implemented by each country. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. However, the number of workers is derived from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. The data are presented in table 79 and figure XLIX. They indicate that overall there has been an increase in the number of monitored workers employed in this practice, from 630,000 in 1975–1979 to 6.7 million in 2000–2002, although the number dropped considerably between the third and fourth periods, from 1,350,000 in 1985–1989 to 950,000 in 1990–1994. For the last two periods the estimated value is a factor of 7 higher than for the previous period. The number of workers involved in interventional procedures represents about 0.1% of the total workforce employed in diagnostic radiology. The latest value is more reliable than the previous ones. The collective effective dose increased from 600 to 760 man Sv over the first three periods, dropped by about 40% in the fourth period (1990–1994) and then increased by a factor of 7 to 3,370 man Sv in 2000–2002, following the same pattern as the number of workers. The average effective dose decreased from 0.94 mSv in 1975–1979 to 0.50 mSv in 1990–1994, and has since remained constant.

604. Only a few countries have provided data that distinguish between the workers engaged in conventional techniques and in interventional procedures; the data are presented in table A-25. On the basis of the reported data, about 85% of the monitored workers are involved in conventional radiology techniques. For conventional techniques, the average annual effective dose is about 0.5 mSv (range 0.02–1.24 mSv) for the monitored workers and 1.2 mSv (range 0.33–3.14 mSv) for the measurably exposed workers. For interventional procedures, the average annual effective dose is about 1.6 mSv for the monitored workers and 3.1 mSv for the measurably exposed workers, with a range of 0.4–29.5 mSv. Considerable variation exists in the effective dose and the percentage of measurably exposed workers. This variation may be explained by differences between countries. Greece has provided data for various job categories for interventional radiology: 1) medical doctors—cardiologists; 2) medical doctors—orthopaedists, surgeons, gastroenterologists; auxiliary staff of similar categories; 3) nurses; and 4) others (table A-25 and figure L). It can be seen that cardiologists are the group most exposed. Their average effective dose is 4 mSv, about a factor of 6 higher than the doses for other medical doctor specialists, nurses and other workers. These data are presented separately to indicate that, although these workers are small in number compared with those involved in the conventional diagnostic use of X-rays, their exposure levels are high. As the interventional techniques are being widely applied, the Committee expects that there will be an increasing trend in the number of workers exposed and consequently in the annual collective effective dose.

605. During interventional procedures, the hands of the medical doctors are in the field of radiation, resulting in high exposure to the hands and arms. According to the literature, the equivalent dose to the skin can considerably exceed 500 mSv. During cardiac and abdominal intravascular angiography, a surgeon may receive annual doses to the hands of 440 mSv and 360 mSv, respectively [J1, S35]. There is a large range in the doses reported in the literature. Only a few countries have reported data on extremity doses. The reported values are low, the highest value being around 10 mSv.

(b) Dental practice

606. Diagnostic X-ray machines are widely available and are used frequently in almost every dental office or clinic. The total number of X-ray devices used in dentistry is thus extremely large. Their range of energy is between 20 and 60 keV. Occupational exposure in dentistry is due to 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 coupled with a steady decrease in collective dose. A majority of dental practitioners do not receive measurable doses, and indeed some regulatory authorities do not require routine individual monitoring except where workload is high [U3].

607. National data on occupational exposures arising from dental practice over the period 1995–2002 are given in the second part of table A-24. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in table 80 and figure LI; they indicate a progressive decline in the number of monitored workers involved in this practice. The value first increased from 370,000 to 500,000 in 1980–1984, decreased to 265,000 in 1990–1994 and increased again to 404,000 in 2000–2002. The annual collective effective dose also fell, from 120 man Sv in 1975–1979 to 24 man Sv in 2000–2002. The average annual effective dose decreased from 0.32 mSv in 1975–1979 to 0.06 mSv in 1990–1994, and then remained steady. The percentage of measurably exposed workers has been about the same over the last three periods at around 5%. About 1% of the workforce received doses higher than 1 mSv; there were no recorded doses higher than 5 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be about 350,000, the collective effective dose would be about 14 man Sv and the average effective dose would be about 0.05 mSv.

(c) Nuclear medicine

608. A broad aim in nuclear medicine is 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 exposures while performing clinical nuclear medicine procedures depends on the precautions taken, including the use of syringe shields when administering injections. Personnel must be close to the patient when giving injections and while positioning the patient and the camera. Usually the imaging process makes the largest contribution to the exposure of staff [B8]. Internal exposures of personnel are usually much lower than external exposures and are controlled by monitoring work surfaces and airborne concentrations, although some medical centres also conduct routine bioassays [N10].

609. Radionuclides used for organ imaging emit penetrating gamma radiation and give rise to exposure of nuclear medicine staff. While some therapeutic procedures are carried out, nuclear medicine departments can generally be characterized by various diagnostic examinations involving intravenous administration of radiopharmaceuticals. Databases on occupational exposure in nuclear medicine rarely distinguish between diagnostic and therapeutic applications. In nuclear medicine, because of the possibility of internal exposure, higher values of annual effective dose are expected for personnel involved in the preparation and assay of radiopharmaceuticals than for medical doctors and nurses.

610. Radionuclides used for organ imaging, for example ^{99m}Tc, emit penetrating gamma radiation and cause 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 μSv/h 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 μSv/h at 1 m from the patient, who therefore will normally be segregated to reduce the exposure of other persons. Work involving the preparation and assay of radiopharmaceuticals is associated with the highest occupational exposures in this field and can give annual doses of up to about 5 mSv. Doses to hands and fingers can range up to the annual limit of 500 mSv. 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 [N10].

611. An evaluation of effective doses received by the staff involved in tasks with ^{131}I in nuclear medicine has shown that the average annual values range from 0.35 mSv to 3.27 mSv; the maximum dose was around 9 mSv. The evaluation was performed using measurements of ^{131}I in the thyroid [K18].

612. Positron emission tomography (PET) is considered one of the most important diagnostic imaging techniques, having the unique ability to provide functional and quantitative information on the target organ of interest. During recent years, great efforts have been made to improve the diagnostic accuracy of this imaging modality through the development of new acquisition/processing systems and the introduction of new β+-emitting radiopharmaceuticals, all of which has increased the interest of clinicians [Z5].

613. Occupational exposure can be higher by a factor of 2–4 for technologists than for physicians involved in PET procedures. External exposures over a period of one year to four workers (two physicians and two technologists) working full time at a PET centre are presented in table 81. The annual doses ranged from 4.6 to 8 mSv for technologists and were about 2 mSv for physicians. In this centre, an ECAT EXACT HR+ state-of-the-art scanner is used, and ^{18}F-labelled fluorodeoxyglucose (^{18}F FDG) whole-body imaging represents the principal clinical activity (about 96% of the patient workload) [Z5].

614. Table 82 shows the doses for various tasks and patient conditions and for different technologists. Each patient was administered 555 MBq of ^{18}F FDG. The doses varied from below the detection limit for the monitoring technique to 6.8 μSv per procedure. The tasks that result in the largest exposures of the technologist were patient positioning, injection of the dosage and measurement, in that order [M17].

615. Assessments of internal dose for workers from some PET centres in Germany have shown that internal exposure is rather low. Of 79 workers, only 13% received measurable annual doses, which ranged from 0.05 to 1.5 mSv [E7]. Similar values of effective dose were found in an evaluation of occupational exposure at a PET/CT installation in Spain. The doses were 2 mSv for the workers involved in PET/CT; this represents 100 times more than the doses received by workers operating conventional nuclear medicine imaging equipment (0.02 mSv) [C27].

616. The radiation exposure of PET technologists can be quite high and has a large variation. Annual doses have been reported variously as 3, 10 and 12 mSv [B28, R16, Z1]. The annual doses for PET technologists are higher than those for technologists performing general nuclear medicine studies, with values averaging about 3 mSv and 2 mSv, respectively. The estimated average dose per PET procedure was 4.1 µSv (11 nSv/MBq) [R24]. An evaluation of occupational doses received by the technologists in a PET centre has shown that the average daily effective dose was about 14.4 µSv. On average, each technologist administered 831 MBq daily. The mean whole-body dose per MBq injected was 0.02 µSv/MBq. The average daily amount of time at close distances (less than 2 m) from a radioactive source was 32 minutes. The average effective dose per minute of close contact was 0.5 µSv [B20].

617. The assessment of occupational doses to staff working within the imaging section of a PET/cyclotron service in Australia has shown that PET involves higher radiation exposure to staff than do other types of imaging. The average dose per patient for a technologist is calculated at 1.25 µSv. Staff attending sick patients also have increased exposure [C28].

618. Comparison of occupational exposure due to the use of ^{18}F FDG with exposure due to other radiopharmaceuticals used in conventional nuclear medicine procedures (such as gallium scan, bone scan and sestamibi cardiac scans) has shown that PET, high-dose ^{67}Ga and high-dose ^{201}Tl do not represent a significantly greater occupational radiation hazard than conventional nuclear medicine procedures; these data are shown in table 83 [W11, Z5].

619. Within the field of therapeutic applications in nuclear medicine, new agents with beta emitters are being increasingly used. In contrast to most gamma emitters, the energy of beta rays can be totally absorbed in a small delimited tissue volume; thus exposure can be limited to the tissue to be treated. The higher effectiveness of beta radiation is reflected in the higher values of beta ray dose coefficients compared with gamma ray dose coefficients. This leads to dose rates for beta emitters that are two orders of magnitude greater than those of gamma emitters for equal activities and short distances [R14]. The increasing number of medical procedures requires proper attention to extremity doses received by radiopharmacy staff members involved in nuclear medicine. During the preparation of solutions and the handling of waste, local skin doses to the hands of the personnel due to beta emitters can reach very high values. For example, the preparation and application of liquid-filled balloon catheters for vascular brachytherapy resulted in a measured daily equivalent dose at the fingertips of a nuclear medicine specialist that could considerably exceed the recommended annual limit for skin, which is 500 mSv. In other radiosynoviorthesis procedures, it was also estimated that the annual skin dose limit was exceeded owing to direct radiation from beta emitters. In the case of unsealed sources, additional exposures are likely because of possible skin contamination [R14]. These therapeutic applications are in fact a combination of nuclear medicine and radiotherapy.

620. Radiation synovectomy or radiosynoviorthesis (RSO) is a new nuclear medicine procedure in rheumatology and orthopaedics that uses beta emitters. With this treatment it is possible to efficiently treat local chronic inflammatory joint diseases. In radiosynoviorthesis, radioactive colloidal solutions (^{169}Er, ^{186}Re or ^{90}Y) are injected into inflammatory joints. Investigations of exposure to medical staff were performed in ten hospitals and doctors' surgeries. Very high local skin doses were measured both for assistants who prepared the syringes and for physicians who injected the radiopharmaceutical solutions. The local equivalent doses to the skin were up to 100 mSv per working day for assistants and up to 200 mSv per working day for the physicians due to direct radiation [B10]. The very high doses for both assistants and physicians resulted largely from holding the upper end of the cannula between thumb and index finger while connecting or separating the cannula and syringe, or while injecting the radiopharmaceutical solutions into the joint. The highest exposure occurred using ^{90}Y solutions, owing to the high beta energy of ^{90}Y. The use of ^{169}Er causes little direct radiation exposure, but for ^{186}Re, exposure is not negligible. The mean specific dose (local skin dose related to applied activity) was about 60 µSv/MBq (range 13–233 µSv/MBq) for ^{90}Y and about 20 µSv/MBq (4–40 µSv/MBq) when using ^{186}Re. In some cases, considerable skin contamination of personnel occurred. Because of the high specific activities of the solutions (for example about 500 MBq/mL of ^{90}Y), very small, invisible contamination spots may cause high local skin doses [R14].

621. Table 84 shows the maximum daily skin doses for radiosynoviorthesis (RSO) procedures in seven different institutions. Although RSO is a well-established and approved method, it can be carried out differently with respect to details that may considerably influence the radiation exposure of the personnel. In the case of right-handed persons, usually the index finger, thumb and middle finger of the left hand were most exposed, because of the manner of holding the vials or syringes. Doses to the right hand were often lower by an order of magnitude. Lack of knowledge on the part of medical staff of the high exposures from beta radiation can lead to inadequate radiation protection measures being applied in the use of beta-emitting radionuclides during RSO [B9].

622. Radioimmunotherapy following the Zevalin™ procedure (^{90}Y ibritumomab tiuxetan) involves administering the drug for the treatment of patients with relapsed and refractory non-Hodgkin's lymphomas. Zevalin™ consists of an anti-CD20 monoclonal antibody linked to the radioisotope ^{90}Y; the monoclonal antibody component allows radioimmunotherapy to be targeted only towards malignant cells expressing CD20 antigen. The beta radiation of ^{90}Y kills the target cells and other malignant cells in the surrounding area. Immediately before administration, the antibody component must be radiolabelled with ^{90}Y on site; activities of about 2 GBq are handled in this procedure. As a result, medical personnel receive significant partial-body doses if adequate radiation protection measures are not followed. In the Zevalin™ protocol, the preparation of the solution is the critical step before injection. It is essential that a syringe shield and adapted shielding be used, since otherwise the dose to the hands can be extremely high. With radiological protection measures implemented, the maximum local skin dose to the fingertips of the nuclear medicine specialist amounted to 25 mSv per treatment during radiolabelling and administration of the therapeutic dose of Zevalin™ to the patient [A21, R14].

623. At the Academic Hospital of the Free University of Brussels, hand doses have been monitored for several years by means of wrist dosimeters and ring dosimeters (TLDs). Both types are convenient to wear but do not necessarily represent the location on the hand where the highest skin dose is received. The number of manipulations, amounts of activity handled and results from routine monitoring have highlighted the need for more detailed dosimetry for radiopharmacy workers. In this study, two radiopharmacists were monitored during more than 300 manipulations at 18 different locations on each hand. The results expressed in dose per unit activity handled during a specific manipulation showed good reproducibility for individual radiopharmacists. Typical values of $H_p(0.07)$ ranged from 50 to 600 µSv/GBq of handled activity; the fingertips received the highest dose. Particular personal habits in handling radiopharmaceuticals determined the location and the magnitude of skin doses, especially in manipulation of radiopharmaceuticals with high exposure rates such as ^{18}F FDG. The results from this study have shown that annual skin doses would reach about 400 mSv. The principal radiopharmaceuticals that contributed to extremity doses at the hospital were ^{99m}Tc (85%) and ^{18}F (10%), with 5% contributed by other radioisotopes (^{123}I, ^{201}Tl, ^{51}Cr, ^{67}Ga, ^{131}I and others) [B21].

624. National data on occupational exposures arising from nuclear medicine over the six periods are given in the third part of table A-24. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in table 85 and figure LII. They indicate a progressive increase in the number of monitored workers involved in this practice, from 61,000 in 1975–1979 to 120,000 in 2000–2002. The collective effective dose increased from 62 man Sv in 1975–1979 to about 90 man Sv in 1990–1994, and then decreased slightly to 87 man Sv in 2000–2002. The average effective dose decreased from 1.0 mSv in 1975–1979 to 0.7 mSv in 2000–2002. The percentage of measurably exposed workers has been about the same over the three last periods at around 56%. About 30% of the workforce received doses higher than 1 mSv; there were no recorded doses higher than 15 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be 124,000, the collective effective dose would be 88 man Sv and the average effective dose would be 0.7 mSv. It is important to point out that the recorded doses are related to external exposure. The doses related to nuclear medicine can be underestimated, since there is some contribution from internal exposure, although it is small compared with external exposure.

625. There is a wide variation in the effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, the mixing of doses from the various procedures performed by the medical staff and the protective measures implemented by each country.

626. In order to obtain improved information about occupational exposures of nuclear medicine workers according to specialty, new questionnaires covering the period 1995–2002 were distributed to Member States requesting information on dose distributions for medical doctors, ward nurses and technicians. Few countries provided information according to worker specialty. A large variation is evident with respect to the estimated average annual effective dose and collective dose; the data are presented in table A-26. The doses for technicians can be substantially higher than the doses for the other staff (medical doctors and nurses). This is to be expected, since the technicians are responsible for the preparation of the injected solutions. However, the doses are dependent on the number of manipulations, the types of radioisotope and the amount of activity handled. Greece has provided data separately for four different job categories: technicians, medical doctors, nurses and others, as illustrated in figure LIII. This shows that the levels of exposure for technicians and medical doctors were higher than for nurses and others. However, the values of average effective doses for the measurably exposed workers were not statistically different.

627. During the preparation of solutions and handling of waste, local skin doses to the hands of the personnel due to beta emitters can reach high values. According to the literature, the equivalent dose at the fingertips of a nuclear medicine specialist can considerably exceed 500 mSv for skin [A21, B9, B10, I59, R14]. There is a large range in the doses reported in the literature. Few countries have reported data on extremity doses, but the values reported are low—around 5 mSv.

(d) Radiotherapy

628. Therapeutic uses of ionizing radiation are quite different in purpose from diagnostic radiology procedures. Radiotherapy

is an important treatment modality for malignant disease (see annex A, "Medical radiation exposures"). In radiotherapy, there are three main treatment categories where occupational exposure may occur: external beam treatment, brachytherapy and therapy simulation. Brachytherapy, where there is manual loading of the radioactive sources, is usually the most significant source of personnel exposure [N10]. Exposures may occur during the receipt and preparation of the sources, during loading and unloading, and during treatment.

629. Personnel are not normally present in the treatment room when external beam therapy is performed, 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, be caused by ^{60}Co teletherapy units as a result of leakage while the source is in the off position and by radiation that penetrates the barrier during use [N10].

(i) Teletherapy

630. The exposures from linear accelerators, betatrons and microtrons depend on the type of beam (photon or electron) and the beam energy. Below 10 MeV, exposure results 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 usually low. Exposures from simulators and other diagnostic imaging equipment used to plan treatments are also usually low [N10].

631. Radiation therapy staff in the treatment rooms of medical accelerators operating with energies of above about 10 MeV are also exposed to radiation due to activated materials. The activation arises primarily from photonuclear reactions and neutron capture. Published estimates of the annual activation dose received by staff during typical operations are in the range 0.7–5 mSv. These numbers demonstrate that the activation dose is not negligible and suggest that, at least in conservatively shielded facilities, the therapist receives a greater occupational dose due to activation than to radiation transmitted through the shielding barriers [A12, R4].

632. Intensity-modulated radiation therapy (IMRT) may play a dominant role in oncology practice in the near future. However, IMRT techniques require a substantial increase in accelerator beam-on time compared with conventional radiation therapy to deliver the same patient dose. This could lead to an increased dose being received by radiation therapists. The increased beam-on time influences radiation exposure in two ways. First, the dose outside the treatment room due to leakage (including neutrons and capture gamma rays) transmitted through secondary barriers will increase, though in principle this can be compensated for by increasing the barrier thickness [M13]. Secondly, in situations where IMRT is delivered using high-energy radiation, the dose inside the treatment room due to induced activation is also expected to increase. The activation dose rates in a treatment room were evaluated for ^{28}Al, ^{56}Mn, ^{24}Na and long-lived isotopes generated at 18 MeV, for different treatment regimes. The largest contribution to doses came from ^{28}Al and ^{56}Mn [R4]. It is worthy of note that the two principal isotopes, ^{28}Al and ^{56}Mn, were also observed to be the dominant isotopes responsible for activation in the treatment room of an accelerator operating at 16 MeV, and interestingly, in the treatment room of a fast neutron facility [Y4]. The isotope ^{24}Na is commonly found in concrete that has been activated by thermal neutrons [N12].

(ii) Brachytherapy

633. Brachytherapy involves the placement of radioactive sources within the body or on its surface so that the radiation source is close to the tissue to be treated. This enables a high dose of radiation to be delivered to malignant tissue and lower doses to normal tissue.

634. Intracavitary brachytherapy is used for the treatment of gynaecological cancers. This involves the placement of radioactive sources into the uterus. Sources can be manually placed into the uterus in a surgical theatre; however, this approach results in the theatre staff, porters and ward nursing staff receiving a high radiation dose. Afterloading was introduced as a means of reducing the radiation dose to staff; in this technique the radioactive sources are remotely placed into position by a treatment machine.

635. A technique of permanent implantation of radioactive seeds into the prostate so that their decay will deliver the prescribed dose to the tumour is in common use. The isotopes used are predominantly ^{125}I and ^{103}Pd. Procedures for seed implantation vary, but there are generally two stages. The first is the manual preloading of needles, which can be performed either by composing loose seeds and spacers or by cutting off strands of seeds and reabsorbable spacers. This process can be done according to a previously approved plan or on the basis of cumulative experience concerning the number of needles and the loading usually needed. The second stage consists of the implantation of these preloaded needles in the operating room. This procedure results in low occupational exposures because of the low activity used per seed and the low energy emitted by ^{125}I. Table 86 shows the mean dose rate levels per implant that best exemplify the dose received by different staff involved during the average 40 min phase of insertion of the seeds into the prostate using the afterloading technique [G4]. The only step in which seeds are not properly shielded is during their movement through the delivery tube, but this process is performed so quickly that it is generally accepted that sufficient protection is provided by stepping back a minimum distance of 50 cm from the tube during the process. Assuming a maximum train of five seeds of maximum activity 40 MBq, the dose rate at 50 cm would be no greater than 0.01 mSv/h [S13].

636. National data on occupational exposures arising from radiotherapy over the six periods are given in the fourth part of table A-24. There is a wide variation in the effective dose and percentage of measurably exposed workers. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in table 87 and figure LIV; they indicate a progressive increase in the number of monitored workers involved in this practice, from 84,000 in 1975–1979 to 127,000 in 2000–2002. The collective effective dose decreased from 190 man Sv in 1975–1979 to 60 man Sv in 2000–2002. The average effective dose decreased from 2.2 mSv in 1975–1979 to 0.5 mSv in 2000–2002. The percentage of measurably exposed workers has been about the same over the last three periods, at around 40%. About 10% of the workforce receives doses higher than 1 mSv; there are no recorded doses higher than 15 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be about 130,000, the collective effective dose would be about 57 man Sv and the average effective dose would be about 0.5 mSv.

(e) All other medical uses

637. The category “all other medical uses of radiation” was intended to cover new and/or 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 has been biomedical research. 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 labelling (for example using ^{3}H, ^{14}C, ^{32}P, ^{35}S and ^{125}I) and irradiators using ^{60}Co or ^{137}Cs sealed sources [U22]. The UNSCEAR 1993 Report [U6] noted that the lack of consistency in reporting data made it difficult to estimate the level of exposure or to draw useful comparisons for this category of exposure. On the basis of the reported data it is possible to conclude that some countries may not record the data separately according to the techniques used in the medical field. In this case, the doses are reported in “all medical uses”.

638. 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 section. The average exposure levels of workers involved in other uses of radiation are in general low. However, the way in which the doses are aggregated may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, that receive doses significantly above the average is for the data to be inspected periodically.

639. National data for the various categories were aggregated by country to give data on exposures to workers arising from all medical uses of radiation; they are presented in table A-27. There is a wide variation in the effective dose and percentage of measurably exposed workers. The analysis of trends for the countries indicates a drastic decrease in the number of monitored workers involved in this practice from 1990–1994 to 1995–1999, and a slight increase of about 20% in the last period. The collective effective dose follows the same pattern as the number of monitored workers. The average effective dose has tended to be the same over the last periods. It is difficult to project with any accuracy the level of exposure for 2007.

(f) Summary

640. National data on occupational exposures arising from all medical uses of radiation averaged over five-year periods are given in table A-27. The Committee has decided to estimate the number of workers on the basis of the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. The average effective dose is estimated on the basis of the data presented in table A-24.

641. The evaluation of trends in occupational exposure for 20 European countries in the medical sector has shown a slight decrease in the average level of exposure. The average collective dose also decreased slightly, from 177 to 171 man Sv, while the average effective dose did not change, having remained at around 1 mSv from 1996 to 2000 [F15].

642. There is a wide variation in the effective dose and percentage of measurably exposed workers. This variation may be explained by many factors, including, the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, the mixing of doses from the various procedures performed by the medical staff and the protective measures implemented by each country.

643. For X-ray diagnostics there is a trend of increasing numbers of workers, increasing collective effective doses and relatively constant values for the average effective dose. The estimated number of workers is around 6.74 million, which represents about 90% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is around 3,370 man Sv, which represents about 95% of the total collective dose for all medical uses. Following the trends from the six periods, the predicted level of occupational exposure for X-ray diagnostic radiology for 2007 would show an increase of 10% in the number of workers and in the average collective dose, and no change in the effective dose. The effective dose has been relatively constant over the last three periods (from 1990–1994 to 2000–2002); this may be due to the influence of the high doses related to interventional procedures. On the basis of the reported data that distinguish between doses from conventional and from interventional procedures, about 0.1% of the monitored workers in diagnostic radiology are involved in interventional procedures. The average annual effective dose due to conventional techniques is about 0.5 mSv (range 0.02–1.24 mSv) for the monitored workers

and 1.2 mSv (range 0.33–3.14 mSv) for the measurably exposed workers. The average annual effective dose for workers involved in interventional procedures is about 1.6 mSv for the monitored workers and 3.1 mSv for the measurably exposed workers, with a range of 0.4 to 29.5 mSv. The doses to the hand can exceed 500 mSv. Although the reported values vary considerably, they are relatively low, and the highest reported value is around 10 mSv.

644. For dental practice there is a trend of decreasing numbers of workers over the six periods (although an increase of about 50% has been observed in the last periods), with decreasing collective effective doses and decreasing average effective doses. The estimated number of workers is about 0.40 million, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is 24 man Sv, which represents about 0.7% of the total collective dose for all medical uses. The estimated average effective dose is 0.06 mSv. Following the trends from the six periods, the predicted level of occupational exposure for dental practice for 2007 would show a 10% increase in the number of workers, a decrease of about 5% in the average collective dose and a 3% decrease in the average effective dose.

645. For nuclear medicine there is a trend of increasing numbers of workers, decreasing collective effective doses and decreasing average effective doses. The estimated number of monitored workers is 0.12 million, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is 87 man Sv, which represents about 10% of the total collective dose for all medical uses. The estimated average effective dose is 0.7 mSv. Following the trends from the six periods, the predicted level of occupational exposure for nuclear medicine for 2007 would show a 3% increase in the number of workers, a 1% decrease in the average collective dose and a 4% decrease in the average effective dose. These dose projections may be underestimates, since new technologies have been introduced, and the use of new radiopharmaceuticals and ^{18}F FDG has increased considerably. During the preparation of solutions and the handling of waste, local skin doses to the hands of the personnel due to beta emitters can reach very high values, exceeding 500 mSv.

646. On the basis of the data from countries that have reported the doses for the different job categories separately, the Committee concludes that the doses for technicians can be substantially higher than the doses for the other staff (medical doctors and nurses). This is expected, since the technicians are responsible for the preparation of the injected solutions. However, the doses are dependent on the number of manipulations, the types of radioisotope and the amount of activity handled.

647. For radiotherapy there is a trend of increasing numbers of workers, decreasing collective effective doses and decreasing average effective doses. The estimated number of workers is 0.13 million, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is 60 man Sv, which represents about 7% of the total collective dose for all medical uses. The estimated average effective dose is 0.5 mSv. Following the trends from the six periods, the predicted level of occupational exposure for radiotherapy for 2007 would show an increase of about 3% in the number of workers, and a decrease of about 5% for both the average collective dose and the average effective dose.

648. For the category “all other medical uses of radiation”, which covers new and/or expanding uses of radiation within the medical sector that do not fit into the categories of diagnostic radiology, dental radiology, nuclear medicine or radiotherapy, the analysis is based on data from only one country that has reported the doses for the five practices within the medical uses. The analysis of trends for this country indicates a drastic decrease in the number of monitored workers involved from 1990–1994 to 1995–1999, and an increase of about 20% in the last period. The collective effective dose follows the same pattern as the number of monitored workers. The average effective dose has tended to remain the same over the last several years. It is difficult to project any level of exposure for 2007. These workers represent about 30% of the total number of monitored workers in the practices related to medical uses of radiation. The average collective dose represents about 25% of the total collective dose for all medical uses.

649. The estimated number of workers involved in the medical uses of radiation is 7.40 million, the collective effective dose is 3,540 man Sv and the average effective dose is 0.5 mSv. The evaluation of the trends in occupational exposure for all medical uses together shows an increasing number of monitored workers, and decreasing collective effective dose and average effective dose, as shown in table 88 and figure LV. The largest contribution to the occupational exposure is from diagnostic radiology. The number of monitored workers has increased over the six periods, dominated by those involved in diagnostic radiology.

3. Industrial uses of radiation

650. 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. 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 low, a fact that contributes to the lack of detail in recorded data. In the UNSCEAR 1993 Report [U6], 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 were introduced in the survey of data for 1995–1999 and 2000–2002: industrial irradiation, industrial radiography, luminizing, radioisotope production, well logging, accelerator operation and all other industrial uses. For the first three periods, the exposure of workers in educational establishments and tertiary education was included within the general category of industrial uses; since the UNSCEAR 2000 Report [U3], these exposures have been included within a "miscellaneous" category in section II.C.4.

651. National data on occupational exposures arising from the industrial use of radiation for the categories mentioned above are given in table A-28. 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 A-29. The Committee has decided not to follow the procedures of the previous UNSCEAR reports to estimate the worldwide level of exposure. The decision was based on the lack of sufficient information to calculate a reliable figure that would reflect the worldwide level of exposure for the last two periods (1995–1999 and 2000–2002). On this basis, it was decided to evaluate the trends for representative countries.

(a) Industrial irradiation

652. The most widespread uses of industrial irradiation are the sterilization of medical and pharmaceutical products, the preservation of foodstuffs, polymer synthesis and modification, and the eradication of insect infestation. 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 petabecquerel range; some ^{137}Cs sources are also used. Dose rates in the irradiation chamber would be of the order of 1 Gy/s, and in some cases there is a need to protect against radiogenic heating that could cause fires. Gamma and electron irradiation facilities must be constructed such that during normal use any radiation exposure of workers will be very low.

653. This category of work was first specified in the previous UNSCEAR Global Survey of Occupational Radiation Exposures [U3]. The available data over the six periods are given in the first part of table A-28; these data are limited and cover only 13 countries. Of crucial importance is the fact that there are very few data from the large industrialized countries, where the greatest number of irradiators are located. It is difficult to evaluate the trend of exposure for lack of information.

654. For this annex, data from China are analysed to show trends over the past periods. Figure LVI indicates an increase in the number of monitored workers, from 100 in 1990–1994 to 1,400 in 2000–2002. The collective effective dose increased from 0.10 man Sv in 1990–1994 to 1.22 man Sv in 1995–1999, and then dropped to 0.88 man Sv in 2000–2002. The average effective dose consistently decreased, from 1.03 mSv in 1990–1994 to 0.63 mSv in 2000–2002. The percentages of measurably exposed workers fell from 90% in 1990–1994 to 63% in 2000–2002 (table A-28). According to the dose distribution data, about 29% of the workers received doses higher than 1 mSv, and 1% of them received doses higher than 15 mSv. As seen in the first part of table A-28, the other countries follow the same pattern of occupational exposure as that described for China, with a decrease in the collective dose and average effective dose. It is difficult to project a level of exposure for 2007 on the basis of the available data.

(b) Industrial radiography

655. Industrial radiography is a non-destructive practice for examining materials for defects. Gamma radiation from ^{137}Cs and ^{60}Co sources as well as X-rays are used to examine welded metal joints. This technique can be applied in three basic formats. The oldest format is direct manual manipulation, either using handling equipment or with the source as an integral part of a shielded "torch". This format, which was prevalent in the 1970s but was already declining in the 1980s, is still used to some extent. 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 being used less frequently. 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 about ten 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. 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.

656. Industrial radiography is performed in two quite different situations. 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 situation, the radiography is conducted at multiple locations in the field, in which case the radiographic equipment is brought to the location where the radiograph is required, this procedure often being referred to as "site radiography". There are usually significant differences in the degree of control that can be exercised in the two situations.

657. The available data over the six periods are given in the second part of table A-28. The worldwide estimate of the level of occupational exposure was based on an analysis of the trends in all countries that have provided information; the data are shown in figure LVII. The number of monitored workers increased from 72,000 in 1975–1979 to 116,000 in 1980–1984 and then remained about the same in the last four periods, being 113,500 in 2002. The collective effective dose followed the same pattern as the number of workers, increasing from 190 to 230 man Sv in the first two periods, then dropping to 170 man Sv and remaining constant for the subsequent periods. The average effective dose dropped from 2.6 to 2.0 mSv for the first two periods and remained about the same for the subsequent periods at 1.5 mSv. The percentages of measurably exposed workers dropped from 50% in 1990–1994 to 44% in the last period (2000–2002). According to the dose distribution data, about 30% of the monitored workers received doses higher than 1 mSv, and 1% of them received doses higher than 15 mSv.

658. Following the trends from the six periods, the predicted level of occupational exposure for industrial radiography for 2007 would show an increase of 4% in the number of workers and the average collective dose, and a slight decrease, of 2%, in the effective dose.

659. The different levels of occupational exposure for multiple-location and single-location industrial radiography have been demonstrated by the data from the United States presented in table 89. About 90% of the workforce is engaged in multiple-location industrial radiography. The average collective effective dose for workers involved in single-location work is less than 1% of that for multiple locations. The average effective dose for workers involved in single-location work is about 7% of that for multiple locations [U29, U30, U31, U32, U33, U34, U36, U37, U38].

(c) Luminizing

660. Luminizing is one of the oldest industrial uses of ionizing radiation. In the past, alpha or beta emitters were mixed with a phosphor, such as zinc sulphide, and then painted on dials, such as watch faces or airplane instrumentation. Present-day practice includes using luminizing compounds in gunsights and as low-level light sources for exit signs and map illuminators.

661. The data for the six periods are given in the third part of table A-28. Only three countries have reported data for the periods 1995–1999 and 2000–2002. Switzerland has reported data for most of the periods, allowing the Committee to analyse the trend in occupational exposure over the years. Figure LVIII indicates that the number of monitored workers varied over the six periods, dropping from 210 in 1975–1979 to 130 in the second period, increasing to 350 in 1995–1999 and dropping to 220 in 2000–2002. The collective effective dose consistently decreased, from 2.31 man Sv in 1975–1979 to 0.18 man Sv in 2000–2002. This was due to a decreasing average effective dose, which fell considerably, from 11.2 mSv in 1975–1979 to 0.80 mSv in 2000–2002. The percentages of measurably exposed workers were evaluated for the last two periods, being 98% in 1995–1999 and 93% in 2000–2002. According to the dose distribution data, 22% of the monitored workers received doses higher than 1 mSv, 2% received doses higher than 10 mSv and 1% received doses higher than 15 mSv. Historically the doses to workers involved in luminizing were high, but in recent years there has been a significant reduction. It is difficult to project the level of occupational exposure for 2007 on the basis of only a few countries.

662. On the basis of all the reported data, the average effective doses have decreased over time: 7.44 mSv (1975–1979), 5.01 mSv (1980–1984), 2.71 mSv (1985–1989), 0.38 mSv (1990–1994), increasing to 1.93 mSv in 1995–1999 and dropping to 0.72 mSv in 2000–2002. Except for the period 1995–1999, the trend is a progressive decrease of the effective dose.

(d) Radioisotope production

663. Radioisotopes are produced for a great variety of industrial and medical purposes. The main source of occupational exposure in radioisotope production and distribution is external irradiation; internal exposure may be significant in some cases. 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 (for example with respect to 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.

664. Among the radioisotopes produced, ^{131}I is the one most likely to contribute a significant dose due to internal exposure. However, ^{131}I has gradually been supplanted by other radionuclides with shorter half-lives. In the past, many countries did not record internal exposures. Control of intakes was accomplished mainly through area monitoring, and little emphasis was given to the use of bioassays, mainly because of the cost and the difficulty of interpreting the results. A retrospective study of ^{131}I-contaminated workers in the radiopharmaceutical industry in Brazil has shown that, even with continuously reinforced implementation of safety principles and good practice in handling iodine, committed effective doses can reach values around 4 mSv/a, since the volatility of iodine makes its compounds readily available for intake by inhalation [G1]. The results of internal exposure monitoring on four individuals who worked for seven to ten years in a ^{131}I radiopharmaceutical production laboratory

in the Islamic Republic of Iran showed the maximum and minimum annual intakes to be 536 and 79 kBq, respectively, although one worker (involved in an incident) had an annual intake estimated at 3.8 MBq [A10].

665. The number of cyclotrons dedicated to the production of positron-emitting radionuclides is increasing in medical institutions/hospitals owing to the well-established role of PET imaging in clinical practice. The radiation safety issues in a cyclotron PET facility are much different from those in conventional nuclear medicine facilities because of the presence in a cyclotron PET facility of penetrating gamma photons of 511 keV, higher specific gamma ray constant of positron emitters and the secondary neutrons from the cyclotron during production. Therefore work practices in a cyclotron-PET facility need to be more stringent. The radiation dose to workers in a cyclotron and radiochemistry laboratory measured over 12 months is shown in table 90. The dose received by workers in a cyclotron facility was less than 5% of the annual dose limit (20 mSv) to the whole body and less than 2% of the annual dose limit (500 mSv) to the extremities. Similarly, the doses received by workers in the radiochemistry laboratory were less than 10% of the annual limit to the whole body and less than 1% of the annual limit to the extremities. This was to be expected, as all the operations in this cyclotron and radiochemistry laboratory are completely automated and have adequate shielding [P3]. The evaluation of the occupational exposure in a cyclotron facility in which the total annual activity of ^{18}F and ^{13}N produced was 31 TBq in 2002 (synthesis of ^{18}F FDG represented 90% of the total activity) showed an average annual effective dose of about 7 mSv and an extremity dose of 36 mSv [P8].

666. The occupational doses were found to be 5–10 times less than the regulatory limits in the cyclotron vault, 8–30 times less than the regulatory limits in the radiochemistry laboratory and 10–200 times less than the regulatory limits outside the cyclotron laboratory during beam operation. Internal doses were found to be negligible in the facility [S18].

667. National data on occupational exposures arising from radioisotope production over the period 1995–2002 are given in table A-28. The worldwide level of occupational exposure has been evaluated on the basis of the analysis of individual country trends. The data are presented in figure LIX. They indicate a progressive increase in the number of monitored workers over the first three periods, from 57,000 to 88,000, followed by a drop to 24,000 in 1990–1994, after which the number began to increase by about 4% for each period, resulting in 34,560 in 2000–2002. The collective effective dose fell from 130 man Sv in 1975–1979 to 47 man Sv in 1990–1994, and then increased to 62 man Sv in 2000–2002. The average effective dose decreased from 2.25 mSv in 1975–1979 to 1.12 mSv in 1985–1989, and then increased to about 2 mSv in the last three periods. The percentage of measurably exposed workers has been around 50–70%. About 55% of the workforce received doses higher than 1 mSv, and about 2% received doses higher than 15 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be 41,472, the collective effective dose would be 75 man Sv and the average effective dose would be 1.8 mSv.

(e) Well logging

668. Well logging is the practice of using radioactive sources or miniature X-ray machines to measure geological characteristics (such as porosity, density and elemental composition) in boreholes drilled for mineral, oil or gas exploration. Well logging has been identified in some countries as an industrial use of radiation 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, for example on oil rigs. Both gamma and neutron sources are used in well logging, but the contributions from each to the reported doses are generally not indicated.

669. The data on well logging are presented in the fifth part of table A-28. In this practice it is difficult to draw a trend in the level of occupational exposure. Only 12 countries have reported data to UNSCEAR on occupational exposure. Canada is more relevant in terms of the number of monitored workers, representing about 60% of the total reported workforce, and has reported data throughout all the periods. The Canadian data are used to illustrate the trend in occupational exposure for this practice. Figure LX indicates a significant increase in the number of monitored workers in the second period, from 450 in 1975–1979 to 1,010 in 1980–1984. The number was then approximately constant from 1985 to 1999: 1,110 (1985–1989), 950 (1990–1994), 1,060 (1995–1999). It increased in the last period to 1,430. The collective effective dose increased from 0.52 man Sv to 1.37 man Sv in 1985–1989 and dropped to 0.71 man Sv in 2000–2002. The average effective dose was about 1.2 mSv in the first three periods and decreased to 0.50 mSv in 2000–2002. The percentages of measurably exposed workers are between 40% and 70%. It is difficult to project levels of exposure for the year 2007, but they would be expected to reflect increasing numbers of workers and declining average collective dose and average effective dose.

670. On the basis of all the reported data, the average effective doses have decreased over time: 1.32 mSv (1975–1979), 1.17 mSv (1980–1984), 1.07 mSv (1985–1989), 0.36 mSv (1990–1994), increasing to 0.92 mSv in 1995–1999 and to 0.96 mSv in 2000–2002. Except for the period 1990–1994, the trend is a progressive decrease of the effective dose.

(f) Accelerator operation

671. Consideration is limited here to occupational exposures arising from accelerators used for nuclear physics research at universities and at 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 those uses 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 resulting from accelerators arise from induced radioactivity and occur mainly during the repair, maintenance and modification of equipment. They result 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 due to external irradiation.

672. 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 before 1960, typical annual collective doses per accelerator were 1–2 man Sv. Such doses still apply for many of the early cyclotrons that remain in operation. Between 1960 and 1980, beam extraction techniques were improved, which led to reduced levels of activation products. However, these reductions were largely offset by the continuing increases in beam power.

673. 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 the exposures during maintenance.

674. The available data are shown in the sixth part of table A-28. In the first three periods, from 1975 to 1989, the reported data were dominated by those of the United States. Since 1990, Canada has contributed the majority of the number of monitored workers. Data from Canada are used to illustrate the trend in occupational exposure for this practice. Figure LXI indicates a significant increase in the number of monitored workers in the first three periods: 580 (1975–1979), 880 (1980–1984) and 1,000 (1985–1989). The number then decreased slightly to 888 in 2000–2002. The collective effective dose increased from 0.17 man Sv in 1975–1979 to 1.06 man Sv in 1985–1989, and then decreased to 0.44 man Sv in 2000–2002. The average effective dose increased from 0.30 mSv in 1975–1979 to 1.1 mSv in 1985–1989, and then decreased to 0.5 mSv in 2000–2002. The percentages of measurably exposed workers are between 26% and 50%, with the highest number in the period 1985–1989. The decrease in the collective dose over the last two periods is influenced by the decrease in average effective dose. According to the dose distribution data, 12% of the monitored workers received doses higher than 1 mSv and 2% of them received doses higher than 5 mSv.

675. On the basis of all the reported data, the average effective doses decreased in the second period and then kept constant over time: 1.62 mSv (1975–1979), 0.76 mSv (1980–1984), 0.62 mSv (1985–1989), 0.75 mSv (1990–1994), 0.62 mSv (1995–1999) and 0.74 mSv (2000–2002).

676. Following the trends from the six periods, the predicted level of occupational exposure for accelerator operation for 2007 would show an increase of about 3% in the number of workers and a decrease of about 10% in the average collective dose and the average effective dose.

(g) All other industrial uses

677. There are many other uses of radiation in industry, for example in soil moisture gauges, thickness gauges and X-ray diffraction, but occupational exposure data for these are in general not separately identified or reported. This category of practice has been incorporated into the UNSCEAR 2000 Report [U3] to accommodate the data from all the other practices not mentioned under the industrial uses of radiation. The number of workers potentially exposed in these other uses may substantially exceed the number in the few occupations for which data have been separately presented in this section. The average exposure levels of workers involved in “other uses of radiation” are in general low. However, the way in which the doses are aggregated may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, that receive doses significantly above the average is for the data to be inspected periodically.

678. The available data are shown in the last part of table A-28. Japan, Germany and France represent about 87% of the reported monitored workers. It certainly is the case that the national systems for collecting such data do not allow the data to be readily separated into the categories used in this review. Although the Netherlands represents just 2% of the total number of reported monitored workers, it is used to illustrate the trend in occupational exposure for this practice, since it has reported data for most of the practices related to industrial uses of radiation. The number of monitored workers has decreased from 2,880 in 1990–1994 to 2,180 in 2000–2002. The collective effective dose decreased from 0.22 man Sv in 1990–1994 to 0.15 man Sv in 2000–2002. The average effective dose remained steady at 0.08 mSv in 1990–1994 and 0.07 mSv in 2000–2002. The percentages of measurably exposed workers were about 20%. According to the dose distribution data, about 1% of the monitored workers received doses higher than 1 mSv.

679. For the great majority of the reported data, the average effective dose was very low, less than 1 mSv. On the basis of the reported data, the average effective dose was 0.45 mSv in 1990–1994, 0.27 mSv in 1995–1999 and 0.26 mSv in 2000–2002.

680. Following the trends from the six periods, the projected level of occupational exposure for all other industrial uses for 2007 would show an increase of about 2% in the number of workers, and a decrease of about 10% in the average collective dose and the average effective dose.

(h) Summary

681. Table A-29 shows the national data from all industrial uses of radiation grouped together. The data are more complete than for the separate categories of industrial uses of radiation, but as with the data for medical uses they suffer from incomplete data for the United States, which is important in the estimation of worldwide exposure. The Committee has decided not to follow the procedures of the previous UNSCEAR reports to estimate the worldwide level of exposure. The decision was based on the lack of sufficient information to calculate a reliable figure that would reflect the worldwide level of exposure. The estimate of the worldwide level of occupational exposure for all industrial uses was based on the trends for all countries and all practices.

682. The trends in the worldwide level of exposure over the six periods are presented in figure LXII. The total number of monitored workers involved in the practices related to the industrial uses of radiation increased by a factor of 1.6, from 530,000 in 1975–1979 to 870,000 in 2000–2002; it is dominated by industrial radiography. The collective effective dose decreased by a factor of 3, from 870 man Sv in 1975–1979 to 348 man Sv in 2000–2002. The average effective dose decreased by a factor of 4, from 1.6 in 1975–1979 to 0.4 mSv in 2000–2002.

683. The evaluation of the trend of occupational exposure in 21 European countries in general industries has shown an slight decrease in the level of exposure. The average effective dose decreased from 2.0 to 1.8 mSv and the average collective dose decreased from 76 to 69 man Sv in the period 1996–2000 [F15].

684. There is a wide variation in the effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, and the protective measures implemented by each country.

685. For industrial irradiation there is a trend of increasing numbers of workers and decreasing collective effective dose and average effective dose. Industrial irradiation represents about 3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 3% of the total collective dose for all industrial uses. There is not sufficient information to have a statistically significant prediction for 2007.

686. The trend of occupational exposure in industrial radiography is an increase in the number of workers and the average collective effective dose and a decrease in the average effective dose. Industrial radiography represents about 20% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 55% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 4% in the number of workers and the average collective dose and a decrease in the effective dose of about 3%.

687. For luminizing there is a trend of an increasing number of workers and a decrease in the collective effective dose and the average effective dose. Luminizing represents about 0.3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 1% of the total collective dose for all industrial uses. There is not sufficient information to have a statistically significant prediction for 2007.

688. For radioisotope production there is a trend of an increasing number of workers and a decrease in the average collective effective dose and the average effective dose. Radioisotope production represents about 3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 10% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for the year 2007 would show an increase of about 20% in both the number of workers and the average collective dose, and no change in the average effective dose.

689. For well logging there is a trend of a slightly increasing number of workers, and a decrease in the average collective effective dose and the average effective dose. Well logging represents about 0.4% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 1% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 4% in the number of workers, a decrease of about 5% in the average collective dose and a decrease of 10% in the average effective dose.

690. For accelerator operation there is a trend of a slightly increasing number of workers, and a decrease of the average collective effective dose and the average effective dose. Accelerator operation represents about 0.3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 1% of the total collective dose for all industrial

uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 3% in the number of workers and a decrease of about 10% in the average collective dose and the average effective dose.

691. For all other industrial uses there is a trend of a slightly increasing number of workers and a decrease in the average collective effective dose and the average effective dose. All other industrial uses represent about 73% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 29% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 2% in the number of workers and a decrease of about 10% in the average collective dose and the average effective dose.

692. In summary the number of monitored workers has increased over the six periods. The average annual effective doses to monitored workers involved in industrial uses of radiation have consistently decreased over the six periods. The greatest contribution to the occupational exposure comes from industrial radiography.

4. Miscellaneous uses

693. There remain a number of occupations where radiation exposure may be involved that are not covered by other categories. These include research in educational establishments, radiology in veterinary medicine, the management of spent radioactive sources, transport of radioactive material and others. The data reported by countries are given in table A-30. The Committee has decided not to follow the procedures of the previous UNSCEAR reports to estimate the worldwide level of exposure. The decision was based on the lack of sufficient information for the last two periods (1995–1999 and 2000–2002) to calculate a reliable figure that would reflect the worldwide level of exposure. On this basis, it was decided to evaluate the trend for representative countries.

(a) Educational establishments

694. 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 [U6], 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 rightfully be attributed to this category are often attributed to other broad practices of radiation, such as research related to 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 a major educational role). Exposures resulting 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.

695. The data reported by countries are given in the first part of table A-30. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in figure LXIII; they indicate a progressive increase in the number of monitored workers, from 140,000 in 1975–1979 to 446,000 in 2000–2002. The collective effective dose decreased from 74 man Sv in 1975–1979 to 38 man Sv in 2000–2002. The average effective dose decreased from 0.55 mSv in 1975–1979 to 0.09 mSv in 2000–2002. The percentage of measurably exposed workers has been about 10%. About 2% of the workforce received doses higher than 1 mSv; there are no records of doses higher than 5 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be 513,360, the collective effective dose would be 42 man Sv and the average effective dose would be 0.08 mSv.

(b) Veterinary medicine

696. 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. However, poor practice may 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 Global Survey of Occupational Radiation Exposures are given in the second part of table A-30. The main contributions of data for 1995–1999 and 2000–2002 came from Canada, Germany and the United Kingdom, and to a lesser extent from Denmark and the Netherlands. The United States made the largest contribution of data for the first three periods but has not reported since then.

697. National data on occupational exposures arising from veterinary medicine are given in the second part of table A-30. The worldwide level of occupational exposure is evaluated on the basis of the analysis of individual country trends. The data are presented in figure LXIV. They indicate a progressive increase in the number of monitored workers from 48,000 in 1975–1979 to 160,000 in 1985–1989, followed by a drop to 45,000 in 1994–1999 and then an increase to 119,030 in 2000–2002. The collective effective dose increased from 25 man Sv in 1975–1979 to 52 man Sv in 1985–1989, decreased in 1990–1994 to 8 man Sv and increased to 18 man Sv in 2000–2002. The average effective dose decreased consistently, from 0.52 mSv in 1975–1979 to 0.15 mSv in 2000–2002. The percentage of measurably exposed workers has been around 30%. About 3% of the workforce received doses higher than 1 mSv; there are no recorded doses higher than 5 mSv.

698. For the great majority of the reported data, the average effective dose was very low over the six periods, less than 1 mSv. The effective doses decreased from 0.73 mSv in 1975–1979 to 0.10 mSv in 2000–2002. The dose distribution has shown that, for the last period, 12% of the 34,540 workers received doses higher than 1 mSv; there are no recorded doses higher than 5 mSv.

699. Following the trends from the six periods, the predicted level of occupational exposure for veterinary medicine in 2007 would show an increase of about 10% in the number of workers; the average collective effective dose would not change, and the average effective dose would decrease by about 8%.

(c) Spent sources

700. Spent radioactive sources result from industrial applications, research and medicine. A survey was performed in Turkey on the management of such spent sources (^{60}Co, ^{137}Cs) at the Waste Processing and Storage Facility, where 11 ^{137}Cs sources (total activity 851 GBq) and four ^{60}Co sources (total activity 27.75 GBq) that had been used as levels and density gauges were conditioned. Reinforced metal drums (200 L in volume) and cement matrix were used for conditioning of these sources to achieve greater confinement for long-term storage. The maximum dose rates at the surface of the conditioned waste packages were 1.60 mSv/h for ^{137}Cs and 1.63 mSv/h for ^{60}Co. Measurements of the final waste packages were presented to fulfil the requirements (<2 mSv/h) of transport according to the regulations for the safe transport of radioactive material [O23].

(d) Transport

701. Essentially all commercially produced radioisotopes eventually need to be transported by air, land or sea, depending on the source size and the regulatory control provisions. In the course of transport, some radiation exposure of the carriers’ staff occurs. According to the IAEA, the annual doses due to transport of radioactive material are in the range 0.2–7 mSv, with an average of about 1 mSv [I42]. The highest doses from transport of radioactive material are to drivers/handlers carrying radiopharmaceuticals. The annual doses to those transporting nuclear fuel is generally low.

702. An evaluation of the occupational doses due to transport was conducted in Canada [E2]. It covered the period 1997–2002 and included 17 companies at 25 sites: a courier company, eight trucking companies, a provincial highway department whose workers transported and used moisture gauges containing radioactive material, a manufacturer, a hospital and a university with shipping/receiving workers, companies involved in internal transport, air cargo terminals, a railway and a port. Overall, nearly 90% of the annual doses in the current study were below 1 mSv. The study participants likely to receive higher doses were the employees of courier companies who physically carried radioactive sources and the drivers/helpers/sorters of radioisotopes for medical use. The histograms in figure LXV show the fractions of annual doses in three dose ranges: <1 mSv, 1–5 mSv and >5 mSv.

703. An important factor in determining worker doses appears to be the size and weight of the package. Small, light packages, such as those handled by couriers, are usually touched, handled and carried close to the body. Intermediate-sized packages, such as those handled by air cargo handlers, are usually moved by handcart, conveyor belt or truck. Large packages, such as those handled in a port or railway yard, or by some truckers, are usually handled only by remote-controlled equipment. Thus doses are inversely related to package size and weight.

704. A survey of the radiological impact of the normal transport of radioactive material by air in the United Kingdom has shown that the highest doses are to handlers carrying radiopharmaceuticals, including ^{131}I and ^{201}Tl, and technetium generators. The average annual effective doses were given as 1–2 mSv and the maximum annual dose was 3.75 mSv. The annual collective dose for the entire handling workforce in the United Kingdom was about 0.1 man Sv. The doses received by the aircrew were very low. The average annual effective doses for aircrew in short- and long-haul passenger flights were 0.003 mSv and 0.064 mSv, respectively (the respective collective doses are 0.13 man Sv and 3.8 man Sv). The average annual effective doses for flight crew of short-haul passenger and cargo flights are 0.0003 mSv and 0.001 mSv, respectively (the respective collective doses are 0.0025 man Sv and 0.024 man Sv). The average annual doses for flight crew in long-haul passenger and cargo flights are 0.007 mSv and 0.036 mSv, respectively (the respective collective doses are 0.13 man Sv and 0.56 man Sv) [W3].

705. A recent survey of occupational exposure related to transport in the United Kingdom of material containing NORM has shown that the maximum annual effective dose to a transport worker would be less than 0.2 mSv [H30].

(e) Other occupational groups

706. The “other occupational groups” category was included in the UNSCEAR Global Survey of Occupational Radiation Exposures to ensure that no sizeable group of exposed persons was overlooked. The data cover disparate groups that often cut across the other categories. This category was incorporated into the UNSCEAR 2000 Report. The data reported by countries are given in the third part of table A-30. As China (Taiwan) has reported data for all three periods recorded and represents about 20% of the reported number of monitored workers, it was selected as an example to evaluate the trend in occupational exposure. There has been a considerable increase in the number of monitored workers, from 1,990 in 1990–1994 to 3,570 in 2000–2002. The collective effective

dose decreased from 1.02 man Sv in 1990–1994 to 0.17 man Sv in 2000–2002. The average effective dose decreased drastically over three of the periods, from 0.51 mSv in 1990–1994 to 0.05 mSv in 2000–2002. The percentages of measurably monitored workers decreased from 34% in 1990–1994 to 6% in 2000–2002. The decreasing collective dose is correlated with the decreasing effective dose.

707. The use of X-rays for security purposes has been reported by two countries in the UNSCEAR survey. Detailed data of occupational exposure for border policeman and customs personnel have shown that the effective doses range from 0.3 mSv to 2 mSv.

708. For the great majority of the reported data, the average effective dose is low over the periods: it decreased from 1.03 mSv in 1990–1994 to 0.17 mSv in 2000–2002. The dose distribution has shown that, for the last period, 4% of the 21,580 workers received doses higher than 1 mSv; there are no recorded doses higher than 5 mSv.

709. Following the trends from the six periods, the predicted level of occupational exposure for other occupational groups for 2007 would show an increase of about 10% in the number of workers, a decrease of about 20% in the average collective effective dose and a decrease of 30% in the average effective dose.

(f) Summary

710. Table A-30 shows the national data from all other categories of workers not included in the categories of natural radiation exposures, nuclear fuel cycle, and medical and industrial uses of radiation. Data that should rightfully be attributed to the miscellaneous uses of radiation include exposures arising in tertiary educational establishments (universities, polytechnics and research institutes with an important educational role), veterinary medicine and all other uses of radiation involving occupational exposures. Exposures resulting 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.

711. There is a wide variation in the effective dose and percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, and the protective measures implemented by each country.

712. For educational establishments there is a trend of increasing numbers of workers, increasing collective effective dose and decreasing average effective dose. Educational establishments represent about 61% of the total number of monitored workers in the “miscellaneous” class. The average collective dose represents about 45% of the total collective dose for all categories classified as miscellaneous. Following the trends from the six periods, the predicted level of occupational exposure for educational establishments for 2007 would show an increase of about 15% and 10% in the number of workers and the average collective effective dose, respectively, but a decrease of about 15% in the average effective dose.

713. For veterinary medicine there is a trend of increasing numbers of workers, no change in the collective effective dose and a decreasing average effective dose. Veterinary medicine represents about 17% of the total number of monitored workers in the “miscellaneous” class. The average collective dose represents about 21% of the total collective dose for all categories classified as miscellaneous. Following the trends from the six periods, the predicted level of occupational exposure for veterinary medicine for 2007 would show an increase of about 10% in the number of workers and in the average collective effective dose, but no change in the average effective dose.

714. For all other categories of workers there is a trend of increasing numbers of workers and decreasing collective effective dose and average effective dose. These other categories represent about 22% of the total number of monitored workers in the “miscellaneous” class. The average collective dose represents about 34% of the total collective dose for all categories classified as miscellaneous. Following the trends from the six periods, the predicted level of occupational exposure for “other occupational groups” for 2007 would show an increase of about 10% in the number of workers and a decrease of about 20% and 30% in the average collective effective and the average effective dose, respectively.

D. Man-made sources for military purposes

715. Radiation exposures of workers in military 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. This approach is no longer continued here, since the countries have not reported the data separately. It is recognized that there may be a degree of overlap between the categories of nuclear facilities and also that the limited number of countries responding to the UNSCEAR Global Survey of Occupational Radiation Exposures constrains the conclusions that can be drawn. National data on occupational exposure resulting from all military activities are presented in table A-31. Data from the United States and the United Kingdom dominate the reported data on occupational exposure for this practice.

716. In the United States, the USDOE is responsible for stewardship of the nuclear weapons stockpile and the associated facilities, for restoring the environment at related sites

and for energy research [U23]. The facilities covered included accelerators, fuel/uranium enrichment, fuel fabrication, fuel processing, maintenance and support, reactor operation, research, waste management, weapons fabrication and testing. Exposures may arise via 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 by gamma rays and, to a lesser extent, neutrons. External irradiation tends to be the dominant source of exposure for those involved in the production, testing and subsequent handling of nuclear weapons.

717. The USDOE notes [U23] that the number of monitored workers may not be indicative of the size of the exposed workforce, because some establishments provide dosimetry to individuals for reasons other than radiation protection, e.g. 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 effective dose decreased from 1.1 mSv in the first period to 0.1 mSv in the last two periods. It appears to have decreased by a factor of 3 between the periods 1985–1989 and 1990–1994 and by a factor of 1.5 between the periods 1990–1994 and 1995–1999. The annual collective dose at USDOE facilities has experienced a dramatic fall since the first period (1975–1979), from 101 to 13 man Sv. The change in operational status of USDOE facilities has had the largest impact on radiation exposure over the years owing to the shift in mission from weapons production to clean-up activities and the shut down of certain facilities. The USDOE weapons production sites have continued to contribute the majority of the collective dose over these periods.

718. In the United Kingdom, the Atomic Weapons Establishment is the organization whose stewardship is comparable to that of the USDOE. The number of monitored workers in the United Kingdom has stayed roughly constant, at around 12,000. The average annual collective effective dose decreased by a factor of 10 over the first five periods (1975–1979 to 1995–1999), from 36 to 3.6 man Sv, and remained constant between the last two periods. A similar pattern is seen with the average annual effective dose incurred by monitored workers, which over the six periods fell from 3.0 to 0.24 mSv.

719. The UNSCEAR 1993 Report [U6] reviewed the potential for extrapolation on the basis of 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 [U6] proposed adopting a very simple approach for estimating worldwide exposures from this source, namely that the worldwide collective dose from military activities is greater by a factor of 3 than the sum of the collective dose in the United Kingdom and the United States. Four assumptions underlay the choice of this factor. First, the levels of military 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 to those in the United Kingdom. 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. On the basis of these assumptions, the estimated worldwide number of monitored workers has been roughly constant, at between 300,000 and 400,000 workers. The collective effective dose from military activities would have been about 400 man Sv in 1975–1979, falling to about 250 man Sv in 1985–1989, 100 man Sv in 1990–1994, 58 man Sv in 1995–1999 and 52 man Sv in 2000–2002 (figure LXVI). Given the coarseness of the underlying assumptions, it is not 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 50–150 man Sv. The average effective dose decreased by a factor of 10, from 1.3 mSv in 1975–1979 to 0.14 mSv in 2000–2002. This estimate is inevitably associated with much uncertainty, which can only be reduced by relevant data from other countries involved in weapons production.

720. The above data need to be qualified with regard to their completeness, in particular concerning whether they include all significant occupational exposures associated with military 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 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 with respect to the correct 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 the commercial nuclear fuel cycle).

721. The data presented above for all military activities include occupational exposures for three countries that have developed and deployed nuclear weapons or that have operated nuclear ships, namely France, the United Kingdom and the United States. Any estimate of worldwide occupational exposures from military activities can therefore be made only by extrapolating from the available data. The result will inevitably be only very approximate.

722. The contributions of each category to overall levels of exposure and trends with time are shown in figure LXVII. The worldwide average annual collective effective doses to workers resulting from nuclear fuel cycle operations in the periods 1995–1999 and 2000–2002 are estimated to be about

1,000 and 800 man Sv, respectively. The contribution of practices involving medical uses is estimated to be about 3,540 man Sv for the two periods, which corresponds to about 75% of the total collective dose resulting from all the practices involving the use of man-made sources of radiation (4,960 and 4,730 man Sv for the last two periods). The collective effective dose resulting from occupational exposures to natural sources (at levels in excess of the average levels of natural background radiation) is estimated to be about 37,260 man Sv. The largest component of this, 30,360 man Sv, is associated with mining: 16,560 man Sv due to coal mining and 13,800 man Sv due to other mining operations (excluding uranium mining, which is accounted for in the nuclear fuel cycle). The mineral processing industries were not distinguished from mining operations, since the available data in the literature rarely distinguish the exposure due to mining operations from that due to mineral processing. The new category called "workplaces other than mines" contributes 6,000 man Sv, and the cosmic ray exposure of aircrew contributes 900 man Sv. However, the estimated collective dose due to natural sources of radiation is associated with much greater uncertainty than is the estimated dose due to man-made sources of radiation. The trends are illustrated in figure LXVIII. Trends in exposure due to man-made sources are illustrated in figure LXIX for each of the main occupational categories considered in this annex. For exposure to natural sources of radiation, the evaluation of the level of occupational exposure was first introduced in the period 1990–1994. With respect to earlier periods, the few data that do exist suggest that exposures during mining operations and mineral processing were greater than those estimated here, and possibly much greater, owing to the fact that somewhat less attention was given in the past to the control and reduction of exposures during underground mining.

1. Other exposed workers

723. There is one other group of exposed workers not considered elsewhere, namely those working in diamond mines, where X-ray screening for diamond theft is conducted under certain conditions in some countries. The security measures are implemented to reduce diamond theft and are explicitly authorized through national regulations and cover a large spectrum from access control to the use of special equipment to prevent the employees having direct contact with the diamonds. The radiation dose is due to X-ray screening of workers to detect if they have swallowed or hidden diamonds in their bodies [I6]. There is no reliable estimate of the total number of workers involved in these diamond mines, of how often they are exposed and of the received dose.

E. Summary on occupational exposure

724. Occupational radiation exposures have been evaluated for six broad categories of work: natural sources of radiation, the nuclear fuel cycle, medical uses of radiation, industrial uses of radiation, military activities and miscellaneous uses (which comprise education, veterinary medicine and all other uses involving occupational exposure). In the previous UNSCEAR reports, the worldwide level of exposure was extrapolated on the basis of the reported data applying a different methodology for the practices in the nuclear fuel cycle and for the other practices, such as those in medical, industrial and miscellaneous uses. Inevitably, the data provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures were insufficient for estimating worldwide levels of dose. Procedures were therefore developed by the Committee to derive estimates of 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. For the occupational groups involved in practices other than those in the nuclear fuel cycle, the approach used in the UNSCEAR 2000 Report to derive estimates of worldwide doses is no longer used here. For the last two periods, 1995–1999 and 2000–2002, the worldwide level of exposure was derived on the basis of the trends for the countries that provided data. The number of workers exposed to radiation in the medical field is estimated on the basis of the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. 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. Hence the degree of extrapolation from reported to worldwide doses is less, and this extrapolation can be carried out more reliably than for other occupational categories. Moreover, worldwide statistics are generally available on the 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.

725. It is difficult to compare the doses among the countries, since there are discrepancies in doses related to the same practice. These can be due to differences in the type of dose that is recorded in the databases, for instance in how the doses below the recording level are recorded, and differences in the criteria for including workers in the individual monitoring programme. Some countries include in their individual monitoring programme workers not who do not work in restricted areas, resulting in an increase in the workforce and a decrease in the average effective dose. Also, some countries record only doses from external exposure, while others record doses from both internal and external exposure. The application of different ICRP methodologies for intake and dose calculations leads to different dose results. This can be an important source of variation in the doses reported by the countries for the period analysed, when most of the countries changed from ICRP Publication 26 [I43] to ICRP Publication 60 [I47] recommendations.

726. Results for the periods 1995–1999 and 2000–2002 are summarized in table 91 and, in abbreviated form, for the whole period of interest (1975–2002) in table 92. The contribution of each category to overall levels of exposure and the trends with time are illustrated in figure XLVII.

727. The total number of workers exposed to ionizing radiation is estimated as approximately 23 million. About 57% are employed in practices that include exposure to natural sources of radiation (13 million workers) and about 43% in practices that include exposure to man-made sources of radiation (10 million workers). For exposure to natural sources of radiation, the greatest number of workers, about 11.50 million, are in mining operations (60% in coal mining and 40% in other mining operations, excluding uranium mining). The estimated number of workers exposed to radon in workplaces other than mines is about 1.25 million, and the number of aircrew exposed to cosmic radiation is 0.30 million. For exposure to man-made sources of radiation, the greatest contribution comes from medical uses of radiation (75% of the number of workers). About 7.40 million workers are involved in medical uses of radiation, 0.66 million in practices related to the nuclear fuel cycle, 0.87 million in practices related to industrial uses of radiation and 0.57 million in other occupational groups, while 0.33 million are involved in military activities.

728. The worldwide average annual collective effective dose to workers exposed to radiation is estimated to be around 42,000 man Sv The worldwide average annual collective effective dose to workers exposed to natural sources of radiation (in excess of the average levels of natural background radiation) is estimated to be around 37,260 man Sv, which represents about 93% of the total collective effective dose. The largest component of this, 30,360 man Sv, comes from mining: 16,560 man Sv due to coal mining and 13,800 man Sv to other mining operations (excluding uranium mining, which is dealt with as part of the nuclear fuel cycle). The mineral processing industries were not distinguished from mining operations, since the available data in the literature rarely distinguish the exposure due to mining operations from that due to mineral processing. The new category called “workplaces other than mines”, which includes industries (food industries, breweries, laundries, etc.), waterworks, shops, public buildings and offices, schools, subways, spas, caves and closed mines open to visitors, underground restaurants and shopping centres, tunnels (construction and maintenance) and sewerage facilities, contributes 6,000 man Sv. The contribution of aircrew exposed to cosmic radiation is 900 man Sv. However, the estimated collective dose due to natural sources of radiation is associated with much greater uncertainty than that due to man-made sources of radiation. The trends are illustrated in figure LXVIII. The worldwide average annual collective effective dose to workers exposed to man-made sources of radiation is 4,730 man Sv. The average annual collective effective dose to workers in the nuclear fuel cycle for the period 2000–2002 is estimated to be about 800 man Sv. The contribution of the practices related to medical uses is estimated to be 3,540 man Sv, and of practices related to industrial uses and miscellaneous uses about 400 man Sv. Medical uses of radiation contribute about 75% of the collective effective dose due to exposure to man-made sources of radiation.

729. The average annual effective dose to monitored workers varies widely from occupation to occupation and also from country to country for the same occupation. On the basis of the reported data, the average annual effective dose to monitored workers in industry is less than 1 mSv. In particular countries, however, the average annual dose for some of these occupations is several millisieverts or even, exceptionally, in excess of 10 mSv. The average annual effective doses to workers in the nuclear fuel cycle are in most cases higher than the doses to those in other occupations. For the fuel cycle overall, the average annual effective dose is about 1.4 and 1.0 mSv for the last two periods (tables 72 and 92). For the mining of uranium, the average annual effective dose to monitored workers in countries reporting data fell from 3.9 mSv in 1995–1999 to about 1.9 mSv in 2000–2002. For uranium milling operations, the average annual effective dose fell from 1.6 mSv in 1995–1999 to about 1.1 mSv in 2000–2002. For fuel fabrication, the average annual effective dose is about 1.6 mSv. For reactor operation, the average annual effective dose is 1.5 mSv and 1.0 mSv for the last two periods. However, there are very wide variations around these average values. The doses for decommissioning are around 2 mSv. The individual doses for fuel reprocessing are about 0.9 mSv, whereas those for fuel enrichment are much lower, less than 0.1 mSv.

730. *Trends in exposure over the period 1975–2002*. Trends in exposure resulting from man-made sources are illustrated in figure LXIX for each of the main occupational categories considered in this annex. For exposure to natural sources of radiation, the evaluation of the level of exposure was first introduced in the period 1990–1994. With respect to earlier periods, the few data that do exist suggest that exposures during mining operations and mineral processing were greater than those estimated here, and possibly much greater, owing to the fact that somewhat less attention was given in the past to the control and reduction of exposures during underground mining.

731. The worldwide average annual number of workers involved with man-made uses of radiation is estimated to have increased from about 2.8 million to about 10 million between the first and sixth periods (table 92). The greatest increase (from about 1.3 million to about 7.4 million) was in the number of monitored workers in medicine, which represents about 75% of the workforce. The number of monitored workers for the nuclear fuel cycle also increased significantly in the first three periods, from about 0.6 million in the first period to about 0.9 million in the third period, but it dropped to 0.8 million for 1990–1994 and to about 0.7 million for 1995–2002. The main reason for this significant decrease is the decline in the number of workers in mining operations.

732. The annual collective effective dose averaged over the five years for each of the first three periods (1975–1989) for all operations in the nuclear fuel cycle varied little around the average value of 2,500 man Sv, despite a factor of 3–4 increase in electrical energy generated by nuclear means. The electrical energy generated has continued to

increase, but the average annual collective effective dose fell by a factor of about 2, to 1,400 man Sv, in 1990–1994, and dropped to 1,000 man Sv and 800 man Sv in the last two periods. A significant part of this decrease 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, 85 man Sv in 1995–1999 and 22 man Sv in 2000–2002. These last figures may be underestimated owing to limited data, besides which some reported data are related to the decommissioning phase, so they 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, a more general move to open-pit mining and the introduction of modern techniques, support the view that a substantial reduction has taken place. In other parts of the nuclear fuel cycle the situation is more varied. In reprocessing, for example, the downward trend in earlier periods—53, 46 and 36 man Sv—has been reversed, with an increase to about 68 man Sv for 2000–2002, associated with an increase in the number of workers. However, apart from mining, the other important element within the nuclear fuel cycle is reactor operation, in which the average annual collective effective dose, after increasing from 600 to 1,100 man Sv over the first three periods, dropped to 900 man Sv for 1990–1994, to 800 man Sv for 1995–1999 and to 620 man Sv for 2000–2002.

733. The average annual effective dose to monitored workers in the nuclear fuel cycle has been consistently reduced over the whole period, from 4.1 mSv to 1.0 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 values for the three latest periods were reported, other indicators at least suggest that the high level of exposure was maintained.

734. The number of monitored workers increased by a factor of 6 over the six periods, from 1.3 million to 7.4 million. The largest increase, from 2.3 million to 7.4 million, was observed in the last two periods (1995–2002), because in this case the estimate was based on more complete information from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. The worldwide average annual collective effective dose due to all medical uses of radiation, about 1,000 man Sv, changed little over the first three five-year periods. It then dropped significantly, to 760 man Sv, in 1990–1994, but increased to 3,540 man Sv over the last two periods. A clear downward trend is evident in the worldwide average effective dose to monitored workers, which decreased from about 0.8 mSv in the first five-year period to about 0.3 mSv in 1990–1994, then increased in the last two periods, reaching 0.5 mSv in 1990–2002. However, there was considerable variation between countries. For diagnostic radiology, the average effective dose remained constant over the last two periods. This may reflect the influence of the higher doses due to interventional procedures. However, the number of workers increased by a factor of 7, from about 1 million to 6.7 million, between 1990–1994 and 1995–2002. Consequently the collective effective dose has increased in the same proportion as the number of workers.

735. The worldwide average annual collective effective dose due to all industrial uses of radiation was fairly uniform over the period 1975–1984 at about 900 man Sv. It decreased, however, by a factor of almost 2 in the second half of the 1980s (to 510 man Sv) and then fell further, to about 360 man Sv in 1990–1994, and to about 300 man Sv in the last two periods. In general, there was a declining trend in collective dose for the last two periods. However, there was a trend of increasing collective dose for industrial radiography. The same trend is reflected in estimates of individual dose: the average annual effective dose to monitored workers decreased from about 1.6 mSv in 1975–1979 to 1.4 mSv in 1980–1984, 0.9 mSv in 1985–1989, 0.5 mSv in 1990–1994 and 0.3 mSv in 2000–2002.

736. It should be noted that in UNSCEAR reports prior to 1990–1994, the category “industrial uses” included a component reflecting “educational uses”, which tended to distort the data. Since then, educational uses have been dealt with in a separate category, and the industrial data for earlier years have been adjusted to remove the educational component. For military activities, the average individual and collective doses both fell by a factor of about 10 over the whole period, from 1.3 mSv to 0.1 mSv and from 420 man Sv to about 50 man Sv, respectively.

737. 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 Global Survey of Occupational Radiation Exposures and the UNSCEAR Global Survey of Medical Radiation Usage and Exposures and have led to improved estimates and understanding of occupational exposures. However, the Committee considers that further guidance on these matters would help improve the quality of its assessments.

738. The Committee’s current estimate of the worldwide collective effective dose due to occupational exposure from man-made sources is 4,430 man Sv (about 800 man Sv to workers in the nuclear fuel cycle, about 3,540 man Sv to workers in medical uses and about 400 man Sv to workers in industrial uses, military activities and miscellaneous activities). This estimate is about the same as that made by the Committee for the late 1970s. This is because, for the latest period, the evaluation of occupational exposure in the medical field is more reliable, and it contributes about 75% of the collective dose. The figure for occupational exposure from man-made sources has changed greatly since 1970, when occupational exposure was dominated by the practices in the nuclear fuel cycle. Except for medical uses, all other practices have shown a reduction in the level of exposure. A significant part of the reduction comes from the nuclear fuel cycle, particularly from uranium mining. However, reductions are seen in all the main

categories: industrial uses, medical uses, military activities and miscellaneous uses. This trend is also reflected in the worldwide average annual effective dose due to occupational exposure, which has fallen from about 1.7 mSv to 0.5 mSv (table 92).

739. No attempt has been made to deduce any trends in the estimates of dose for occupational exposure to natural sources of radiation, because the supporting data are somewhat limited. The UNSCEAR 1988 Report [U7] made a crude estimate of about 20,000 man Sv for this source, which was subsequently revised downward to 8,600 man Sv in the UNSCEAR 1993 Report [U6]. The UNSCEAR 2000 Report [U3] estimated a value of 11,700 man Sv, of which 6,000 man Sv was due to elevated levels of radon and its progeny in workplaces other than mines, 5,700 man Sv to extraction and processing activities, and 800 man Sv to the exposure of aircrew to cosmic radiation. In the current report, the estimate for the collective dose has risen to 37,260 man Sv, the largest contribution coming from mining operations—16,560 man Sv from coal mining and 13,800 man Sv from other mining. About 6,000 man Sv is due to exposure to radon and its progeny in workplaces other than mines, and 900 man Sv is due to the exposure of aircrew to cosmic radiation. The estimate is still considered to be crude, although the data on occupational exposure in Chinese coal mines have reduced some of the uncertainty in this estimate. The main contributor to the average collective dose is coal mining. On the basis of the data presented in the literature, the level of exposure may be declining, since the average effective dose decreased by a factor of 2 for workers in the Chinese coal mines [T4]. According to the literature, the level of exposure has decreased in nine European countries, while the average collective dose and average effective dose decreased by a factor of almost 2 from 1996 to 2000 [F15].

740. The doses for each practice for the year 2007 were projected on the basis of the trends for all countries. In general, the trend is for an increasing number of workers, and decreasing collective doses and effective doses for all the practices in the categories of medical and industrial uses of radiation, and also for the category of miscellaneous uses.

CONCLUSIONS ON PUBLIC AND WORKER EXPOSURE

741. Exposure to natural sources of radiation is an unavoidable fact of the human condition. The estimates of the global average per caput values of exposure to natural sources of radiation are essentially the same as in the UNSCEAR 2000 Report. The estimated value of worldwide average annual exposure to natural radiation sources remains at 2.4 mSv. The normal range of exposures to the various components is presented in table 12. The dose distribution worldwide is expected to follow approximately a log-normal distribution, and most annual exposures would be expected to fall in the range 1–13 mSv.

742. The values for occupational exposure for the periods 1995–1999 and 2000–2002 have changed greatly compared with those in the UNSCEAR 2000 Report. The collective effective dose resulting from exposures to natural sources (in excess of the average levels of natural background) is estimated to be about 37,260 man Sv, about three times higher than the value estimated in the UNSCEAR 2000 Report [U3]. The largest component of this, 30,360 man Sv, comes from mining (16,560 man Sv due to coal mining and 13,800 man Sv due to other mining operations, excluding uranium mining); 6,000 man Sv is due to “workplaces other than mines” and 900 man Sv is due to the exposure of aircrew to cosmic radiation. The large difference with respect to the UNSCEAR 2000 Report comes from the level of exposure in coal mines. For the current period, the estimate is based on an assessment of exposure in Chinese mines, which represents a very large number of workers. No matter how the estimates are made, the collective dose due to natural sources of radiation is associated with much greater uncertainty than that due to man-made sources of radiation. The trends are presented in table 92.

743. Residues due to conventional mining operations also give rise to very large quantities of material with enhanced levels of naturally occurring radionuclides; these represent a challenge regarding both the disposal of the residues and site restoration. The large diversity of ores containing low levels of nuclides from the uranium and thorium families, which may be concentrated in products, by-products and wastes, complicates the problem, and the detailed picture of worldwide exposure is far from complete. Although doses to the public are usually low, of the order of a few microsieverts or less, some exposed groups can receive doses in the millisievert range, which may deserve attention.

744. For all fuel cycle operations (mining and milling, reactor operation and fuel reprocessing), the local and regional exposures are estimated to be 0.72 man Sv/(GW a). For the present world nuclear energy generation of 278 GW a, the collective dose per year of practice is of the order of 200 man Sv. The collective doses due to globally dispersed radionuclides are delivered over very long periods; if the practice of nuclear power production is continued for 100 years at the present capacity, the maximum annual per caput effective dose to the global population would be less than 0.2 µSv. This dose rate is low compared with that due to natural background radiation.

745. The current estimate for the total collective dose to workers in practices using man-made sources of radiation has changed the figure of occupational exposure. The collective effective dose has in the past been dominated by practices in the nuclear fuel cycle, but the current estimate has shown that occupational exposure in the medical field has become dominant. The collective effective dose in practices

using man-made sources of radiation may be around 4,730 man Sv (about 800 man Sv to workers in the nuclear fuel cycle, about 3,540 man Sv to workers in medical uses, and about 400 man Sv to workers in industrial uses, military activities and miscellaneous uses). These figures have increased compared with the estimates in the UNSCEAR 2000 Report [U3]; the most important decrease was due to the nuclear fuel cycle. The trends are presented in table 92 and figure LXVII.

746. The main contribution to the global collective dose to the public due to man-made sources comes from the testing of nuclear weapons in the atmosphere in the period between 1945 and 1980. The estimated global average annual per caput effective dose reached a peak of 110 μSv in 1963 and has since decreased to about 5 μSv (mainly due to residual levels of ^{14}C, ^{90}Sr and ^{137}Cs in the environment). The average annual doses are higher than the global average by 10% in the northern hemisphere (where most of the testing took place) and are lower in the southern hemisphere.

747. In addition to areas related to atomic bomb production and testing, military uses of radiation have also left a legacy of numerous small contaminated sites across the planet. Efforts to decontaminate these sites and return them to public use have been a focus of attention in many countries. Exposures and collective doses are site-specific; once the areas are defined, exposures can be constrained and clean-up procedures implemented. In general, site release criteria consider annual individual doses for a hypothetical critical group of people in the range 0.3–1.0 mSv. Average local and regional annual individual doses will be at least one order of magnitude lower, and the contribution to the worldwide population doses will most probably be negligible.

TABLES

Tables available as MS Excel workbooks on the attached CD-ROM

Public.xls

Workers.xls

Table 1. Dose conversion factors and dose conversion coefficients for natural radionuclides [U3]

Radionuclide	*Dose conversion factor[a], DCF_{soil} ((nGy/h)/(Bq/kg))*	
^{40}K	0.041 7	
^{238}U series	0.462	
^{232}Th series	0.604	
Radionuclide	*Dose conversion coefficient[b] (Sv/Bq)*	
	Inhalation, $e_{inh}(50)$	*Ingestion, $e_{ing}(50)$*
^{238}U	2.9×10^{-6}	4.5×10^{-8}
^{234}U	3.5×10^{-6}	4.9×10^{-8}
^{230}Th	1.4×10^{-5}	2.1×10^{-7}
^{226}Ra	3.5×10^{-6}	2.8×10^{-7}
^{210}Pb	1.1×10^{-6}	6.9×10^{-7}
^{210}Po	3.3×10^{-6}	1.2×10^{-6}
^{232}Th	2.5×10^{-5}	2.3×10^{-7}
^{228}Ra	2.6×10^{-6}	6.9×10^{-7}
^{228}Th	4.0×10^{-5}	7.2×10^{-8}
^{235}U	3.1×10^{-6}	4.7×10^{-8}

[a] External dose rates due to radionuclides in soil.

[b] Effective dose per unit intake due to internal exposure for adults.

Table 2. Collective effective dose per unit release of radionuclides from nuclear reactors [U3]

Type of release	*Radionuclide*	*Reactor type[a]*	*Pathway*	*Collective dose per unit release (man Sv/PBq)*
Airborne	Noble gases	PWR, LWGR, FBR, HWR	Immersion	0.11
		BWR	Immersion	0.43
		GCR	Immersion	0.9
	^{3}H	All	Ingestion	2.1
	^{14}C	All	Ingestion	270
	^{131}I	All	External	4.5
			Ingestion	250
			Inhalation	49
	Particulate	All	External	1 080
			Ingestion	830
			Inhalation	33
Liquid	^{3}H	All	Ingestion/ inhalation	0.65
	Other	All	Ingestion	330

[a] PWR: pressurized water reactor; LWGR: light-water-cooled, graphite-moderated reactor; FBR: fast breeder reactor; HWR: heavy-water-cooled and -moderated reactor; BWR: boiling water reactor; GCR: gas-cooled, graphite moderated reactor.

Table 3. Collective effective dose per unit release of radionuclides from fuel reprocessing plants [U3]

Type of release	*Radionuclide*	*Collective dose per unit release (man Sv/TBq)*
Airborne	^{3}H	0.0021
	^{14}C	0.27
	^{85}Kr	0.000007 4
	^{129}I	44
	^{131}I	0.3
	^{137}Cs	7.4
Liquid	^{3}H	0.000001 4
	^{14}C	1
	^{90}Sr	0.0047
	^{106}Ru	0.0033
	^{129}I	0.099
	^{137}Cs	0.098

Table 4. Population distribution of cosmic ray dose rates outdoors at sea level [U3]

Latitude (degrees)	*Population in latitude band (%)*		*Effective dose rate (nSv/h)*	
	Northern hemisphere	*Southern hemisphere*	*Directly ionizing component*	*Neutron component*
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
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
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			30.9	5.5

Table 5. Population-weighted average annual effective doses (mSv) due to cosmic radiation [U3]

Conditions	*Directly ionizing component*			*Neutron component*			*Total*
	Northern hemisphere	*Southern hemisphere*	*World*	*Northern hemisphere*	*Southern hemisphere*	*World*	*World*
Outdoors, at sea level	0.27	0.27	0.27	0.05	0.04	0.05	0.32
Outdoors, adjusted for altitude	0.34	0.33	0.34	0.12	0.09	0.12	0.46
Adjusted for altitude, shielding and occupancy	0.29	0.28	0.28	0.10	0.07	0.10	0.38

Table 6. Absorbed dose rates in air (nGy/h)

Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Population* *(10^6)* [C17]	*Outdoors*						*Indoors*					
		Cosmic radiation		*Terrestrial radiation*		*Total*		*Cosmic radiation*		*Terrestrial radiation*		*Total*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
Africa													
Libyan Arab Jamahiriya	5.9	28	25–31	23	18–24	51	48–54						
Mauritius	1.24					98	80–126					105	80–126
Tanzania (United Rep. of) [B6]	37.4					104	98–121						
North America													
Canada	33.1			24	11–44	54	31–75						
Mexico	107					88.3	23–184					105	37–217
Central America													
Costa Rica [M25, M30]	5.5	36	29.3–80.2	29.9	5.6–66.6	65.9	35–147					151	85–191
Cuba [T6, T7]	11.4	34	32–67	24	4–162	55	38–196	27	26–54	30	10–76	44	37–103
East Asia													
Azerbaijan	8	37	30–45	102	45–160	140	75–205	21	16–26	123	87–160	144	103–186
Bangladesh [A4, A5, A6, H24, U40]	147			120	44–245					156	57–319		
China [C11, Z4]	1 313			69.9	12.7–1 300	81.5	11.6–523					124.1	1.12–174.1
—Taiwan [L11, L12]	23	27	25.7–58	52	24–68	79		24	23–52	101	66–189	125	
India [N2]	1 095			41.5									
Indonesia	245	27.5	21.1–61.9	40	23.9–40.1	67.5	45–102						
Japan [A2, F4]	124.76	35.3	30.1–59.4									78.3	52.4–106.5
Kazakhstan	15.2				60–500						150–280		
Korea, Rep. of [K16]	48.8					79	18–200						
Pakistan [B50]	166			59	1.0–97								
Philippines	75.9	21		24		45							

Region/country	*Population (10⁶)* [C17]	*Outdoors*						*Indoors*					
		Cosmic radiation		*Terrestrial radiation*		*Total*		*Cosmic radiation*		*Terrestrial radiation*		*Total*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
West Asia													
Armenia	2.98												
Islamic Republic of Iran	68.7	40.5	33.0–57.6	71	36–130	111.5	69–187.6	16.8	13.2–31.3	115	70–165	131.8	83.2–196.3
Kuwait	2.4	35		52		87		29		90		119	
Turkey [K2]	70.4	15.7	8.4–35.6	48.8	15–80	65	32–94						
North Europe													
Denmark [A1, N14, S36, U42]	5.5	31		35	25–70	66	56–101	31		54	19–259	85	50–290
Finland [A19, A20]	5.2	32		71	45–139	103	77–171	32		73	24–181	105	56–213
Iceland [E4]		31		40	4–83	71		25		23	14–32	48	
Lithuania [L3]	3.45	33	32–35	62	46–82	95	79–115	26	26–28	81	34–224	107	53–250
Sweden[a,b] [M27, M29, S15]	9	33	32–50	64	10–580	97	40–630	36	17–75	98	10–1 250	120	20–1 300
West Europe													
Belgium [G10]	10.4	33[a]	32–36	43	13–80	76	45–120	26	20–36	60	32–180	86	55–200
Germany	82.4	32		57		89				80	20–700		
Ireland [C24, M9, M15, M16]	3.84	33		32	2–110	65	35–143	26		62	10–140	94	43–168
Italy [B29, C4]		38	32–54	74	11–209	112	57–243	31	26–43	105	0–690	136	29–717
Liechtenstein	0.03	38		34.6		72.6							
Luxembourg	0.22	32		49	14–73	81							
Spain [Q1, Q2, Q6, S42, S43]	40.4	34.6	30.8–41.0	50.4	19–88	85	50–129	22.1	19.7–26.2	73.1	40–124	95.2	60–151
Switzerland [L22]	7.5	39	34–68	42	14–118	81	53–155	31	27–54			100	55–215

Region/country	*Population (10^6)* [C17]	*Outdoors*						*Indoors*					
		Cosmic radiation		*Terrestrial radiation*		*Total*		*Cosmic radiation*		*Terrestrial radiation*		*Total*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
East Europe													
Bulgaria	7.4	30	27–42	70	48–96	100	75–140	25	22–35	75	57–93	100	80–130
Czech Republic [M18]	10.2	34	32–62	66	6–245	100	40–285	34[c]		85	42–2 000[d]	119	74–2 000
Poland [B24, B25]	38.15	33.5	31.3–60.8	47.4	18.8–86.0	80.9	51.0–126.2					93.8	54.7–193.8
Romania [B1, B2, C20, C21, C22, I1]	21.3	33	32–38	59	20–125	92	52–163	27	26–30	83	30–170	110	56–200
Slovenia [A18]	2.0	32	30–47	56	4–147					75	40–250		
South Europe													
Albania [I4]	3.6					94	77.2–103						
Croatia	4.5					115	70–140						
Greece [C18, C19, P14, S5]	10.7			31	17–88					36	20–101		
Montenegro	0.63			63	28–150								
Oceania													
New Zealand	4.1	32[a]		44	2–90	76	34–122	32[c]		23	0–77	55	32–109

[a] Ionizing component.

[b] Average values refer to population-weighted mean.

[c] Assumed same as outdoor.

[d] Excluding area in Jachymov contaminated with naturally occurring radioactive material.

Table 7. Distribution of population with respect to the outdoor absorbed dose rate in air due to terrestrial gamma radiation
Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Population (10^6)*	*Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air (nGy/h)*											
		<20	*20–29*	*30–39*	*40–49*	*50–59*	*60–69*	*70–79*	*80–89*	*90–99*	*100–199*	*200–299*	*>300*
Africa													
Libyan Arab Jamahiriya	1.50	1 500											
Central America													
Costa Rica	5.5	605	918.5	605	2 926	412.5		27.5					
Cuba	11.20	6 000	5 000	200	2	<1							
East Asia													
Bangladesh	57.08				1 200	1 510	12 001	4 780	10 970	2 921	16 810	6 890	
China	1 282.35	94 884			232 426	364 745	279 327	122 493	75 404	36 074	75 011	1 984	
Indonesia	213.68	48 203	31 975	35 616	17 301	3 929	2 968	1 431	620	3 096	10 252	832	
Japan [U3]	124.76		9 619	26 463	20 561	23 382	39 546	5 193					
Korea, Rep. of [U3]	44.61	1 760	3 096	9 605	4 097	2 220	1 724	4 421	4 421	2 211	11 053		
Malaysia [U3]	19.64					984	213	1 214	2 498	8 487	6 248		
Philippines	75.90	26 775	27 922	14 535	4 284	1 377	688.5	275.4	45.90				
West Asia													
Azerbaijan	8.00	6 000	1 500	500									
Islamic Republic of Iran	63.76			3 188	1 402.72	16 832.64	12 050.64	24 356.32	2 550.4	318.8	3 060.48		
North Europe													
Denmark [A17]	5.20		250	2 100	2 200	600	50						
Estonia [U3]	1.47	6	5	25	149	314	367	592	9				
Iceland [E4, T3]	0.30			150	150								
Finland [A19, A20, C5]	5.20					922	1 143	2 633	174	328			
Lithuania [G14]	3.45				816	606	1 386	188	455				
Sweden [S15, S45]	8.88	214	396	798	1 135	1 370	1 289	1 094	1 024	840	564	2	0.2

Region/country	Population (10^6)	Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air (nGy/h)											
		<20	20–29	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100–199	200–299	>300
West Europe													
Belgium [G10]	10.22	300	2 200	2 400	2 600	2 500	200	20					
Germany [U3]	81.10	700	8 600	10 000	20 900	28 000	9 600	1 500	800	700	300		
Ireland [C6, M9]	3.84	298	787	1 148	992	251	7	41	0	0	2		
Italy [B29, B31, C4]	57.30	125		50	5 600	28 050	8 100	1 950	250	3 550	6 500	3 125	0
Luxembourg	0.45	31.9	14.3	57.2	250.2	90.2	4.4						
Netherlands [U3]	15.58	3 459	5 484	2 353	2 976	1 262	47						
Switzerland	6.71	60	620	1 100	3 900	570	70	160	70	60	100		
United Kingdom [U3]	54.00	6 000	12 000	30 000	6 000								
East Europe													
Bulgaria	9.41				170	357	4 756	1 130	214	1 472			
Czech Rep. [M7]	10.30	3	89	262	605	1 898	4 342	1 846	829	252	177		
Hungary [U3]	10.14	163	479	836	1 017	1 316	3 488	1 163	765	367	530		17
Poland	38.12	426	3 219	13 097	15 528	4 208	1 193	419	30				
Romania [I1]	21.83		293.1	1 309.1	4 149.2	6 404.2	5 096.3	3 878.6	721.6	562.8	45.1		
Russian Fed. [U3]	148.10	450		460	7 150	22 800	84 470	5 730	17 800	5 330	3 910		
Slovakia [U3]	5.29		22	192	721	1 364	1 292	868	498	243	85		
South Europe													
Albania [U3]	3.50		50	50	100	100	500	2 000	300	200	100	50	50
Greece	10.36			1 160	5 605	1 067	1 250	572	147	225	231	50	50
Montenegro	0.60	31	45	155	117	173			80				
Portugal [U3]	9.43	333	444	1 814	606	1 325	653	313	582	417	2 352	594	
Spain	40.84			1 198	5 644	5 181	10 403	2 871	912	2 424	8 477		

Region/country	*Population (10^6)*	*Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air (nGy/h)*											
		<20	*20–29*	*30–39*	*40–49*	*50–59*	*60–69*	*70–79*	*80–89*	*90–99*	*100–199*	*200–299*	*>300*
							Oceania						
New Zealand	3.80	1 570	1 390	600	200	40	<10						
							Total						
Total		136 641	148 346	193 504	373 330	526 162	488 173	193 160	122 170	66 983	145 808	13 527	117
Fraction of total		0.056 7	0.061 6	0.080 4	0.155 0	0.218 5	0.202 7	0.080 2	0.050 7	0.027 8	0.060 6	0.005 6	0.000 1
Cumulative fraction		0.056 7	0.118 4	0.198 7	0.353 8	0.572 3	0.775 0	0.855 2	0.906 0	0.933 8	0.994 3	0.999 9	1.000 0

Table 8. Reference annual intake of air, food and water [U3]

Intake	*Infants (1 year)*	*Children (10 years)*	*Adults*
Breathing rate (m^3/a)			
Air	1 900	5 600	7 300
Food consumption rate (kg/a)			
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 9. Reference values for concentration of radionuclides of the uranium and thorium series in human tissues (mBq/kg) [U3]

Radionuclide	*Lung*	*Liver*	*Kidney*	*Muscle and other tissues*	*Bone*
^{238}U	20	3	30	5	100
^{230}Th	20	9	5	1	20–70
^{226}Ra	4.1	4.1	4.1	4.1	260
^{210}Pb	200	400	200	100	3 000
^{210}Po	200	600	600	100	2 400
^{232}Th	20	3	3	1	6–24
^{228}Ra	20	3	2	2	100

Table 10. Examples of areas of high natural radiation background
Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Area*	*Reference*	*Soil concentration (Bq/kg)*				*Exposure rate in air (nGy/h)*		*^{222}Rn (Bq/m^{3})*		*^{222}Rn (Bq/L)*
			^{40}K	*^{238}U*	*^{226}Ra*	*^{232}Th*	*Outdoors*	*Indoors*	*Outdoors*	*Indoors*	*Water*
High cosmic radiation											
China	Ganzu[a]	[Z1]					73				
China	Qinghai[a]	[S16, Z1]					95 (65–127)				
China	Sichuan[a]	[Z2]					82				
China	Tibet[a]	[S16, Z1]					121 (80–140)				
United States	Denver, Colorado	[S26]					196				
Uranium areas											
Brazil	Araxá	[V18]					2 800				
Brazil	Caetité	[B27]							69	82	
Brazil	R.G. Norte	[M3, M4]	941		50	69	108 (54–253)			4–140	
Brazil	Phosphate area, PE	[A15, M4]		38–300	29–207						
United States	Reading Prong, New Jersey	[S27]						170			
Uranium and thorium areas (volcanic intrusive)											
Brazil	Pocos de Caldas, MG, urban areas	[S2]					145 (93–244)				
Brazil	Pocos de Caldas, MG, rural areas	[V18]					280 (130–1 500)	200 (130–340)	130 (56–280)	204 (50–1 046)	
Czech Republic	Central Bohemia, Pluton middle area	[M7]	988–1 599	68–220	76–275	74–159	90–170	119	2–25	442 (10–20 870)	
Italy	Lazio	[B29, B32]					175 (120–270)	250 (105–440)		119 (26–1 036)	
Italy	Campania	[B29, B32]					198 (141–243)	310 (115–720)		95 (13–172)	
Italy	Orvieto	[U3]					560				
Italy	Southern Tuscany	[B30]					150–300	190 (40–350)		200 (30–1 240)	
Niue Island	Pacific	[S27]					Max. 1 100				
Romania	Crucea and Grinties	[B38]	486	57		31					

Region/country	Area	Reference	Soil concentration (Bq/kg)				Exposure rate in air (nGy/h)		^{222}Rn (Bq/m^3)		^{222}Rn (Bq/L)
			^{40}K	^{238}U	^{226}Ra	^{232}Th	Outdoors	Indoors	Outdoors	Indoors	Water
Monazite sand coastal areas											
Brazil	Guarapari and Meaipe, ES	[S2]					84 (26–300)[b]				
China	Yangjiang, Quangdong	[S27]					370				
Egypt	Roseta coastal area	[S27]					20–400				
India	Kerala and Madras	[G3, N1]					1 500 (845–5 270)				
Thermal waters											
Austria	Bad Gastein	[S27]									1 480
China	Sichuan, Jiangzha	[X1]					256–9 140		(22–22 000	68 000–340 000	
Hungary	Mount Gellért	[S27]									Up to 7.15
India	Tuwa	[S27]									4–40
Indonesia	West Java	[S27]	48–252		2.4–422	0.5–66	97 (33–224)				45–83
Islamic Republic of Iran	Ramsar	[M32, S27]	300–945		80–50 000	15–47	765 (80–100 000)	1 153 (100–105 000)	65 (0–500)	2 745 (55–31 000)	64 (1–160)
Islamic Republic of Iran	Mahallat	[S26, S27]	364–873		500–7 300	15–41	300–3 800		30 (6–200)	600 (55–1 000)	710 (145–2 730)
Japan	Misasa	[S27]									437
Slovenia	Podcetrtek	[S27]									1–63
Slovenia	Spas	[V13]						60–154		15–279	
Others											
Azerbaijan			800–1 000	100–7 000	500–2 500	100–1 000	877–8 770				
China	Cave dwellings, Ganzu	[S16, Y1]								21–3 660	
China	Cave dwellings, Yanan	[W12]								32–278	
Indonesia	Bangka Island						330 (90–540)			167 (max. 416)	
Indonesia	Karimu Island						310 (200–410)				
Philippines	San Vicente						300 (75–1 558)				
Russian Federation	Yssyk-Kul (Kyrgyzstan)	[Z3]			100–150	10–160	Up to 300			162–352	

Region/country	*Area*	*Reference*	*Soil concentration (Bq/kg)*				*Exposure rate in air (nGy/h)*		*^{222}Rn (Bq/m^3)*		*^{222}Rn (Bq/L)*
			^{40}K	*^{238}U*	*^{226}Ra*	*^{232}Th*	*Outdoors*	*Indoors*	*Outdoors*	*Indoors*	*Water*
Spain	Galicia South, Arribes del Duero, Sierra de Guadarrama, Campo de Arañuelo	[M11, Q6, Q8]	810–1 240		60–250	42–71	136–260	197–377	10–210	150–1 400	
Switzerland	Tessin, Alps, Jura	[S27]					100–200				
United Kingdom	Kerrier district, south-west peninsular	[W1]								<2–17 000	
United Kingdom	South Wales caves	[F16]								max. 3 094	
World average for natural background radiation											
UNSCEAR 2000 Report		[U3]	420	33	32	45	59	84		39	

[a] External exposure not including neutrons.

[b] Kerma rates of up to 5 460 nGy/h can be measured at localized spots [S2].

Table 11. High-background areas: distribution of population with respect to total effective dose

Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Area*	*Distribution of population (10^3) residing in high-background areas with various levels of total effective dose (mSv/a)*										
		3.0–3.49	*3.50–3.99*	*4.0–4.49*	*4.5–4.99*	*5.0–5.99*	*6.0–6.99*	*7.0–7.99*	*8.0–8.99*	*9.0–9.99*	*>10*	*Population (10^3)*
West Asia												
Islamic Republic of Iran [S28]	Ramsar	110	125	120	140	20	10	23	31	20	200	799
East Europe												
Czech Republic [M7]	Central Bohemian Pluton	41	39	32	31	49	36	28	20	15	54	345
	Central Bohemian Pluton	2	3	3	3	6	6	5	5	4	28	65
	Central Moldanubian Pluton	36	29	21	18	25	16	11	7	5	12	180
	Trebic Massif	22	21	18	17	27	20	15	11	8	29	188
	Krkonose-Jizera Pluton	59	44	30	24	31	18	12	7	5	11	241
	Carlsbad Pluton	48	37	25	21	27	17	11	7	4	11	208
West Europe												
Spain	Galicia South, Arribes del Duero, Sierra de Guadarrama, Campo de Arañuelo	40	800				1 000				20	1 860

Table 12. Public exposure to natural radiation

Source of exposure		*Annual effective dose (mSv)*	
		Average	*Typical range*
Cosmic radiation	Directly ionizing and photon component	0.28	
	Neutron component	0.10	
	Cosmogenic radionuclides	0.01	
	Total cosmic and cosmogenic	0.39	0.3–1.0[a]
External terrestrial radiation	Outdoors	0.07	
	Indoors	0.41	
	Total external terrestrial radiation	0.48	0.3–1.0[b]
Inhalation	Uranium and thorium series	0.006	
	Radon (^{222}Rn)	1.15	
	Thoron (^{220}Rn)	0.1	
	Total inhalation exposure	1.26	0.2–10[c]
Ingestion	^{40}K	0.17	
	Uranium and thorium series	0.12	
	Total ingestion exposure	0.29	0.2–1.0[d]
Total		2.4	1.0–13

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

Table 13. Doses to members of the public due to the industrial release of NORM in the United Kingdom [W6]

Industry	*Discharge route*	*Pathway*	*Annual dose (μSv)*	
			Critical group	*General public*
Coal-fired power station	Atmospheric releases via stack	All	1.5	0.1
	Building material made from ash	Radon inhalation	600	
		External	900	
Oil and gas extraction	Authorized discharges to sea, and scales	Ingestion of seafood and external exposure due to fishing gear	<30	
Gas-fired power station	Atmospheric releases via stack	All	0.75	0.032
Steel production	Atmospheric releases via stack	All	<100	<2
	Building material made from slag	Radon inhalation	550	
		External	800	
Zircon sands	Atmospheric releases via stack	Inhalation	<1	<1

Table 14. Worldwide uranium production [O16, O17, O21, W8]

Country	*Annual production (t)*						*Cumulative production (t)*
	1998	*1999*	*2000*	*2001*	*2002*	*2003*	*Total to 2003*
Argentina	7	4	0	0	0	0	2 631
Australia	4 894	5 984	7 579	7 720	6 854	7 573	113 304
Belgium	15[a]	0	0	0	0	0	680[a]
Brazil	0	0	80	56	272	230	1 645
Bulgaria	0	0	0	0	0	0	16 735
Canada	10 922	8 214	10 683	12 522	11 607	10 455	374 548
China	590[b]	700[b]	700[b]	700[b]	730[b]	730[b]	27 689[b,c]
Congo, D.R.	0	0	0	0	0	0	25 600
Czech Republic	610	612	507	456	465	452	108 649[d]
Finland	0	0	0	0	0	0	30
France	452	416	296	184	18[e]	9	75 965
Gabon	725	0	0	0	0	0	25 403
Germany	30	29	28	27[e]	221[e]	150[e]	219 239
Hungary	10	10	10	10	10	4	21 080
India	207[f]	207[f]	207[f]	230[f]	230[f]	230[f]	7 963[f]
Japan	0	0	0	0	0	0	84
Kazakhstan[g]	1 270	1 560	1 870	2 114	2 822	3 327	24 639
Madagascar	0	0	0	0	0	0	785
Mexico	0	0	0	0	0	0	49
Mongolia	0	0	0	0	0	0	535
Namibia	2 780	2 690	2 715	2 239	2 333	2 037	78 794
Niger	3 714	2 907	2 911	2 919	3 080	3 157	91 186
Pakistan	23[f]	23[f]	23[f]	46[f]	38[f]	40[f]	931[f]
Poland	0	0	0	0	0	0	660
Portugal	19	10	14	4	0	0	3 680
Romania	132	89	86	85[e]	90[e]	90[e]	17 989[e]
Russian Federation[g]	2 530	2 610[f]	2 760[f]	3 090[f]	2 850[f]	3 073[f]	32 136
South Africa	965[h]	927[h]	838[h]	878[h]	828[h]	747[h]	157 618[h]
Spain	255	255	255	30[e]	37[e]	0	6 156
Sweden	0	0	0	0	0	0	91
Ukraine[g]	1 000	1 000	1 000	750[f]	800[f]	800[f]	9 900[f,g]
United States	1 810	1 773	1 522[f]	1 015	902	769	356 485
Uzbekistan[g]	1 926	2 159	2 028	1 945	1 859	1 603	23 682
Zambia	0	0	0	0	0	0	102
World total	34 886	32 179	36 112	37 020	36 042	35 492	2 204 656[i]

[a] Produced from imported phosphates.

[b] Estimate for continental China.

[c] Production in China since 1990.

[d] Total production since 1946.

[e] Production resulting from decommissioning.

[f] Provisional data.

[g] Production since 1992.

[h] Uranium is by-product of gold mining.

[i] Includes 377 613 t of uranium produced in the former Soviet Union from 1945 to 1991, and 380 t produced in the former Yugoslavia before 1991.

Table 15. Worldwide installed capacity for fuel cycle installations [I35]

Country	*Conversion to UF_6 (t U/a)*	*Enrichment (10^3 SWU/a)[a]*	*Fuel fabrication (t/a)[b]*	*Reprocessing (t/a)[b]*
Argentina	62[c]	20[c]	150	
Belgium			435	
Brazil	40		280	
Canada	12 500		2 700	
China	1 500	1 000	400	
France	14 350	10 800	1 585	1 700
Germany		1 800	650	
India			594	
Japan		1 050	1 689	120
Korea, Rep. of			800	
Netherlands		2 500		
Pakistan		5	20	
Romania			110	
Russian Federation	30 000	15 000	2 600	400
Spain			400	
Sweden			600	
United Kingdom	6 000	2 300	1 680	2 700
United States	14 000	11 300	3 450	
Total	78 452	45 775	18 143	4 920

[a] SWU: separative work unit. The SWU is a complex unit that is a function of the amount of uranium processed, the degree to which it is enriched and the level of depletion of the remainder. It is indicative of the energy used in enrichment when feed and product quantities are expressed in kilograms.
[b] Tonnes of heavy metal.
[c] Design capacity.

Table 16. Electrical energy generated (GW)

Reactor type	*1998*	*1999*	*2000*	*2001*	*2002*	*Average 1998–2002*
AGR	6.52	6.39	6.14	6.26	0.33	5.13
BWR	64.06	66.86	67.32	69.09	64.77	66.42
FBR	0.28	0.43	0.41	0.44	0.43	0.40
GCR[a]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LWGR	7.29	8.14	8.30	7.87	8.06	7.93
HWR	11.35	12.17	12.56	13.71	13.66	12.69
PWR	154.27	158.19	164.59	167.09	170.91	163.10
WWER	20.46	20.62	22.52	23.58	25.62	22.56
All	264.23	272.80	281.84	288.05	283.79	278.23

[a] n.a. = not available.

Table 17. Historical values for normalized releases of radionuclides from nuclear reactors (TBq/(GW a))

Period	*PWR*[a]	*BWR*	*GCR*[b]	*HWR*	*LWGR*	*FBR*	*Total*[c]
Noble gases							
1970–1974	530	44 000	580	4 800	5 000[d]	150[d]	13 000
1975–1979	430	8 800	3 200	460	5 000[d]	150[d]	3 300
1980–1984	220	2 200	2 300	210	5 500	150[d]	1 200
1985–1989	81	290	2 100	190	2 000	820	330
1990–1994	27	354	2 050	2 100	1 700	380	330
1995–1997	13	180	252	250	460	210	130
1998–2002	11	44	28	80	3 156	36	112
Tritium							
1970–1974	5.4	1.8	9.9	680	26[d]	96[d]	448
1975–1979	7.8	3.4	7.6	540	26[d]	96[d]	38
1980–1984	5.9	3.4	5.4	670	26[d]	96[d]	44
1985–1989	2.7	2.1	8.1	690	26[d]	44	40
1990–1994	2.3	0.94	4.7	650	26[d]	49	36
1995–1997	2.4	0.86	3.9	330	26	49[d]	16
1998–2002	2.1	1.6	3.3	874	26[d]	49[d]	43
Iodine-131							
1970–1974	0.003 3	0.15	0.001 4[d]	0.001 4	0.08[d]	0.003 3[d]	0.047
1975–1979	0.005	0.41	0.001 4[d]	0.003 1	0.08[d]	0.005[d]	0.12
1980–1984	0.001 8	0.093	0.001 4	0.000 2	0.08	0.001 8[d]	0.03
1985–1989	0.000 9	0.001 8	0.001 4	0.000 2	0.014	0.000 9[d]	0.002
1990–1994	0.000 33	0.000 8	0.001 4	0.000 4	0.007	0.000 3[d]	0.000 7
1995–1997	0.000 2	0.000 3	0.000 4	0.000 1	0.007	0.000 2	0.000 4
1998–2002	0.000 3	0.000 6	0.000 07	0.000 1	0.009 9	0.000 2[d]	0.000 6
Carbon-14							
1970–1974	0.22[d]	0.52[d]	0.22[d]	6.3[d]	1.3[d]	0.12[d]	0.71
1975–1979	0.22	0.52	0.22[d]	6.3[d]	1.3[d]	0.12[d]	0.70
1980–1984	0.35	0.33	0.35[d]	6.3	1.3[d]	0.12[d]	0.74
1985–1989	0.12	0.45	0.54	4.8	1.3	0.12[d]	0.53
1990–1994	0.22	0.51	1.4	1.6	1.3[d]	0.12[d]	0.44
1995–1997	—	—	—	—	—	—	—
1998–2002	0.22	0.53	1.3	1.2	1.3[d]	0.12[d]	0.39
Particulates							
1970–1974	0.018	0.04	0.001[d]	0.000 04[d]	0.015[d]	0.000 2[d]	0.019
1975–1979	0.002 2	0.053	0.001	0.000 04	0.015[d]	0.000 2[d]	0.017
1980–1984	0.004 5	0.043	0.001 4	0.000 04	0.016	0.000 2[d]	0.014
1985–1989	0.002	0.009 1	0.000 7	0.000 2	0.012	0.000 2	0.004
1990–1994	0.000 2	0.18	0.000 3	0.000 05	0.014	0.012	0.04
1995–1997	0.000 1	0.35	0.000 2	0.000 05	0.008	0.001	0.085
1998–2002	0.000 03	0.049	0.000 2[d]	0.000 03	0.002 7	0.000 1	0.012

Period	*PWR*[a]	*BWR*	*GCR*[b]	*HWR*	*LWGR*	*FBR*	*Total*[c]
Tritium (liquid)							
1970–1974	11	3.9	9.9	180	11[d]	2.9[d]	19
1975–1979	38	1.4	25	350	11[d]	2.9[d]	42
1980–1984	27	2.1	96	290	11[d]	2.9[d]	38
1985–1989	25	0.78	120	380	11[d]	0.4	41
1990–1994	22	0.94	220	490	11[d]	1.8	48
1995–1997	19	0.87	280	340	11[d]	1.7	38
1998–2002	20	1.8	402	817	0.78	1.7[d]	59
Other (liquid)							
1970–1974	0.2[d]	2	5.5	0.6	0.2[d]	0.2[d]	2.1
1975–1979	0.18	0.29	4.8	0.47	0.18[d]	0.18[d]	0.7
1980–1984	0.13	0.12	4.5	0.026	0.13[d]	0.13[d]	0.38
1985–1989	0.056	0.036	1.2	0.03	0.045[d]	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	0.7	0.044	0.006	0.023	0.04
1998–2002	0.011	0.008	0.7[d]	0.260	0.002	0.023[d]	0.03

[a] Includes all PWRs and WWERs.
[b] Includes GCRs and AGRs.
[c] Weighted by the fraction of energy generated by the reactor types.
[d] Estimated values.

Table 18. Estimated average annual collective doses due to effluents from nuclear power plants for the period 1998–2002

Nuclides	*Quantity*	*PWR*[a]	*BWR*	*GCR*[b]	*HWR*	*LWGR*	*FBR*
Atmospheric releases							
Noble gases	Total release (PBq)	2.0×10^{0}	2.92×10^{0}	148×10^{-1}	1.0×10^{0}	2.5×10^{1}	1.4×10^{-2}
	Collective dose (man Sv)	2.2×10^{-1}	1.25×10^{0}	1.3×10^{-1}	1.1×10^{-1}	2.8×10^{0}	1.6×10^{-3}
Tritium	Total release (PBq)	3.9×10^{-1}	1.1×10^{-1}	1.7×10^{-2}	1.1×10^{1}	2.0×10^{-1}	2.0×10^{-2}
	Collective dose (man Sv)	8.2×10^{-1}	2.2×10^{-1}	3.6×10^{-2}	2.3×10^{1}	4.3×10^{-1}	4.1×10^{-2}
^{131}I	Total release (PBq)	5.6×10^{-5}	2.1×10^{-5}	3.6×10^{-7}	1.3×10^{-7}	7.9×10^{-5}	8.0×10^{-8}
	Collective dose (man Sv)	2.5×10^{-4}	1.8×10^{-4}	1.6×10^{-6}	5.7×10^{-6}	3.5×10^{-4}	3.6×10^{-7}
Particulates	Total release (PBq)	5.6×10^{-6}	3.3×10^{-3}	1.0×10^{-6}	3.8×10^{-7}	2.1×10^{-5}	4.0×10^{-8}
	Collective dose (man Sv)	4.8×10^{-3}	2.8×10^{0}	8.9×10^{-4}	3.3×10^{-4}	1.9×10^{-2}	3.5×10^{-5}
^{14}C	Total release (PBq)	4.1×10^{-2}	3.5×10^{-2}	7.0×10^{-3}	1.5×10^{-2}	1.0×10^{-2}	4.8×10^{-5}
	Collective dose (man Sv)	1.0×10^{1}	9.5×10^{0}	1.8×10^{0}	4.1×10^{0}	2.8×10^{0}	1.3×10^{-2}
Liquid releases							
Tritium	Total release (PBq)	3.7×10^{0}	1.2×10^{-1}	2.1×10^{0}	1.0×10^{1}	6.2×10^{-3}	6.8×10^{-4}
	Collective dose (man Sv)	2.4×10^{0}	7.8×10^{-2}	1.3×10^{0}	6.7×10^{0}	4.0×10^{-2}	4.4×10^{-4}
Others	Total release (PBq)	2.0×10^{-3}	5.3×10^{-4}	3.6×10^{-6}	3.3×10^{-3}	9.2×10^{-6}	9.2×10^{-6}
	Collective dose (man Sv)	6.7×10^{-1}	1.8×10^{-1}	1.2×10^{-3}	1.1×10^{0}	5.2×10^{-3}	3.0×10^{-3}

Summary[c]	
Total collective dose (man Sv)	75
Total normalized collective dose due to airborne effluents (man Sv/(GW a))	0.22
Total normalized collective dose due to liquid effluents (man Sv/(GW a))	0.05
Total normalized collective dose due to releases from nuclear power plants (man Sv/(GW a))	0.27

[a] Includes all PWRs and WWERs.
[b] Includes GCRs and AGRs.
[c] Weighted by the fraction of energy generated by the reactor types.

Table 19. Releases from reactors no longer in commercial operation

Reactor	*Shut down*	*Atmospheric releases in 2002 (GBq)*				*Liquid releases in 2002 (GBq)*	
		Noble gases	*Tritium*	*Iodine-131*	*Particulates*	*Tritium*	*Other nuclides*
BWR							
Big Rock Point-1	1997	0	9.5	0	0.001 6	0.15	0.12
Lacrosse-1	1987	0	1.1	0	0.000 5	3.1	0.60
Humboldt Bay	1976	0	0	0	0	0.15	0.008 5
Millstone-1	1998	0	33	0	0.000 5	0	0
Browns Ferry-1	1985	35 855	1 463	3.4	0.075	0	0
Dresden-1	1978	2 184	1 346	0.047	0.22	1 253	0.34
PWR							
Haddam Neck-1	1996	0	57	0	0.001 7	79	0.67
Maine Yankee-1	1977	0	47	0	0.001 8	7.2	0.097
Rancho Seco-1	1989	0	52	0	0.000 4	427	0.050
San Onofre-1	1992	0	53	0	0.000 07	214	0.42
Three Mile Island-2	1979	0	34	0	0	0.020	0.000 4
Trojan-1	1992	852	278	0	0	3	0.084
Yankee Rowe-1	1991	0	0	0	0	0	0
Zion-1	1998	0	0	0	0.006 6	0	0.000 4
Zion-2	1998	0	0	0	0.006 6	0	0.000 4
Indian Point-1	1974	31 997	16 262	0.020	1.6	19 703	10

Table 20. Collective doses due to fuel reprocessing

Airborne effluents						
Quantity	^{3}H	^{14}C	^{85}Kr	^{129}I	^{131}I	^{137}Cs
Total releases for the five-year period 1998–2002 (TBq)	2 001	44.16	2 160 300	0.14	0	0.003 2
Collective dose conversion factor (man Sv/TBq)	0.002 1	0.27	0.000 007 4	44	0.3	7.4
1998–2002 collective dose (man Sv)	4.20	11.9	16.0	6.17	0	0.024
Collective dose from all nuclides (man Sv)	38.31					
Average annual collective dose (man Sv)	7.66					
Normalized annual collective effective dose (man Sv/(GW a))	0.028					
Liquid effluents						
Quantity	^{3}H	^{14}C	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs
Total release for the five-year period 1998–2002 (TBq)	84 473	105.5	133.6	131.9	12.18	39.44
Collective dose conversion factor (man Sv/TBq)	0.000 001 4	1	0.004 7	0.003 3	0.099	0.098
1998–2002 collective dose (man Sv)	0.118	105.5	0.63	0.44	1.21	3.87
Collective dose from all nuclides (man Sv)	111.8					
Average annual collective dose (man Sv)	22.35					
Normalized annual collective effective dose (man Sv/(GW a))	0.081 4					

Table 21. Spent fuel and arisings of low- and intermediate-level radioactive waste from nuclear power plants

Type	*Country*	*Reference plant*	*Spent fuel*[a]	*Low- and intermediate-level radioactive waste*	
			t/MW(e)	*m^3/MW(e)*	*Bq/MW(e)*
BWR	Spain Switzerland	Cofrentes, S.M.Garoña Leibstadt, Muehleberg	0.02	0.10	1.32×10^{10}
PHWR	Argentina Canada Korea, Rep.	Atucha Gentily-2, Point Lepreau Wolsong	0.18	0.07	1.02×10^{10}
PWR	Switzerland Korea, Rep. Spain	Beznau, Goesgen Kori, Ulchin, Yongwang Almaraz, Vandellós	0.02	0.04	5.17×10^{9}
WWER	Hungary	Paks	0.04	0.26	n.a.[b]

[a] Tonnes of heavy metal.
[b] Not available.

Table 22. Normalized collective effective doses (man Sv/(GW a)) to local and regional population groups due to radionuclides released in effluents of the nuclear fuel cycle

Source	*1970–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1995–1997*	*1998–2002*
Mining	0.19	0.19	0.19	0.19	0.19	0.19
Milling	0.008	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	0.04
Fuel fabrication	0.003	0.003	0.003	0.003	0.003	0.003
Reactor operation						
Airborne effluents	2.8	0.7	0.4	0.4	0.4	0.22
Liquid effluents	0.4	0.2	0.06	0.05	0.04	0.05
Reprocessing						
Airborne effluents	0.3	0.1	0.06	0.03	0.04	0.028
Liquid effluents	8.2	1.8	0.11	0.10	0.09	0.081
Transportation	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total (rounded)	12	3.1	0.97	0.92	0.91	0.72

Table 23. Annual collective doses (man Sv) due to transport for three types of spent fuel management in Germany [B7]

Population group	*Comments*	*Nuclear reprocessing centre*[a]	*Integrated back-end concept*[b]	*Alternative back-end concept*[c]
Railway personnel handling radioactive material in shunting yards	Average: 0.52 man Sv per transport	4	10.8	3.9
Train drivers	No structure shielding considered	0.026	0.068	0.026
Railway passengers	124 passengers per train	0.2	0.51	0.2
Inhabitants in the proximity of shunting yards		0.054	0.110	0.052
Total	All population groups	4.3	12	4.2

[a] Transfer directly to nuclear reprocessing centres.
[b] Transfer using separate sites for interim storage of spent fuel, reprocessing and waste disposal.
[c] Direct disposal of spent fuel at the repository with no reprocessing.

Table 24. Number of packages and total activity of Suez Canal shipments from 1986 to 1992 [S1]

Material	*Package type*[a]	*Number of packages*	*Cumulative transport index*[b]	*Total activity (Bq)*
^{60}Co	B	36	122.4	5.06×10^{16}
^{137}Cs	A	30	59.1	5.68×10^{14}
UF_6	B	920	1 265.5	9.70×10^{13}
U_3O_8	A	1 852	9 651.4	5.85×10^{14}
UO_2	B	145	397.6	2.32×10^{13}
^{252}Cf	A	1	0.5	8.89×10^{9}
^{85}Kr	A	17	13.0	1.85×10^{13}
^{3}H	A	19	27.0	1.02×10^{14}

[a] Packages type refers to those described in reference [I33].

[b] The cumulative transport index refers to the sum of the transport index for all cargoes in the period 1986–1992.

Table 25. Number of packages containing radioactive material carried by aircraft in the United Kingdom in 2001 [W3]

Situation	*Short-haul*[a]				*Long-haul*[b]		*Total*
	Passenger		*Cargo*		*Passenger*	*Cargo*	
	Unit[c]	*Loose*[d]	*Unit*[c]	*Loose*[d]	*Unit*[c]	*Unit*[c]	
Into United Kingdom	245	981	4 111	4	2 920	1 383	9 644
From United Kingdom	2 533	3 104	14 540	2 746	13 197	26 015	62 135
Within United Kingdom	0	379	0	39	—	—	418
In transit	0	310	600	595	23	23	1 551
Number of consignments	25	1 042	2 530	337	2 840	90	6 864

[a] Short-haul: flights that take up to 4 h.

[b] Long-haul: flights that take over 4 h.

[c] Wide-body aircraft loaded with unit load devices (UDLs) to carry cargo.

[d] Narrow-bodied aircraft unable to take UDLs; cargo is loaded loose in the aircraft.

Table 26. Collective doses due to transport of radioactive material by air in the United Kingdom in 2001 [W3]

Exposed group	*Subgroup*	*Type of flight*	*Collective dose (man Sv/a)*
Handlers	—	All	0.1
Aircrew	Cabin crew	Short-haul passengers	0.13
		Long-haul passengers	3.8
	Flight crew	Short-haul passengers	0.002 5
		Short-haul cargo	0.024
		Long-haul passengers	0.13
		Long-haul cargo	0.56
Passengers	—	Short-haul passengers	0.43
	—	Long-haul passengers	2.8

Table 27. Estimated collective and individual doses to the public due to the normal transport of radioactive and nuclear material [I5, W8]

Country	*Period*	*Product*	*Mode of transport*	*Collective dose (man Sv/a)*	*Individual dose (mSv/a)*
Former GDR	1975–1984	Spent fuel	Road	0.15	0.01
Italy	1981	Fuel elements, PWR	Road	0.01	
United Kingdom	1981	Spent fuel	Road and rail	0.001	0.002
India	1982	Radioactive materials for medicine and industry	Road and air	0.1	[b]
Italy	1982	Medical use	Road	0.006	
United Kingdom	1982	All	Mainly road	0.004	0.04
Germany, Fed. Rep.	1983	Fresh and spent fuel, UF_6, ores, wastes	Rail	0.019	
Austria	1984	^{192}Ir, ^{99}Mo, ^{60}Co, ^{123}I, ^{131}I, ^{133}Xe	Air, road, rail	0.23	
Finland	1982–1985	Spent fuel	Road and rail	$(0.6–1.4) \times 10^{-3}$	
Turkey	1984	^{192}Ir, ^{60}Co, ^{131}I, ^{99m}Tc, ^{137}Cs, ^{241}Am	Road and air	0.429	
United States	1985	All from fuel cycle	All	19	0.02
		All	All	100	0.02
United Kingdom	2001	Medical and industrial sources	Air	3.23[a]	
United Kingdom	2003	Medical and industrial sources	Road	0.24	
United Kingdom	2003	Spent fuel	Road and rail	0.003	

[a] Doses to the public. Total annual collective dose, including passengers, crew and other workers, is 8 man Sv.

[b] Dose rate to the public: 1–55 μGy/h.

Table 28. Maximum annual doses (μSv) to members of the public due to the transport of various fuel cycle materials and by various modes [W14]

Material	*Road*	*Rail*	*Sea*
Non-irradiated material	<4	<1	<20
Spent fuel	<4	<6	<1
Waste (low- and intermediate-level)	<4	<4	
High-level waste		20	<1
MOX/plutonium			<1

Table 29. Doses to the public from consumer products and miscellaneous items
Conservative estimates [W6]

Item	*Estimated annual individual effective dose (μSv)*
Radioluminous wristwatch containing ^{147}Pm	0.3
Radioluminous wristwatch containing ^{3}H	10
Smoke alarms	0.07
Uranium glazed wall tiles	<1
Geological specimens	100
Photographic lenses[a]	200–300
^{210}Po in tobacco [C23, N9]	10

[a] No longer in use.

Table 30. Annual doses from by-products and radioactive materials in the United States [U35]

Effective dose (mSv)	*By-product*
<0.01	Automobile lock illuminators
	Precision balances
	Automobile shift quadrants
	Marine compasses and navigational instruments
	Thermostat dials and pointers
	Self-luminous products
0.01–<0.1	Timepieces, hands and dials
	Electron tubes
	Gas and aerosol detectors
0.1–<1.0	Ionizing radiation measurement instruments
	Spark gap irradiators
Effective dose (mSv)	*Source material*
<0.01	Vacuum tubes
	Electric lamps for illuminating purposes
	Germicidal lamps, sunlamps and lamps for outdoor or industrial lighting
	Personnel neutron dosimeters
	Piezoelectric ceramic
	Photographic film, negatives and prints
	Uranium in fire detection units
0.01–<0.1	Glassware
	Uranium shielding in shipping containers
0.1–<1.0	Glazed ceramic tableware
	Finished tungsten–thorium or magnesium–thorium alloy products or parts
	Uranium in counterweights
	Thorium in finished optical lenses
	Aircraft engine parts containing nickel–thorium alloy
1.0–<10	Unrefined and unprocessed ore
	Incandescent gas mantles
	Welding rods
≥10	Chemical mixtures, compounds, solutions or alloys
	Rare earth metals and compounds, mixtures and products

Table 31. Summary of annual per caput doses due to peaceful uses of atomic energy (μSv)

Local component		
Nuclear fuel cycle and energy generation	Mining and milling	25
	Fuel fabrication	0.2
	Reactor operation	0.1
	Reprocessing	2
Other uses	Transport of radioactive waste	<0.1
	By-products	0.2
Regional component		
Nuclear fuel cycle and energy generation	Fuel fabrication	<0.01
	Reactor operation	<0.01
	Reprocessing	0.02
Solid waste disposal and global component		
Nuclear fuel cycle and energy generation	Globally dispersed radionuclides	0.2
Other uses	Disposal of radioactive waste	<0.01

Table 32. Atmospheric nuclear tests at each test site [adapted from reference U3]

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	11.4
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	10.19	0.23	0.58	5.37
United Kingdom							
Monte Bello Island	3	0.1	0	0.1	0.05	0.049	0.000 7
Emu	2	0.018	0	0.018	0.009	0.009	0
Maralinga	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	3.3	6.65	0	1.09	2.26
Total	21	4.22	3.83	8.05	0.08	1.75	2.39
United States							
New Mexico	1	0.021	0	0.021	0.011	0.01	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	0.05
Atlantic	3	0.004 5	0	0.004 5	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	195	81.5	72.2	153.8	28.2	8.23	44.9

Test site	*Number of tests*	*Yield (Mt)*			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Former Soviet Union							
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	0.04	0	0.04	0.000 15	0.037	0.003
Kapustin Yar	10	0.68	0.3	0.98	0	0.078	0.61
Total	219	85.3	162	247.2	0.13	4.28	80.8
All countries							
Total	502	189	251	440	29	15	145

Table 33. Number and total yield of weapons tests and other events by country [B16, U3]

Type	*United States*	*Former Soviet Union*	*United Kingdom*	*France*	*China*	*India*	*Pakistan*	*Democratic People's Republic of Korea*	*Total*
Atmospheric nuclear tests									
Airburst	13	8	9	0	0	0	0	0	30
Air drop	52	174	1	3	16	0	0	0	246
Balloon	24	0	1	34	0	0	0	0	59
Tower/surface	66	34	10	4	6	0	0	0	120
Barge	35	0	0	4	0	0	0	0	39
Underwater	5	3	0	0	0	0	0	0	8
Total	195	219	21	45	22	0	0	0	502
Fission (Mt)	82	85	4	6	12	0	0	0	189
Fusion (Mt)	72	162	4	4	9	0	0	0	251
Underground nuclear tests									
Number of tests	908	750	24	160	22	6	6	1	1 877
Yield (Mt)	46	38	2	3	1				90
Total atmospheric and underground tests									
Number of tests	1 103	969	45	205	44	6	6	1	2 379
Yield (Mt)	200	285	10	13	22				530
Other events with nuclear weapons									
Safety trials	22	0	12	5	0	0	0	0	39
Operational	2	0	0	0	0	0	0	0	2

Table 34. Radionuclides produced and globally dispersed in atmospheric nuclear tests [U3]

Radionuclide	*Half-life*	*Global release (PBq)*
^{3}H	12.33 a	186 000
^{14}C	5 730 a	213
^{54}Mn	312.3 d	3 980
^{55}Fe	2.73 a	1 530
^{89}Sr	50.53 d	117 000
^{90}Sr	28.78 a	622
^{91}Y	58.51 d	120 000
^{95}Zr	64.02 d	148 000
^{103}Ru	39.26 d	247 000
^{106}Ru	373.6 d	12 200
^{125}Sb	2.76 a	741
^{131}I	8.02 d	675 000
^{140}Ba	12.75 d	759 000
^{141}Ce	32.5 d	263 000
^{144}Ce	284.9 d	30 700
^{137}Cs	30.07 a	948
^{239}Pu	24 110 a	6.52
^{240}Pu	6 563 a	4.35
^{241}Pu	14.35 a	142

Table 35. Latitudinal distribution of radionuclides from atmospheric nuclear tests based on ^{90}Sr measurements [U3]

Latitude band (°)	*Population distribution (%)*	*Integrated deposition of ^{90}Sr (PBq)*	*Deposition in band (%)*	*Deposition density per unit deposition ((Bq/m^2)/PBq)*	*Latitudinal value relative to hemispheric value*
Northern hemisphere					
80–90	0	1	0.2	0.56	0.12
70–80	0	7.9	1.7	1.48	0.32
60–70	0.4	32.9	7.1	3.78	0.81
50–60	13.7	73.9	16.1	6.27	1.35
40–50	15.5	101.6	22.1	7.01	1.51
30–40	20.4	85.3	18.5	5.09	1.09
20–30	32.7	71.2	15.5	3.85	0.83
10–20	11	50.9	11.1	2.58	0.56
0–10	6.3	35.7	7.8	1.76	0.38
Southern hemisphere					
80–90	0	0.3	0.2	0.53	0.14
70–80	0	2.5	1.7	1.5	0.4
60–70	0	6.7	4.6	2.46	0.66
50–60	0.5	12.1	8.4	3.28	0.88
40–50	0.9	28.1	19.5	6.19	1.65
30–40	13	27.6	19.1	5.26	1.4
20–30	14.9	28.1	19.5	4.85	1.29
10–20	16.7	17.8	12.3	2.89	0.77
0–10	54	21	14.6	3.3	0.88

Table 36. Estimated average effective doses (μSv) due to global fallout received by the world population [B46, U3, U6]

Radionuclide	*Received before 2000*				*To be received 2000–2100*	*To be received beyond 2100*
	External irradiation	*Inhalation*	*Ingestion*	*All pathways*	*All pathways*	*All pathways*
^{3}H	—	—	24	24	0.1	
^{14}C	—	—	144	144	120	2 230
^{54}Mn	19	0.1		19	—	
^{55}Fe	—	0.01	6.6	6.6	—	
^{89}Sr	—	2.6	1.9	4.5	—	
^{90}Sr	—	9.2	97	106	8.6	0.02
^{91}Y	—	4.1	—	4.1	—	
^{95}Zr	81	2.9	—	84	—	
^{103}Ru	12	0.9	—	13	—	
^{106}Ru	25	35	—	60	—	
^{125}Sb	12	0.1	—	12	0.003	
^{131}I	1.6	2.6	64	68	—	
^{140}Ba	27	0.4	0.5	28	—	
^{141}Ce	1.1	0.8	—	1.9	—	
^{144}Ce	7.9	52	—	60	—	
^{137}Cs	166	0.3	154	320	124[a]	13
^{239}Pu	—	20	—	20	—	
^{240}Pu	—	13	—	13	—	
^{241}Pu	—	5	—	5	—	
Total	353	149	492	994	253	2 243

[a] 114 μSv from external irradiation and 10 μSv from internal irradiation.

Table 37. Estimated effective doses for several regions of Maralinga and Emu [H7]

Zone	*Annual effective dose (mSv)*	*Principal pathway*	*Principal nuclide*
Taranaki North Plume, ^{241}Am A contour 10-year-old child	5	Inhalation	^{239}Pu
Taranaki Northwest, ^{241}Am A contour 10-year-old child	4	Inhalation	^{239}Pu
Kuli ^{238}U D contour 10-year-old child	23	Inhalation; external gamma	$^{234/238}$U
Kuli ^{238}U A contour 10-year-old child	3	Inhalation; external gamma	$^{234/238}$U
Northeast One Tree: 2 kBq/m^{2} of ^{137}Cs 3-month-old infant	2	Soil ingestion; inhalation	^{239}Pu
TM100, ^{241}Am A contour 10-year-old child	5	Inhalation	^{239}Pu
Emu—Totem II, ^{241}Am A contour 10-year-old child	9	Inhalation	^{239}Pu

Zone	*Annual effective dose (mSv)*	*Principal pathway*	*Principal nuclide*
Emu—Totem I, ^{137}Cs A contour 10-year-old child	0.5	Inhalation; ingestion	^{239}Pu
Inner Taranaki 10-year-old child	470	Inhalation	^{239}Pu
Emu—centre of Totem II 10-year-old child	31	Inhalation	^{239}Pu

Table 38. Median (and mean) activities[a] of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am per unit dry weight of soil on Bikini Island (Bq/g) [I9]

Soil depth (cm)	*^{137}Cs*	*^{90}Sr*	*$^{239+240}$Pu*	*^{241}Am*
Interior of island				
0–5	2.3 (3.0)	1.7 (2.1)	0.32 (0.42)	0.26 (0.30)
0–40	0.70 (0.91)	1.1 (1.5)	0.17 (0.21)	0.11 (0.14)
Village area				
0–5	1.2 (2.0)	1.0 (2.0)	0.20 (0.40)	0.11 (0.22)
0–40	0.67 (1.1)	1.6 (1.5)	0.24 (0.29)	0.13 (0.17)

[a] Decay corrected to 1999. The numbers in parentheses are the arithmetic means.

Table 39. Radionuclide and pathway contributions to hypothetical doses on Bikini Island assuming a local diet [I9]

Exposure pathway		*Annual dose (mSv)*
External gamma		0.4
Ingestion	^{137}Cs	14.6
	^{90}Sr	0.15
	$^{239+240}$Pu	0.001 9
	^{241}Am	0.001
Inhalation	$^{239+240}$Pu	0.000 74
	^{241}Am	0.000 49
Total (rounded)		15

Table 40. Absorbed dose rates in air in settlements outside and inside the Semipalatinsk nuclear test site [I10]

Location	*Dose rate at 1 m above ground (μGy/h)*
Outside the nuclear test site	
Entire perimeter (over 500 measurements)	0.06–0.17
Dolok	0.07
Sarzhal and surrounding pasture	0.08–0.09
Kainar	0.08–0.11
Akzhar and surrounding pasture	0.08
Dolon	0.09
Other settlements	0.07–0.14

Location	*Dose rate at 1 m above ground (μGy/h)*
Inside the nuclear test site	
Lake Balapan	0.1–33
Ground Zero	
1 km from centre	0.1
Within 1 km	0.1–17
South-eastern plume	0.09
Polygon farm	0.1
Beriozka State Farm	0.2
Sary-Uzen	0.5
Lake Tel'kem-2	0.2–1.0

Table 41. Estimated annual effective doses to persons living around the Semipalatinsk test site, to visitors to Lake Balapan and Ground Zero, and to potential future permanent inhabitants

Pathway	*Annual dose (mSv)*			
	Outside test area		*Inside test area*	
	Dolon	*Other settlements*	*Frequent visitors*	*Future permanent inhabitants*
External gamma	0.01	0.01	10	90
Inhalation				
^{238}Pu	0.007		0.05	1.2
$^{239+240}$Pu	0.04	0.01	0.2	3.5
^{241}Am	0.004		0.02	0.4
Ingestion				
^{137}Cs	0.03	0.03	3	30
^{90}Sr	0.02	0.02	0.06	10
^{238}Pu	0.004		0.07	0.6
$^{239+240}$Pu	0.02	0.001	0.2	2
^{241}Am	0.002		0.02	0.2
Total (rounded)	0.14	0.06	14	140

Table 42. Summary of residual radionuclide inventory on the Nevada Test Site as of January 1996 [U25]

Source of radioactivity	*Type of area*	*Environmental media*	*Major known isotopes or wastes*	*Depth*	*Activity (Bq)*
Atmospheric and tower tests	Above-ground nuclear weapons proving area	Surficial soil and test structures	Am, Cs, Co, Pu, Eu, Sr	At land surface	$\sim 7.4 \times 10^{10}$
Safety trials	Above-ground experimental area	Surficial soil	Am, Cs, Co, Pu, Sr	<0.9 m	$\sim 1.3 \times 10^{12}$
Nuclear rocket development area	Nuclear rocket, motor, reactor and furnace testing area	Surficial soil	Cs, Sr	<3 m	$\sim 3.7 \times 10^{10}$
Shallow borehole tests	Underground nuclear testing area	Soils and alluvium	Am, Cs, Co, Eu, Pu, Sr	<61 m	$\sim 7.4 \times 10^{13}$
Shallow land disposal	Waste disposal landfill	Soils and alluvium	Dry packaged low-level and mixed wastes	<9 m	$\sim 1.85 \times 10^{15}$
Crater disposal	Test-induced subsidence crater with sidewalls, cover and drainage	Soils and alluvium	Bulk contaminated soil and equipment	<30 m	$\sim 4.6 \times 10^{13}$
Greater confinement disposal	Monitored underground waste disposal borehole	Soils and alluvium	Am, tritium	37 m	$\sim 3.4 \times 10^{17}$ ($\sim 300 \times$ m^3)
Deep underground tests	Underground nuclear testing area	Soils, alluvium and consolidated rock	Tritium, fission and activation products	Typically less than 640 m but may be deeper	$>1.1 \times 10^{19}$

Table 43. Properties of uranium isotopes ^{238}U, ^{235}U and ^{234}U and their relative abundance in natural and depleted uranium [I7]

Isotope	Average energy per transformation (MeV/Bq)			Half-life	Natural uranium			Depleted uranium		
					Specific activity	Relative isotopic abundance (%)		Specific activity	Relative isotopic abundance (%)	
	Alpha	Beta	Gamma	(a)	(Bq/mg U)	By mass	By activity	(Bq/mg U)	By mass	By activity
^{238}U	4.26	0.01	0.001	4.51×10^9	12.44	99.28	48.2	12.44	99.8	87.5
^{235}U	4.47	0.04	0.154	7.1×10^8	0.6	0.72	2.2	0.16	0.2	1.1
^{234}U	4.84	0.001 3	0.002	2.47×10^5	12.44	0.005 5	49.5	1.61	0.000 7	11.4

Table 44. Estimated amount of depleted uranium used in armed conflict

Conflict	Total DU (t)
Gulf War I (1991)	286
Bosnia and Herzegovina (1994–1995)	3
Kosovo (1999)	10
Serbia and Montenegro (1999)	0.7

Table 45. Lands contaminated with radionuclides at enterprises of Minatom of Russia

As of 1 January 2000 [L2]

Enterprise	Area (km^2)	Area (km^2) with exposure rates of greater than 2 µGy/h
Priargun Mining and Chemical Association	8.53	—
Mining and Metallurgical Plant (Lermontov)	1.34	1.03
Machine-building Plant (Elektrostal)	0.26	0.261
Novosibirsk Plant of Chemical Concentrates	0.15	0.14
Moscow Plant of Polymetals	0.016	0.001
Chepetsk Mechanical Plant (Glazov)	1.35	0.062
Zabaikalski Mining and Enrichment Combine	0.04	
Mayak Production	452.16	65.7
Mining and Chemical Complex (Zheleznogorsk)	4.7	0.203
Siberian Chemical Complex (Seversk)	10.39	4.191
Kirovo-Chepetsk Chemical Complex	0.7	
All-Russian Research Institute of Technical Physics (Snezhinsk)	0.13	0.01
Research Institute of Atomic Reactors (Dimitrovgrad)	0.39	0.081
Institute of Physics and Power Engineering (Obninsk)		0.001
Total	480.32	71.68

Table 46. Number of particles retrieved and their average activity close to the Dounreay site as of May 2007 [D5]

Particle location	Number of particles found	Average particle activity (Bq)
Marine sediment	930	1.4×10^6
Dounreay offshore	248	5.5×10^6
Sandside Beach	94	7.3×10^4
Dunnet Beach	1	8.9×10^3
Murkle Beach	1	1.3×10^4
Dounreay site (estimate)	86	n.a.[a]

[a] Not available.

Table 47. Maximum total annual individual doses estimated for selected population groups close to the Kara Sea [I11]

Scenarios	*Annual doses (µSv)*	
	Seafood consumers – Groups (a) and (c)	*Military personnel – Group (b)*
Best estimate scenario	<0.1	700
Plausible worst scenario	<1	4 000
Climate change scenario	0.3	3 000

Groups:

(a) Living in Ob and Yenisei estuaries and on Taimyr and Yamal peninsulas; habits typical of subsistence fishing communities in Arctic.

(b) Hypothetical group of military personnel patrolling, for 100 hours in a year, foreshores of fjords containing dumped radioactive material.

(c) Seafood consumers representative of northern Russian population situated on Kola Peninsula.

Table 48. Practices for which UNSCEAR evaluates occupational exposure

Category of practice	*Practice*
Exposure to natural sources of radiation	Civilian aviation Coal mining Other mineral mining Oil and natural gas industries Workplace exposure to radon other than in mines
Nuclear fuel cycle	Uranium mining Uranium milling Uranium enrichment and conversion Fuel fabrication Reactor operation Decommissioning Fuel reprocessing Research in the nuclear fuel cycle Waste management
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
Miscellaneous	Educational establishments Veterinary medicine Other occupations
Military activities	All military activities

Table 49. Occupational exposure of aircrew

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures and the literature [S38]

Country	*Number of workers*	*Collective dose (man Sv)*	*Average effective dose (mSv)*	*Maximum effective dose (mSv)*
Canada	100	0.6	1.36	
Czech Republic	1 195	1.5	1.28	3.5
Denmark	3 990	6.8	1.7	—
Finland	2 520	4.2	1.7	—
Germany	31 000	60.0	2.0	6.5
Lithuania	160	0.2	1.2	
Netherlands	12 500	17.0	1.3	<6
United Kingdom	40 000	80.0	2.0	—
United States	150 000[a]		0.2–5.0[b]	

[a] Data from reference [U27].
[b] Data from references [W2, W16].

Table 50. Estimated effective doses for specific flight routes leaving Frankfurt, Germany

Destination	*Range of the dose[a] (µSv)*
Gran Canaria	10–18
Johannesburg	18–30
New York	32–75
Rio de Janeiro	17–28
Rome	3–6
San Francisco	45–110
Singapore	28–50

[a] A range of values is given because of differences in flying altitude and variations in the intensity of the cosmic ray flux due to varying solar activity.

Table 51. Dose equivalent rate and mission dose equivalent in crewed space missions [R7, R8]

Mission	*Inclination (grad)*	*Altitude (km)*	*Mission duration (h)*	*Dose equivalent rate (mSv/d)*	*Mission dose equivalent (mSv)*
SL1	57	250	247.5	0.46	4.7
D-1	57	324	168	0.48	3.3
IML-1	57	348	194	0.38	3.0
MIR92	51.5	400	190	0.64	5.1
D-2	28.5	296	240	0.19	1.9
IM-L2	28.5	296	353	0.26	3.8
Euromir ’94	51.5	400	756	~0.86	~27

Table 52. Annual doses to underground coal miners in China [C12]

Type of coal mine	*Average annual effective dose (mSv)*	*Collective dose (man Sv)*
Large-sized	0.28	280
Medium-sized	0.55	550
Small-sized	3.3	13 200
Bone-coal	10.9	545
Average	2.4	14 600

Table 53. Occupational exposure in underground gold mines in South Africa [W17]

Year	*Average annual dose (mSv)*	*Number of workers*	*Number of workers receiving doses of >20 mSv*
1997	6.3	258 080	12 904
1998	4.9	232 500	2 325
1999	5.4	175 333	5 260
2000	7	123 333	3 700

Table 54. Estimated external doses for workers in Abu-Tartor phosphate mine tunnels

Estimates based on individual and workplace monitoring using TLDs [K11]

Type of worker	*Mean*	*SE*[a]	*SD*[b]	*Minimum*	*Maximum*	*Number*[c]
Effective dose rate estimated using individual monitoring (mSv/a)						
Mine workers	15.55	2.73	12.20	6.78	53.52	20
Mine maintenance workers	10.25	0.97	3.64	5.90	18.23	14
Ore crushing and transport workers	11.34	1.03	1.78	9.83	13.31	3
Beneficiation factory workers	10.95	0.35	0.79	10.09	12.11	5
Ore drying and storage workers	10.21	0.15	0.26	9.97	10.49	3
Average	11.66	—	—	—	—	—
Effective dose rate estimated using workplace monitoring (mSv/a)						
Mine	8.51	0.60	3.36	2.19	17.09	31
Ore crushing	10.06	0.31	0.70	8.94	10.81	5
Processing facility	8.35	0.52	1.08	6.82	9.07	4
Average	8.97	—	—	—	—	—

[a] Standard error of the mean.
[b] Standard deviation.
[c] Number of measurements.

Table 55. Doses received by workers in zircon milling plants [I41]

Location	*Annual effective dose (mSv)*		
	Gamma radiation	*Dust inhalation*[a]	*Total*
Australia			
— New autogenous mill, dust extraction, enclosed bagging, good industrial hygiene	0.4	0.27	0.67
— Old roller mill, no special dust extraction during bagging	0.3	0.73	1.03
— Old ball mill, no special dust extraction	0.1	0.56	0.66
— Old ball mill, semi-automatic bagging, no special dust extraction	0.4	0.56	0.96
Netherlands			0.8
South Africa			
— Mill operators (mill areas)	0.102	0.163	0.265
— Mill operators and maintenance personnel (warehouse)	0.238	0.046	0.284
— Maintenance personnel (mill areas)	0.067	0.042	0.109
— General workers (mill areas)	0.096	0.06	0.156
— General workers (warehouse)	0.210	0.04	0.250
South Africa[c]			
— Mill attendant	0.275	0.165	0.44
— Shift supervisor	0.18	0.094	0.274
— Cleaner	0.2	0.134	0.33
South Africa			
— Wet mill operator	0.16	0	0.16
United Kingdom		0.5	
United States: bagger operator (respiratory protection mandatory)			
— Without respiratory protection[b]	0.2	1.9	2.1
— With respiratory protection			<1

[a] Except where otherwise stated, values are based on the assumption that no respiratory protection was used.

[b] Doses calculated from values of gamma exposure, airborne dust activity concentration and occupancy period using the inhalation dose coefficients for an AMAD of 5 μm.

[c] Maximum values measured after implementation of the following dose reduction measures: reduction of dust generation through revised engineering practices, reduction of stockpile quantities and thus of gamma exposures, and reduction of surface contamination by continuous cleaning practices [I41].

Table 56. Occupational exposure in Germany due to radon inhalation in workplaces other than mines

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Workplace	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
					Monitored workers	*Measurably exposed workers*
Spas	1995–1999	0.002	0.002	0.01	4.77	4.77
	2000–2002	0.004	0.002	0.01	4.09	4.47
Waterworks	1995–1999	0.128	0.075	0.24	1.85	3.12
	2000–2002	0.081	0.047	0.11	1.39	2.50
Tourist caves and visitor mines	1995–1999	0.135	0.101	0.31	2.26	3.01
	2000–2002	0.131	0.087	0.23	1.76	2.63

Table 57. Estimated worldwide levels of annual exposure due to natural sources of radiation for the period 1995–2002
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures and the literature

Workplace	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
Coal mining	6 900	16 560	2.4
Other mining (excluding uranium mining)	4 600	13 800	3.0
Workplaces other than mines	1 250	6 000	4.8
Aircrew	300	900	3.0
Total	13 050	37 260	2.9

Table 58. Estimated worldwide levels of annual exposure in uranium mining
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Annual amount of ore extracted (kt U)*	*Collective dose per unit mass (man Sv/kt)*	*Monitored workers (10^3)*	*Annual collective dose (man Sv)*	*Annual effective dose (mSv)*
1975–1979	52	26	240	1 300	5.5
1980–1984	64	23	310	1 600	5.1
1985–1989	59	20	260	1 100	4.4
1990–1994	39	8	69	310	4.5
1995–1999	34	2	22	85	3.9
2000–2002	34	1	12	22	1.9

Table 59. Exposure to workers from underground and above-ground uranium mining
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country/type of uranium mine	*Period*	*Monitored workers (10^3)*		*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
		Total	*Measurably exposed*		*Total*	*Measurably exposed*
Canada						
Above-ground	1995–1999	1.30	0.64	0.61	0.44	0.97
	2000–2002	1.06	0.50	0.48	0.45	0.99
Underground	1995–1999	1.03	0.77	3.05	3.13	4.13
	2000–2002	0.65	0.48	1.46	0.95	2.00
Germany						
Above-ground	1995–1999	0.73	0.73	0.96	1.32	1.32
	2000–2002	0.53	0.53	0.15	0.28	0.28
Underground[a]	1995–1999	1.04	0.90	2.10	2.01	2.46
	2000–2002	0.88	0.88	0.94	1.07	1.07

[a] Extracted only in connection with decommissioning of mining facilities.

Table 60. Contribution of internal and external exposure to the effective dose due to uranium mining
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Type of mine	*Percentage contribution of internal and external exposure to the effective dose*					
	Dose less than 1 mSv			*Dose more than 1 mSv*		
	Radon progeny	*Ore dust*	*External exposure*	*Radon progeny*	*Ore dust*	*External exposure*
Canada						
Underground	82%	—	—	62%	—	—
Above-ground	74%	—	—	41%	—	—
Czech Republic						
Underground	45%	39%	16%	72%	20%	8%
Germany						
Underground	36%	32%	32%	37%	53%	10%
Above-ground	23%	34%	43%	51%	40%	9%

Table 61. Effective dose to workers in above-ground and underground uranium mines
Reports on Canadian occupational radiation exposure [H9, H10, H11, H12, H13, H14]

Year	*Personnel*			*Maintenance*			*Miner*		
	Number of workers	*Average effective dose (mSv)*	*Per cent radon progeny*	*Number of workers*	*Average effective dose (mSv)*	*Per cent radon progeny*	*Number of workers*	*Average effective dose (mSv)*	*Per cent radon progeny*
Above-ground uranium mines									
1995	50	0.59	80	211	1.31	77	154	1.24	59
1996	61	0.75	71	247	1.33	73	214	1.30	51
1997	102	0.32	62	202	0.55	66	244	0.94	23
1998	126	0.37	79	176	0.36	93	96	0.80	50
1999	177	0.35	62	219	0.40	73	74	0.83	11
2000	186	0.64	74	194	0.64	45	89	1.35	52
2001	208	0.58	68	189	0.57	51	47	2.15	55
Underground uranium mines									
1995	368	0.98	64	109	5.37	66	386	10.90	63
1996	387	0.82	60	101	3.85	62	469	9.62	58
1997	476	0.69	39	103	1.48	64	354	5.53	39
1998	346	0.55	75	139	0.93	87	362	1.97	78
1999	155	1.01	71	204	0.90	79	341	2.60	63
2000	111	0.88	53	194	0.71	70	284	2.57	40
2001	73	0.48	54	115	0.46	64	161	2.29	32

Table 62. Estimated worldwide levels of exposure due to uranium milling
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy (GW a)*	*Monitored workers (10^3)*	*Collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	53	240	12	124	10.1
1980–1984	64	290	23	117	5.1
1985–1989	58	260	18	116	6.3
1990–1994	39	180	6	20	3.3
1995–1999	34	155	3	4	1.6
2000–2002	34	155	3	3	1.1

Table 63. Contribution of internal and external exposure to the effective dose due to uranium milling
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Uranium milling	*Percentage contribution of internal and external exposure to the effective dose*					
	Dose less than 5 mSv			*Dose more than 5 mSv*		
	Radon progeny	*Ore dust*	*External exposure*	*Radon progeny*	*Ore dust*	*External exposure*
Canada	70			50		
Germany	35	35	30	19	72	9

Table 64. Estimated worldwide levels of exposure due to uranium enrichment
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Collective effective dose (man Sv)*	*Average effective dose (mSv)*
1975–1979	11.0	5.30	0.46
1980–1984	4.3	0.78	0.18
1985–1989	5.0	0.43	0.08
1990–1994	12.6	1.28	0.10
1995–1999	17.2	1.34	0.08
2000–2002	18.2	1.70	0.09

Table 65. Estimated worldwide levels of exposure due to fuel fabrication
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	20	36	1.8
1980–1984	21	21	1.0
1985–1989	28	22	0.8
1990–1994	21	22	1.0
1995–1999	22	30	1.4
2000–2002	20	31	1.6

Table 66. Summary of worldwide exposures due to reactor operations

Period	*PWR*	*BWR*	*HWR*	*GCR*	*LWGR*	*All*
Average number of monitored workers (10^3)						
1975–1979	63	59	7	13	5	147
1980–1984	140	102	14	25	10	291
1985–1989	230	139	18	31	13	431
1990–1994	310	160	20	30		530
1995–1999	265	144	18	21		448
2000–2002	283	113	23	18		437
Average annual effective dose to monitored workers (mSv)						
1975–1979	3.5	4.7	4.8	2.8	6.6	4.1
1980–1984	3.1	4.5	3.2	1.4	6.4	3.6
1985–1989	2.2	2.4	3.4	0.8	13.2	2.5
1990–1994	1.3	1.6	1.7	0.5		1.4
1995–1999	1.9	1.7	1.6	0.3		1.5
2000–2002	1.7	1.4	1.6	0.2		1.0
Average annual collective effective dose (man Sv)						
1975–1979	220	279	32	36	36	603
1980–1984	450	454	46	34	62	1 046
1985–1989	500	331	60	24	173	1 088
1990–1994	415	240	35	16	190	896
1995–1999	506	237	29	7		779
2000–2002	415	160	38	4		617
Normalized collective effective dose per unit electrical energy (man Sv/(GW a))						
1975–1979	8.1	18.3	11.0	6.6	8.2	10.9
1980–1984	8.0	18.0	8.0	5.8	8.3	10.4
1985–1989	4.3	7.9	6.2	3.2	16.7	5.7
1990–1994	2.8	4.8	3.0	2.0	20.3	3.9
1995–1999	3.0	3.8	2.4	0.7		2.5
2000–2002	2.2	2.4	2.9	2.6		2.5
Normalized collective effective dose per reactor (man Sv per reactor)						
1975–1979	2.8	5.5	2.6	0.9	3.0	3.1
1980–1984	3.3	7.0	2.4	0.8	3.8	3.7
1985–1989	2.3	4.0	2.3	0.5	8.7	2.8
1990–1994	1.7	2.7	1.1	0.4	9.4	2.1
1995–1999	2.0	2.6	1.2	0.2		1.5
2000–2002	1.6	1.8	1.0	0.2		1.1

Table 67. Annual occupational doses for reactor operation by job category

From ISOE and Canadian National Dose Registry

Country	*Refuelling*[a]			*Maintenance*[b]			*Inspection*[c]			*Servicing*[d]			*Other*		
	Annual collective effective dose			*Annual collective effective dose*			*Annual collective effective dose*			*Annual collective effective dose*			*Annual collective effective dose*		
	Average number of reactors over the period	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*
1995–1999															
BWR															
Germany	4.4	284.5	64.7	5.8	1 851.7	319.3	4.6	382.3	83.1	5.4	1 187.1	219.8	3.4	269.3	79.2
Mexico	1.2	339.1	282.6	1.2	2 492.9	2 077.5	1.0	107.4	107.4	1.2	466.9	389.1	0.8	131.9	164.9
Spain	1.8	162.3	90.1	2.0	1 266.8	633.4	2.0	227.1	113.6	2.0	971.5	485.8	2.0	1 058.9	529.5
Sweden	8.6	337.7	39.3	9.0	8 111.6	901.3	8.8	1 013.5	115.2	9.0	4 502.6	500.3	6.6	2 416.0	366.1
Switzerland	2.0	150.6	75.3	2.0	386.0	193.0	1.6	101.2	63.2	2.0	282.1	141.1	1.8	739.1	410.6
HWR															
Canada	14	2 008	28.6	14	30 834	440	14	6 146	87.8	14	16 986	243	14	21 143	302
LWGR															
Lithuania	2.0	451.9	226.0	1.6	1 267.9	792.5	1.6	125.2	78.3	1.6	1 210.9	756.83	1.6	3 635.3	2 272.1
PWR															
Armenia							0.2	6.4	32.2	0.3	43.9	175.4	0.2	16.4	81.8
Belgium	6.2	417.8	67.4	6.2	1 809.7	291.9	5.8	288.1	49.7	6.0	763.1	127.2	4.6	419.1	91.1
China	2.0	136.0	68.0	2.0	444.2	222.1	1.0	15.8	15.8	2.0	269.8	134.9	1.4	134.3	95.9
Finland	2.0	69.5	34.7	2.0	441.8	220.9				2.0	359.8	179.9	0.8	87.7	109.6
France	46.8	5 295.1	113.1	46.8	25 087.7	536.1	46.0	3 257.6	70.8	46.6	13 398.6	287.5	46.0	5 118.3	111.3
Germany	9.2	579.2	63.0	10.6	4 872.9	459.7	6.2	810.2	130.7	8.8	2 552.6	290.1	4.4	688.2	156.4
Hungary	4.0	234.0	58.5	4.0	1 139.9	285.0				4.0	704.2	176.0	4.0	354.5	88.6
Netherlands	1.0	95.9	95.9	1.0	252.9	252.9	1.0	135.9	135.9	1.0	247.7	247.7	1.0	45.0	45.0
South Africa	1.6	111.2	69.5	1.6	522.9	326.8	1.4	57.1	40.8	1.6	248.4	155.3	0.8	19.7	24.6
Slovenia	1.0	179.5	179.5	1.0	685.3	685.3	0.8	21.1	26.4	1.0	205.7	205.7	0.8	11.1	13.9
Spain	5.6	723.9	129.3	5.6	2 179.6	389.2	5.6	326.6	58.3	5.6	1 353.1	241.6	0.8	128.3	160.4
Sweden	3.0	201.5	67.2	3.0	980.7	326.9	2.2	37.2	16.9	3.0	290.2	96.7	0.4	0.6	1.6

Switzerland	2.6	258.2	99.3	2.6	469.7	180.7	1.6	61.6	38.5	2.6	282.0	108.5	1.8	200.8	111.6
United Kingdom	0.6	49.9	83.2	1.0	119.5	119.5	0.6	16.7	27.8	1.0	53.8	53.8	1.0	68.1	68.1
2000–2003															
BWR															
Finland	1.5	40.8	27.2	1.8	290.5	166.0	1.8	121.1	69.2	1.5	189.8	126.6			
Germany	5.5	273.1	49.7	6.0	1 224.1	204.0	4.5	324.1	72.0	5.3	760.0	144.8	2.5	348.6	139.5
Mexico	1.3	282.5	226.0	1.3	2 100.8	1 680.6	1.3	48.5	38.8	1.3	410.8	328.6			
Spain	1.3	144.2	115.4	1.3	1 085.1	868.1	1.3	188.6	150.9	1.3	435.5	348.4	1.3	449.8	359.8
Sweden	7.3	286.3	39.5	7.3	3 254.3	448.9	7.3	311.5	43.0	8.0	2 223.2	277.9	6.5	1 622.0	249.5
Switzerland	2.0	103.3	51.6	2.0	110.2	55.1	1.5	126.9	84.6	1.5	354.9	236.6	0.3	8.6	34.5
HWR															
Canada	14	1 069	19.0	14	23 483	419	14	4 550	81.3	14	14 195	254	14	28 126	502
PWR															
Armenia	0.8	57.0	75.9	1.0	235.0	235.0	0.8	49.9	66.5	1.0	149.7	149.7	1.0	178.2	178.2
Belgium	6.3	182.1	29.1	6.3	921.9	147.5	6.3	192.7	30.8	6.3	471.2	75.4	5.0	215.6	43.1
Brazil	1.5	227.0	151.3	1.5	486.8	324.5	1.0	50.8	50.8	1.5	288.6	192.4	1.5	183.1	122.0
China	2.3	78.4	34.8	2.5	702.8	281.1	2.0	42.1	21.1	1.0	225.8	225.8	0.8	20.4	27.2
Czech Republic	2.0	2.2	1.1	2.0	236.3	118.2				2.0	474.4	237.2	1.5	72.3	48.2
Finland	2.0	83.4	41.7	2.0	169.5	84.7				4.0	686.1	171.5	4.0	949.7	237.4
France	47.3	2 708.1	57.3	47.3	13 891.9	294.0	47.3	3 821.4	80.9	47.3	9 712.0	205.6	46.0	296.6	6.5
Germany	11.0	726.5	66.1	11.8	2 828.5	240.7	8.3	1 034.8	125.4	10.5	1 886.4	179.7	3.5	57.2	16.4
Hungary	4.0	224.7	56.2	4.0	1 170.1	292.5									
Netherlands	1.0	14.3	14.3	1.0	76.7	76.7	0.8	4.1	5.5	1.0	64.0	64.0	0.3	16.3	65.0
Slovenia	1.0	138.2	138.2	1.0	306.5	306.5	1.0	24.9	24.9	1.0	86.4	86.4	0.3	63.9	255.5
South Africa	1.5	59.2	39.4	1.5	538.8	359.2	1.3	114.5	91.6	1.5	221.2	147.5	1.0	83.3	83.3
Spain	5.5	513.6	93.4	5.5	944.9	171.8	5.5	193.5	35.2	5.5	631.2	114.8	5.3	419.4	79.9
Sweden	3.0	178.6	59.5	3.0	845.7	281.9	3.0	81.1	27.0	3.0	237.6	79.2			
Switzerland	6.0	446.9	74.5	2.8	392.0	142.6	0.8	19.0	25.3	2.0	410.4	205.2	0.5	10.0	20.0
United Kingdom	1.0	49.4	49.4	1.0	116.8	116.8	0.8	5.6	7.5	1.0	63.3	63.3	1.0	96.0	96.0

[a] Refuelling: all activities related to refuelling, including the cleaning of the refuelling pool.

[b] Maintenance: work on reactor vessel or internals, steam generators, residual or shutdown heat removal system and safety injection system, chemical and volume control system, pressurizer, reactor water clean-up system, reactor coolant pumps, primary circuit, valves, steam system, recirculation system and coolant pump seal water system, control rod drives.

[c] Servicing: general work, scaffolding and insulation.

[d] Other: other work not listed above.

Table 68. Occupational exposure due to the decommissioning of 13 nuclear power plants in the United States

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Measurably exposed workers (10^3)*	*Annual collective dose (man Sv)*	*Average annual effective dose (mSv)*
1995–1999	1.90	3.83	2.01
2000–2002	2.17	4.15	1.91

Table 69. Estimated worldwide levels of exposure due to fuel reprocessing

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	8	53	7.1
1980–1984	9	46	4.9
1985–1989	17	36	2.5
1990–1994	45	67	1.5
1995–1999	59	61	1.1
2000–2002	76	68	0.9

Table 70. Estimated worldwide levels of exposure due to nuclear fuel cycle research

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	120	170	1.4
1980–1984	130	150	1.1
1985–1989	130	100	0.8
1990–1994	120	90	0.8
1995–1999	96	37	0.4
2000–2002	90	36	0.4

Table 71. Occupational exposure due to radioactive waste management in the nuclear fuel cycle

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective dose*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*			
				Total (man Sv)	*Monitored workers*	*Measurably exposed workers*	*NR_{20}*	*NR_{10}*	*NR_5*	*NR_1*
China[a]	1990–1994	1.51		5.33	3.53			0.09		
	1995–2000	1.30		4.03	3.10			0.08		
United Kingdom[b]	1995–1999	0.29		0.09	0.30					
	2000–2002	0.35		0.07	0.20					
United States[c]	1995–1999	8.05	1.90	1.22	0.15	0.65	0.00	0.00	0.00	0.04
	2000–2002	5.88	1.76	1.07	0.18	0.61	0.00	0.00	0.00	0.05

[a] Data from reference [T4].

[b] Data from reference [I38].

[c] Data from the UNSCEAR Global Survey of Occupational Radiation Exposures.

Table 72. Worldwide average annual exposures due to the commercial nuclear fuel cycle[a]

Practice	*Monitored workers*[b] *(10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv/GW a)*	*Average annual effective dose to monitored workers (mSv)*	*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	124	0.5	10	0.41	0.76
Enrichment[e]	11	5	0.02	0.5	0.00	0.00
Fuel fabrication	20	36	0.6	1.8	0.012	0.38[g]
Reactor operation	150	600	11.0	4.1	0.078[h]	0.60[i]
Reprocessing[j]	78	53	0.7	7.1	0.16	0.29
Research	120	170	1.0	1.4	0.035	0.42
Total	560	2 300	20	4.4	0.20	0.63
1980–1984						
Mining[e,f]	310	1 600	5.5	5.1	0.30	0.61
Milling[e,f]	23	117	0.4	5.1	0.30	0.64
Enrichment[e]	4	1	0.02	0.2	0.00	0.00
Fuel fabrication	21	21	0.2	1.0	0.002	0.11[g]
Reactor operation	290	1 000	10.0	3.6	0.069[h]	0.52[i]
Reprocessing[j]	9	46	0.8	4.9	0.10	0.39
Research	130	150	1.0	1.1	0.021	
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	116	0.4	6.3	0.18	0.43
Enrichment[e]	5.0	0.4	0.02	0.1	0.00	0.00
Fuel fabrication	28	22	0.1	0.8	0.002	0.019[g]
Reactor operation	430	1 100	5.7	2.5	0.033[h]	0.34[i]
Reprocessing[j]	12	36	0.7	3.0	0.064	0.12[j]
Research	130	100	1.0	0.8	0.011	0.30
Total	888	2 500	12	2.6	0.10	0.42

Practice	*Monitored workers*[b] *(10³)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv/GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Distribution ratio*[c]	
					NR_{15}[d]	SR_{15}
1990–1994						
Mining[e,f]	69 (62)	310	1.7	4.5 (5.0)	0.10	0.32
Milling[e,f]	6	20	0.1	3.3	0.00	0.01
Enrichment[e]	13	1	0.02	0.1	0.00	0.00
Fuel fabrication	21 (11)	22	0.1	1.0 (2.0)	0.01	0.11
Reactor operation	530 (300)	900	3.9	1.4 (2.7)	0.00[h]	0.08
Reprocessing[j,k]	45 (24)	67	3.0	1.5 (2.8)	0.00	0.13
Research	120 (36)	90	1.0	0.8 (2.5)	0.00	0.22
Total	800 (450)	1 400	9.8	1.8 (3.1)	0.01	0.11
1995–1999						
Mining[e,f]	22	85	0.5	3.9	0.04	0.14
Milling[e,f]	3	4	0.03	1.6		
Enrichment[e]	17	1	0.02	0.1	0.00	0.00
Fuel fabrication	22	30	0.1	1.4	0.00	0.01
Reactor operation	448	779	2.5	1.5	0.00	0.03
Reprocessing[j,k]	59	61		1.1		
Research	96	37	1	0.4	0.01	0.22
Total	700	1 000	1	1.4	0.01	0.07
2000–2002						
Mining[e,f]	12	22	0.1	1.9	0.05	0.14
Milling[e,f]	3	3	0.02	1.1		
Enrichment[e]	18	2	0.02	0.1	0.00	0.00
Fuel fabrication	20	31	0.1	1.6	0.01	0.01
Reactor operation	437	617	2.5	1.0	0.02	0.13
Reprocessing[j,k]	76	68		0.9		
Research	90	36	1	0.4	0.01	0.02
Total	660	800	1	1.0	0.02	0.07

[a] Data are annual values averaged over the indicated periods.

[b] Data in parentheses are for measurably exposed workers.

[c] The values of the distribution ratios should be considered as only indicative of worldwide levels, as they are in general based on data from far fewer countries than the data for the number of workers and collective doses.

[d] Ratio applies to monitored workers.

[e] Also includes 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 for exposure to radon daughters (10 mSv/WLM 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 the revised data is not linear, because exposure occurs from other sources besides the inhalation of radon progeny. For 1990–1994 a conversion factor of 5.0 mSv/WLM for exposure to radon daughters has been used.

[g] 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.

[h] Does not include data for LWGRs, FBRs and HTGRs.

[i] Does not include data for GCRs, LWGRs, FBRs and HTGRs.

[j] Also includes the reprocessing of some fuel from the defence nuclear fuel cycle.

[k] In the absence of sufficient data on equivalent electrical energy generated by reporting countries for 1990–1994, the Committee has taken the normalized average annual collective effective dose per unit energy generated to be the same as that for the previous period.

Table 73. Exposure of physicians during lung biopsy (mGy per minute of fluoroscopy) [N15]

Fluoroscopy conditions set	*A*		*B*	
Use of needle holder	*No*		*Yes*	
Physician	*Operating*	*Assisting*	*Operating*	*Assisting*
Corner of the eye, right	93 ± 44	15.0 ± 10.4	15.3 ± 2.9	2.54 ± 0.93
Corner of the eye, left	23 ± 14.8	4.9 ± 3.6	3.1 ± 0.48	1.23 ± 0.78
Neck (thyroid)	86 ± 46	15.2 ± 10.1	8.0 ± 1.02	2.3 ± 1.54
Upper arm, right	125 ± 68	21 ± 24	18.1 ± 6.2	2.4 ± 0.83
Upper arm, left	19.8 ± 11.9	7.8 ± 5.9	2.8 ± 2.5	1.27 ± 1.13
Back of the hand, right	10 900 ± 11 600	8.4 ± 7.5	240 ± 125	1.76 ± 0.99
Back of the hand, left	150 ± 117	6.6 ± 5.5	140 ± 0.08	1.10 ± 0.90
Fingers, right	2 600 ± 2 100	45 ± 80	84 ± 101	2.45 ± 1.02
Fingers, left	590 ± 400	4.2 ± 3.2	6.9 ± 0.53	1.66 ± 1.43
Back of the head	38 ± 20	5.2 ± 5.5	1.27 ± 1.05	0.79 ± 0.65
Back	4.2 ± 2.7	0.98 ± 1.05	2.4 ± 0.47	0.70 ± 0.20
Inside of femur	3.3 ± 3.0	2.3 ± 3.0	0.68 ± 0.40	0.85 ± 0.90
Chest, inside protector	7.6 ± 5.4	2.3 ± 2.9	0.94 ± 0.46	1.35 ± 1.50
Abdomen, insider protector	6.9 ± 4.6	1.23 ± 1.35	0.54 ± 0.54	0.76 ± 0.69
Chest, outside protector	66 ± 35	9.8 ± 8.5	9.0 ± 1.83	1.48 ± 0.97
Abdomen, outside protector	68 ± 39	7.9 ± 8.8	13.1 ± 2.2	1.11 ± 0.59

Table 74. Occupational doses incurred by primary medical doctors during interventional procedures [S21]

Procedure type (number of measurements)	*TLD position/ dosimetric quantity*	*Range of dose (mSv)*	*Average dose (mSv)*	*Average time of fluoroscopy (min)*	*Average number of frames*
Coronariography ($n = 62$)	Chest outside the apron/*Hp(10)*	0–2.35	0.29	7.8	991
	Chest inside the apron/*Hp(10)*	0–0.27	0.06		
	Right hand/*Hp(0.07)*	0–2.54	0.26		
	Left hand/*Hp(0.07)*	0–3.88	0.38		
	Knee/*Hp(0.07)*	0–1.61	0.21		
	Neck without collar/*Hp(10)*	0.18–2.88			
	Neck with collar/*Hp(10)*	0–0.27	0.13		
	Forehead/*Hp(3)*	0–0.82	0.14		
Angioplasty ($n = 30$)	Chest outside the apron/*Hp(10)*	0–0.18	0.04	13	762
	Chest inside the apron/*Hp(10)*	0–0.18	0.02		
	Right hand/*Hp(0.07)*	0–0.30	0.05		
	Left hand/*Hp(0.07)*	0–0.40	0.13		
	Knee/*Hp(0.07)*	0–0.72	0.10		
	Neck without collar/*Hp(10)*	0.14–0.27			
	Neck with collar/*Hp(10)*	0–0.14	0.07		
	Forehead/*Hp(3)*	0–0.33	0.05		
Arteriography ($n = 4$)	Chest outside the apron/*Hp(10)*	0–0.18	0.09	4	390
	Chest inside the apron/*Hp(10)*	0–0.13	0.07		
	Right hand/*Hp(0.07)*	0–0.18	0.05		
	Left hand/*Hp(0.07)*	0–0.65	0.16		
	Knee/*Hp(0.07)*	0–0.18	0.09		
	Neck without collar/*Hp(10)*	0.18–0.18			
	Neck with collar/*Hp(10)*	0–0	0.05		
	Forehead/*Hp(3)*	0–0	0.00		

Procedure type (number of measurements)	*TLD position/ dosimetric quantity*	*Range of dose (mSv)*	*Average dose (mSv)*	*Average time of fluoroscopy (min)*	*Average number of frames*
Valvuloplasty ($n = 5$)	Chest outside the apron/*Hp(10)*	0–0.18	0.04	16	225
	Chest inside the apron/*Hp(10)*	0–0.27	0.08		
	Right hand/*Hp(0.07)*	0–0	0.00		
	Left hand/*Hp(0.07)*	0–0.37	0.07		
	Knee/*Hp(0.07)*	0–0.34	0.12		
	Neck without collar/*Hp(10)*	0–0			
	Neck with collar/*Hp(10)*	0–0	0.00		
	Forehead/*Hp(3)*	0–0	0.00		

Table 75. Mean and maximum doses for the staff of the interventional cardiology (IC) and interventional radiology (IR) services of a university hospital [V9]

Year	*Professionals*	*Mean dose (mSv/a)*		*Maximum dose (mSv/month)*	
		Whole body (under the apron)	*Shoulder (on the apron)*	*Hand (wrist)*	*Shoulder*
1999	IC physicians	0.1	1.0	1.1	13.7
	IC fellows	0.3	2.3		
	IC nurses	0.2	0.9		
2000	IC physicians	0.2	0.7	1.3	18.8
	IC fellows	0.2	2.5		
	IC nurses	0.1	0.9		
2001	IC physicians	0.1	2.0	9.3	10.5
	IC fellows	0.3	2.6		
	IC nurses	0.1	1.0		
1999	IR physicians	0.1	2.7	2.9	5.8
	IR technicians	0.1	0.4		
2000	IR physicians	0.1	2.1	3.2	7.1
	IR technicians	0.1	0.2		
2001	IR physicians	0.1	2.1	3.6	3.5
	IR technicians	0.1	0.4		

Table 76. Dose per procedure in vascular interventional radiology, measured by TLD [V7]

TLD location	*Sample size*	*Average dose (μSv)*	*Median dose (μSv)*	*Range (μSv)*
Left shoulder	21	283	182	45–1 214
Right eye	18	296	122	45–2 103
Left eye	19	284	95	40–1 683
Forehead	19	222	159	19–1 013
Neck	19	325	138	48–2 104
Right hand	23	260	120	47–974
Left hand	23	396	184	40–2 150
Left forearm	22	326	225	40–1 886
Arm	29	365	243	50–1 068

Table 77. Dose per procedure in interventional cardiology, measured by TLD [V7]

TLD location	*Sample size*	*Average dose (μSv)*	*Median dose (μSv)*	*Range (μSv)*
Average of doses with and without lead screen				
Left shoulder	55	252	185	30–1 031
Right eye	53	167	140	39–742
Left eye	54	294	193	53–1 005
Forehead	53	236	178	40–934
Neck	54	269	214	43–816
Right hand	54	191	144	45–921
Left hand	58	364	256	60–1 500
Left forearm	54	646	445	88–2 890
Arm	54	618	414	70–1 919
With lead screen				
Left shoulder	29	136	145	30–250
Right eye	29	136	140	52–252
Left eye	29	170	148	53–460
Forehead	29	145	150	40–415
Neck	29	163	160	43–398
Right hand	28	147	128	45–466
Left hand	31	235	195	60–740
Left forearm	29	440	350	88–2 890
Arm	30	265	237	70–727
Without lead screen				
Left shoulder	26	382	308	125–1 031
Right eye	24	205	138	39–742
Left eye	25	439	425	158–1 005
Forehead	26	344	330	103–934
Neck	27	392	389	60–816
Right hand	25	242	149	45–921
Left hand	25	514	372	65–1 500
Left forearm	25	885	801	168–2 006
Arm	24	1 061	1 027	108–1 919

Table 78. Occupational doses associated with specific interventional procedures

Dose per procedure (mSv)	*Procedure type*	*X-ray system*	*Relevant exposure parameters*	*Protection tools used*	*Reference*
0.215–0.370 (at thyroid level)	Coronary angiography	Philips Polydiagnost C2	2.8–3.4 min fluoroscopy, 637–1 058 frames	Ceiling-mounted screen, 1 mm lead	[S37]
0.008–0.113 (forehead)	Cardiac catheterization	Three centres, five X-ray units	2–3 min fluoroscopy, 500–2 000 frames, 4 400 cGy/cm^2	Ceiling-mounted screen, protective eye shields (reduction in exposure rate by a factor of about 20)	[P12]
0.05–0.14 (neck)	Vascular and liver	Philips Integris 3000 GE L-U	5 400–6 700 cGy/cm^2	Ceiling-mounted screen in only one room	[W15]
0.28 (left eye), 0.20 (thyroid)	Cardiac catheter ablation	Siemens Angioskop D	44 min fluoroscopy	Ceiling-mounted screen	[C1]
0.05 (collar level)	Coronariography and PTCA	Philips Integris 3000 DC	6 600 cGy/cm^2	Movable shield	[Z6]

Dose per procedure (mSv)	*Procedure type*	*X-ray system*	*Relevant exposure parameters*	*Protection tools used*	*Reference*
0.43 (forehead, eye)	Coronary angiography and PTCA	14 laboratories	Cine 53 s, fluoroscopy 6.8 min	Protective eyeglasses	[K3]
0.014 (eye)	Cerebral angiography, arterial embolization	CGR DG 300	4 850 cGy/cm^2, 12 220 cGy/cm^2	Waist-height lead shield	[M10]
1–2 (eye)	Interventional radiology	General Electric Phasix 80	10 images, 10 min fluoroscopy	No ceiling-mounted screen; lead apron and gloves	[V8]

Table 79. Worldwide levels of occupational exposure due to diagnostic radiology
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	630		600	0.9	
1980–1984	1 060		720	0.7	
1985–1989	1 350		760	0.6	
1990–1994	950	350	470	0.5	1.3
1995–1999	6 670		3 300	0.5	
2000–2002	6 670		3 300	0.5	

Table 80. Worldwide levels of occupational exposure due to dental practice
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	370		120	0.32	
1980–1984	500		93	0.20	
1985–1989	480		25	0.05	
1990–1994	265	17	16	0.06	0.89
1995–1999	404		24	0.06	
2000–2002	404		24	0.06	

Table 81. Annual doses incurred by PET workers [Z5]

Worker	*Effective dose (mSv)*	*Equivalent dose to hands (mSv)*	*Film monthly dose range (mSv)*	*Ring monthly dose range (mSv)*
Technologist 1	8.0	90.0	0.4–1.1	4.1–9.9
Technologist 2	4.6	63.5	0.3–0.7	0.7–9.1
Physician 1	2.2	5.2	0.1–0.7	0.2–1.2
Physician 2	1.9	6.0	0.1–0.7	0.3–4.2

Table 82. Occupational doses (μSv) for various tasks, different patients and different technologists

Each patient was administered 555 MBq of ^{18}F FDG [M17]

	Patient 1 *Technologist A*	*Patient 2* *Technologist A*	*Patient 3* *Technologist B*	*Patient 4* *Technologist B*
	PC C[c]	*PC A*[a]	*PC A*[a]	*PC B*[b]
Measure dosage	1.4	0.2	4.0	2.4
Carry dosage	0.1	0.0	0.1	0.9
Inject	1.8	0.7[d]	1.9	3.9
Escort to waiting area	0.5	0.8	0.0	1.8
Interview	1.8	0.0	0.0	0.7
Escort to imaging lab	1.4	0.3	0.5	0.5
Position	2.0	3.4	1.2	6.8
Reposition after 1 h	0.0	0.0	0.0	1.1
Exit	0.2	0.0	0.0	0.8
Total	9.2	5.4	7.7	18.9

[a] PC A: patient fully ambulatory and able to follow instructions.

[b] PC B: patient haltingly ambulatory, occasionally in a wheelchair.

[c] PC C: patient confined to a wheelchair, able to follow instructions with physical assistance.

[d] Physician performed injection.

Table 83. Occupational exposures due to the use of different types of scan [W11]

Scan	*Isotope*	*Number of patients*	*Median administered activity (MBq)*	*Median time post-injection (h)*	*Median exposure (μSv/h) for distance*			
					2 m	*1 m*	*0.5 m*	*0 m*
PET	^{18}F	41	57.4	1.1	2.0	5.2	14.1	71.0
Bone	Tc-MDP	57	760.2	3.5	1.8	3.4	9.0	43.0
LVEF[a]	Tc-RBC	23	900.0	0.3	3.0	8.0	21.0	144.0
Thallium	^{201}Tl	28	250.0	1.0	1.1	1.9	5.2	28.0
Renal	Tc-DTPA	33	389.6	2.0	1.0	2.1	4.6	23.0
Gallium	^{67}Ga	38	400.0	120.0	0.9	1.6	4.2	19.1
Cardiac	Sestamibi	31	900.0	1.0	4.1	9.4	19.3	110.3

[a] Left ventricular ejection fraction.

Table 84. Maximum daily dose to skin of the hands during radiosynoviorthesis [B9]

Measurement cycle	*Maximum daily dose Hp(0.07) (mSv)*			*^{90}Y administered (MBq)*	*Specific dose (μSv/MBq)*
	Preparation	*Application*	*Assistance*		
A-1[a]	82	43	5	805	53
A-2	101	132	10	1 675	79
A-3	16	16	2	620	26
A-4	18	33	Not measured	1 480	22
A-5	Not measured	1[b]	Not measured	555	1.8
A-6	Not measured	1[b]	Not measured	1 110	0.9
B-1	108	27	Not measured	2 035	13
C-1	14	41	Not measured	555	74
F-1	7	62	9	460	135
F-2	8	1[b]	36	2 005	0.5
G-1	15	5	1	180	28
G-2	4	11	2	360	31
H-1	55	207	None	888	233
I-1	8	31 (Doctor 1)	None	1 332	23
I-2	Not measured	84 (Doctor 2)	None	2 442	34
I-3	6	1[b] (Doctor 1)	None	1 554	0.6
I-4	Not measured	1[b] (Doctor 2)	None	1 332	0.8

[a] Seven different institutions.

[b] Use of forceps during application of radionuclides.

Table 85. Worldwide levels of occupational exposure in nuclear medicine
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	61	65	62	1.0	1.4
1980–1984	81		85	1.0	
1985–1989	90		85	1.0	
1990–1994	115		90	0.8	
1995–1999	117		89	0.8	
2000–2002	120		87	0.7	

Table 86. Mean dose per application of ^{125}I in prostate using afterloading technique, and annual effective dose incurred by staff at various distances from the source [G4]

Staff	*μSv per application (annual) for distance*			
	0.5 m	*1 m*	*2 m*	*3 m*
Physicians	15 (1 200)	4.3 (347)	0.2 (13)	0.06 (4.8)
Physicist		4.3 (347)	1.3 (104)	
Nurses	15 (1 200)	4.3 (347)	0.2 (14)	0.06 (4.8)
Assistants				0.06 (4.8)

Table 87. Worldwide levels of occupational exposure in radiotherapy
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	84	48	190	2.2	1.3
1980–1984	110		180	1.6	
1985–1989	110		100	0.9	
1990–1994	120		65	0.6	
1995–1999	264		132	0.5	
2000–2002	264		132	0.5	

Table 88. Trends of occupational exposure in all medical uses
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	1 280	650	993	0.8	1.5
1980–1984	1 890	520	1 140	0.6	1.7
1985–1989	2 220	590	1 030	0.5	1.7
1990–1994	2 320	550	760	0.3	1.4
1995–1999	7 440		3 540	0.5	
2000–2002	7 440		3 540	0.5	

Table 89. Occupational exposure in industrial radiography in the United States [U29, U30, U31, U32, U33, U34, U36, U37]

Year	*Multiple-location*					*Single-location*				
	Monitored workers	*Measurably exposed workers*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Monitored workers*	*Measurably exposed workers*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*				*Monitored workers*	*Measurably exposed workers*
1995	3 245	2 404	13.32	4.10	5.54	285	61	0.06	0.21	0.99
1996	3 340	2 477	13.75	4.12	5.55	291	60	0.10	0.35	1.67
1997	3 140	2 370	12.81	4.08	5.40	296	84	0.10	0.34	1.19
1998	4 571	3 355	18.51	4.05	5.52	369	84	0.08	0.22	0.95
1999	3 571	2 777	15.44	4.32	5.56	266	50	0.07	0.26	1.41
2000	3 029	2 399	14.80	4.89	6.17	258	78	0.08	0.31	1.01
2001	3 522	3 082	21.05	5.98	6.83	256	79	0.06	0.23	0.75
2002	3 292	2 773	17.19	5.22	6.20	112	55	0.04	0.40	0.81
1995–1999	3 573	2 677	14.77	4.13	5.51	301	68	0.08	0.28	1.24
2000–2002	3 281	2 751	17.68	5.36	6.40	209	71	0.06	0.31	0.86

Table 90. Radiation dose to workers in a cyclotron and radiochemistry laboratory

As measured by national personnel monitoring service using $CaSO_4$:Dy TLD badges [P3]

Occupational exposure in cyclotron/ radiochemistry laboratory	*Whole-body dose (mSv)*	*Extremity (wrist) dose (mSv)*
Cyclotron	0.35	7.95
Cyclotron	0.85	0.45
Radiochemistry	0.60	4.45
Radiochemistry	1.80	3.4

Table 91. Global occupational exposures due to the nuclear fuel cycle and natural sources of radiation

Practice	*Monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose to monitored workers (mSv)*
Nuclear fuel cycle			
1995–1999			
Mining	22	85	3.9
Milling	3	4	1.6
Enrichment	17	1	0.1
Fuel fabrication	22	30	1.4
Reactor operation	448	779	1.5
Reprocessing	59	61	1.1
Research	96	37	0.4
Total	670	1 000	1.4
2000–2002			
Mining	12	22	1.9
Milling	3	3	1.1
Enrichment	18	2	0.1
Fuel fabrication	20	28	1.6
Reactor operation	437	600	1.0
Reprocessing	76	68	0.9
Research	90	36	0.4
Total	660	800	1.0
Natural sources of radiation			
1995–1999 and 2000–2002			
Coal mining	6 900	16 560	2.4
Other mining	4 600	13 800	3.0
Workplaces other than mines	1 250	6 000	4.8
Aircrew	300	900	3.0
Total	13 050	37 260	2.9

Table 92. Global occupational exposures associated with man-made and natural sources of radiation

Source of exposure	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1995–1999*	*2000–2002*
Number of monitored workers (10^3)						
Natural radiation				6 500	13 050	13 050
Nuclear fuel cycle	560	800	888	800	670	660
Medical uses	1 280	1 890	2 220	2 320	7 440	7 440
Industrial uses	530	690	560	700	790	869
Military activities	310	350	400	420	378	331
Miscellaneous	140	180	160	360	476	565
Total (man-made)	2 820	3 910	4 228	4 600	9 754	9 865
Total	2 820	3 910	4 228	11 100	22 804	22 915
Annual collective effective dose (man Sv)						
Natural radiation				11 700	37 260	37 260
Nuclear fuel cycle	2 300	3 000	2 500	1 400	1 000	800
Medical uses	1 000	1 140	1 030	760	3 540	3 540
Industrial uses	870	940	510	360	315	289
Military activities	420	250	250	100	52	45
Miscellaneous	70	40	20	40	53	56
Total (man-made)	4 660	5 370	4 310	2 660	4 960	4 730
Total	4 660	5 370	4 310	14 360	42 220	41 990
Average annual effective dose (mSv)						
Natural radiation				1.8	2.9	2.9
Nuclear fuel cycle	4.4	3.7	2.6	1.8	1.4	1.0
Medical uses	0.8	0.6	0.5	0.3	0.5	0.5
Industrial uses	1.6	1.4	0.9	0.5	0.4	0.3
Military activities	1.3	0.7	0.7	0.2	0.1	0.1
Miscellaneous	0.5	0.3	0.2	0.1	0.1	0.1
Total (man-made)	1.7	1.3	1.0	0.6	0.5	0.4
Total	1.7	1.3	1.0	1.3	1.8	1.8

FIGURES

Figure I. Variation in solar activity in terms of the historical monthly average sunspot numbers during solar cycles [N4]

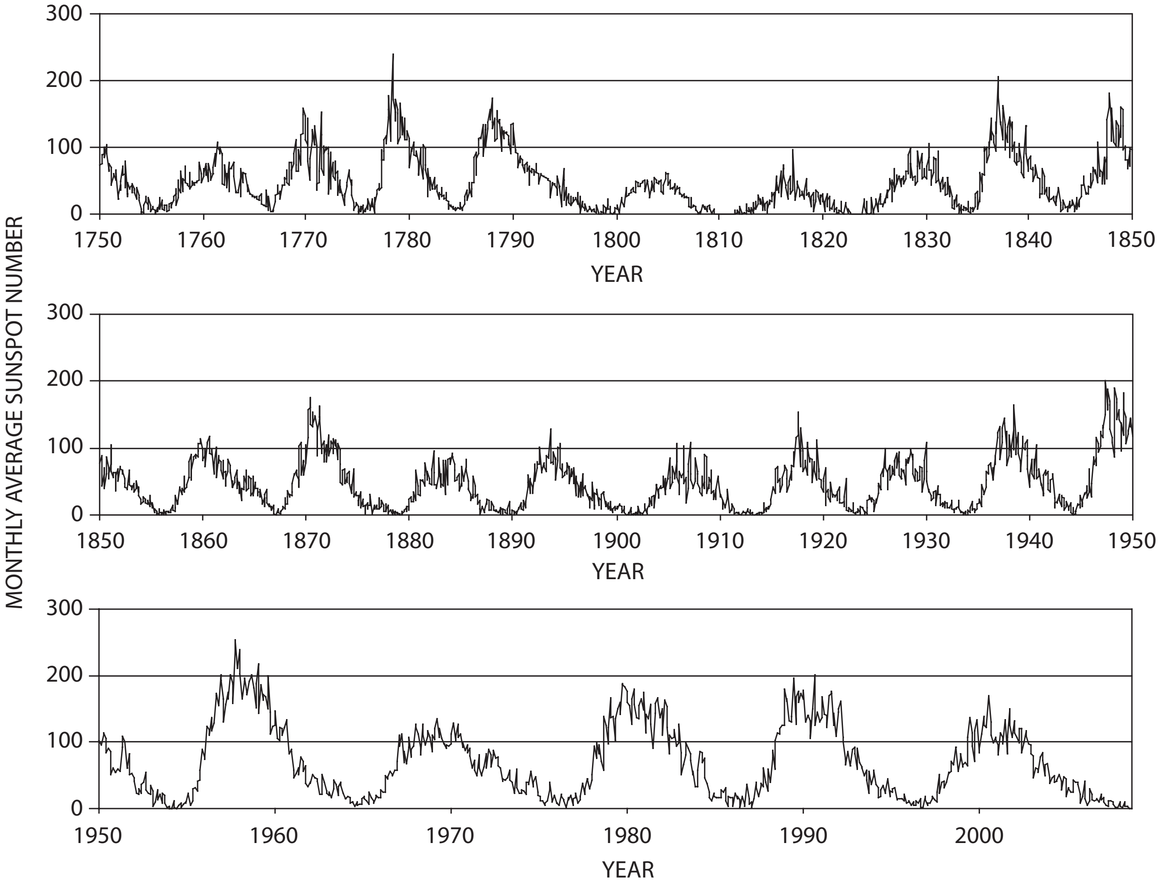


Figure II. Example of the influence of variation in solar activity on cosmic ray dose received during a return transcontinental flight between Frankfurt and New York City [S38]

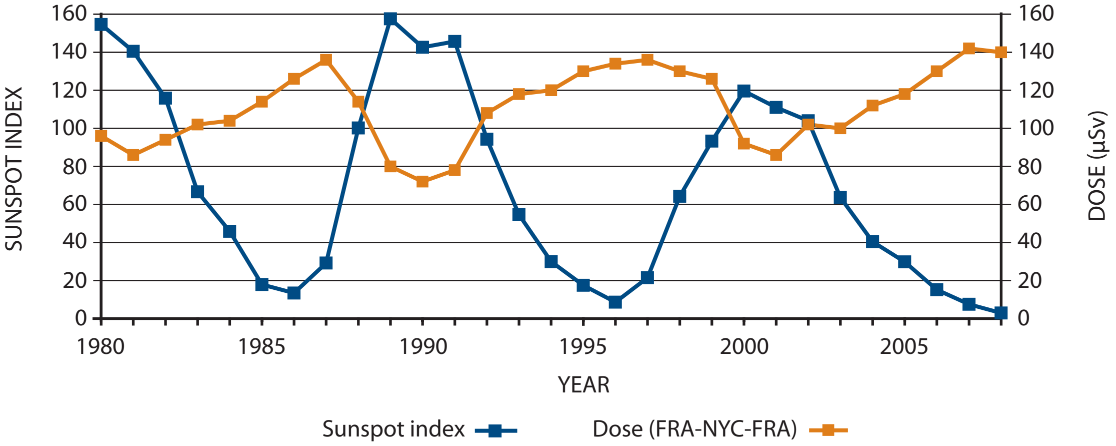


Figure III. Vertical cut-off rigidity, R_c (in GV), at 20 km altitude [S30]

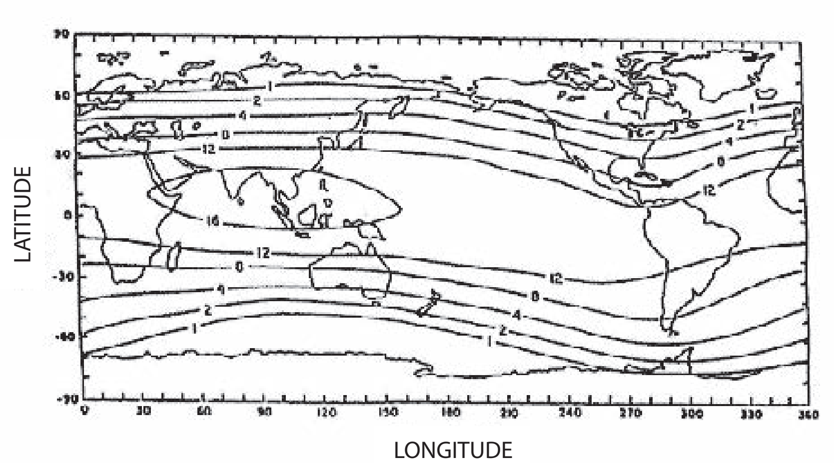


Figure IV. Components of the dose equivalent rate due to cosmic rays in the atmosphere [U3]

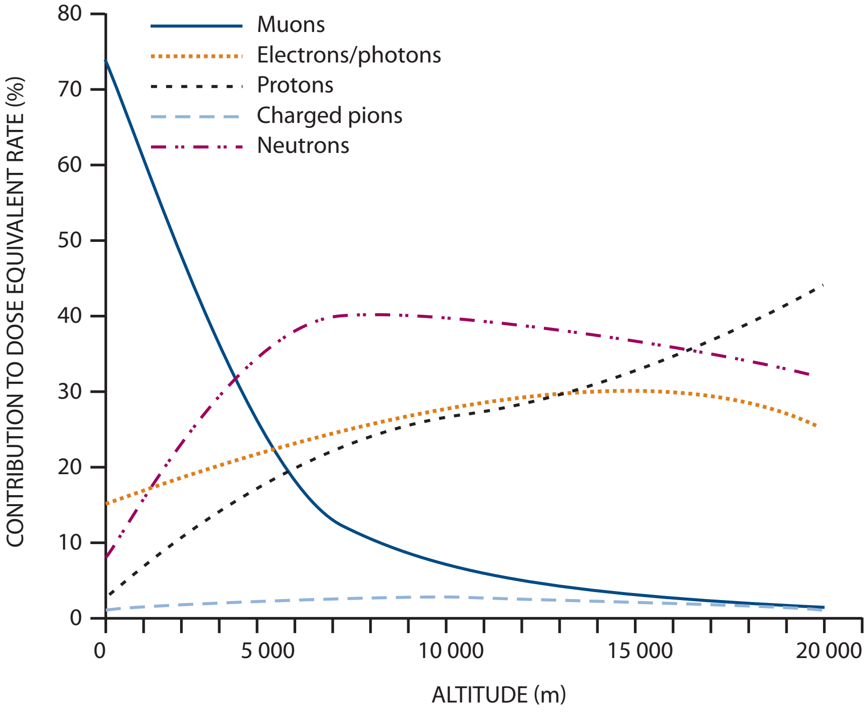
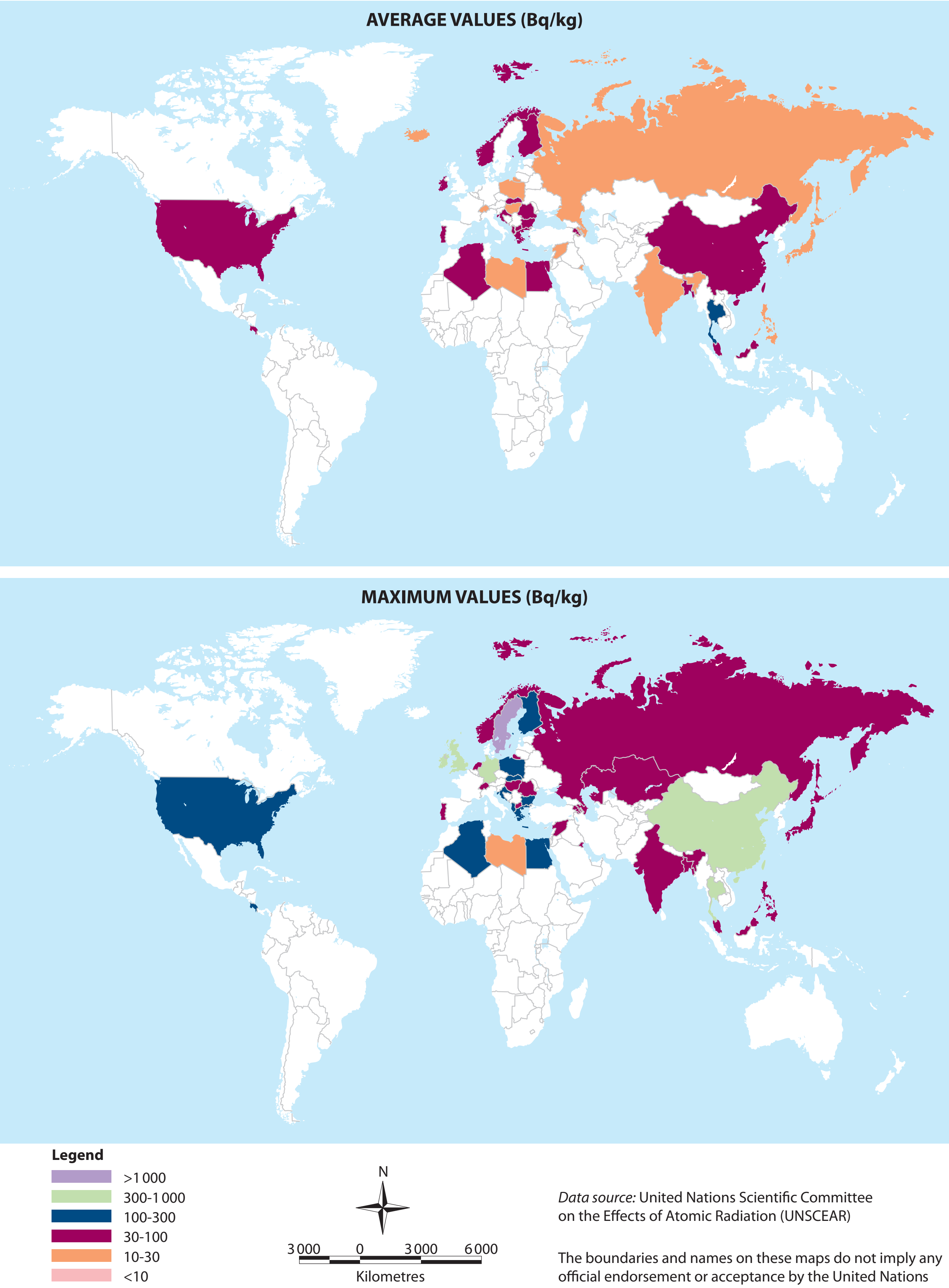


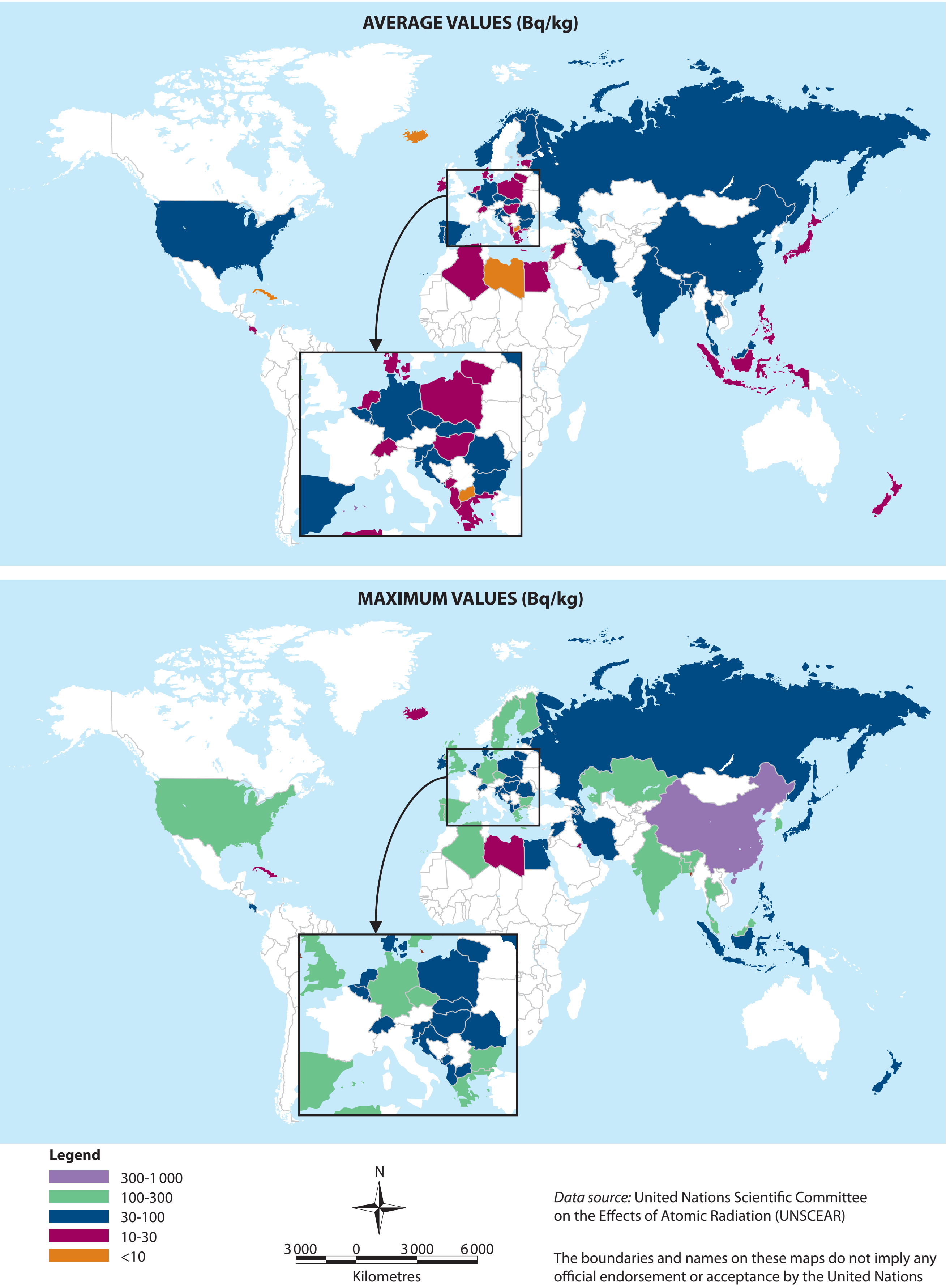
Figure V. Reported concentrations of ^{238}U in soil
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources



Data source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

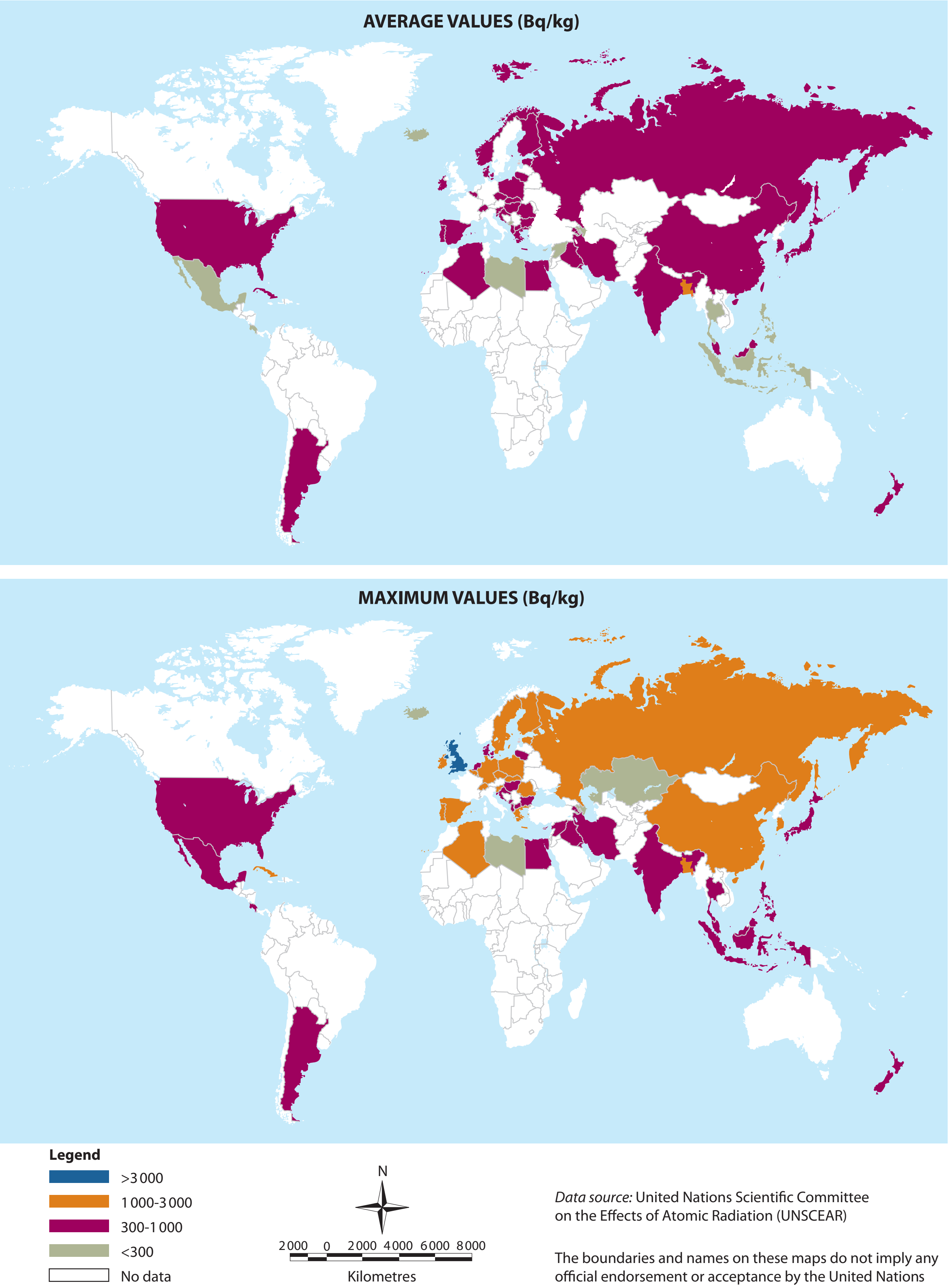
Figure VI. Reported concentrations of ^{232}Th in soil
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources



Data source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

Figure VII. Reported concentrations of ^{40}K in soil
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources.



Data source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

Figure VIII. Distribution of population with respect to ranges of absorbed dose rate in air
(Left: number of persons in each range; right: per cent cumulative distribution fraction for each range)

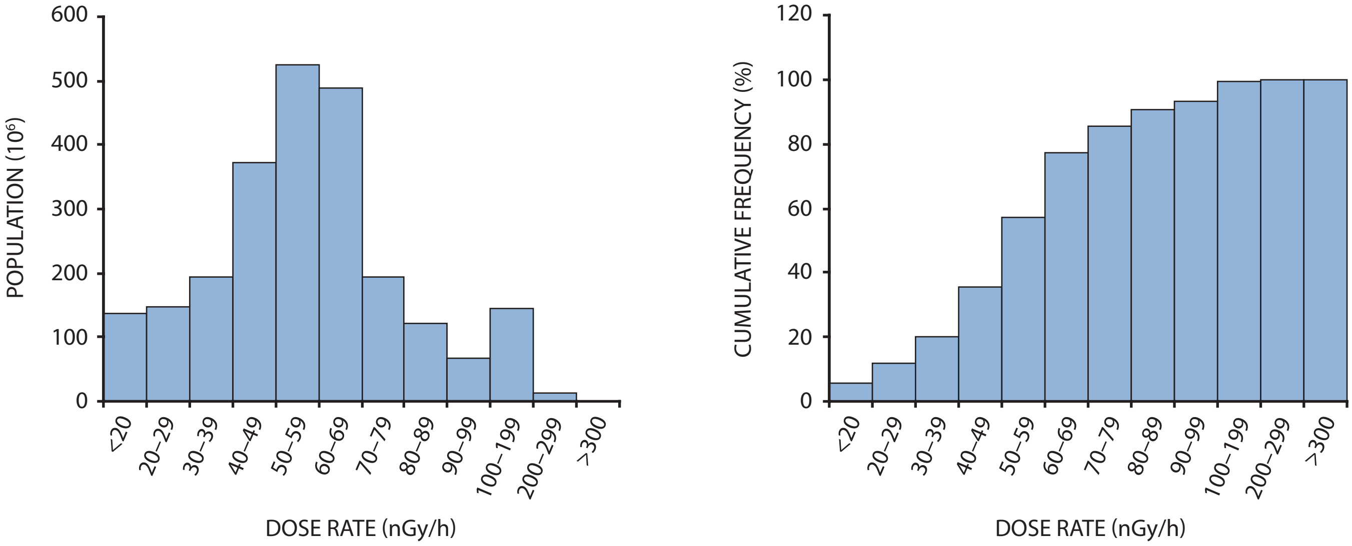
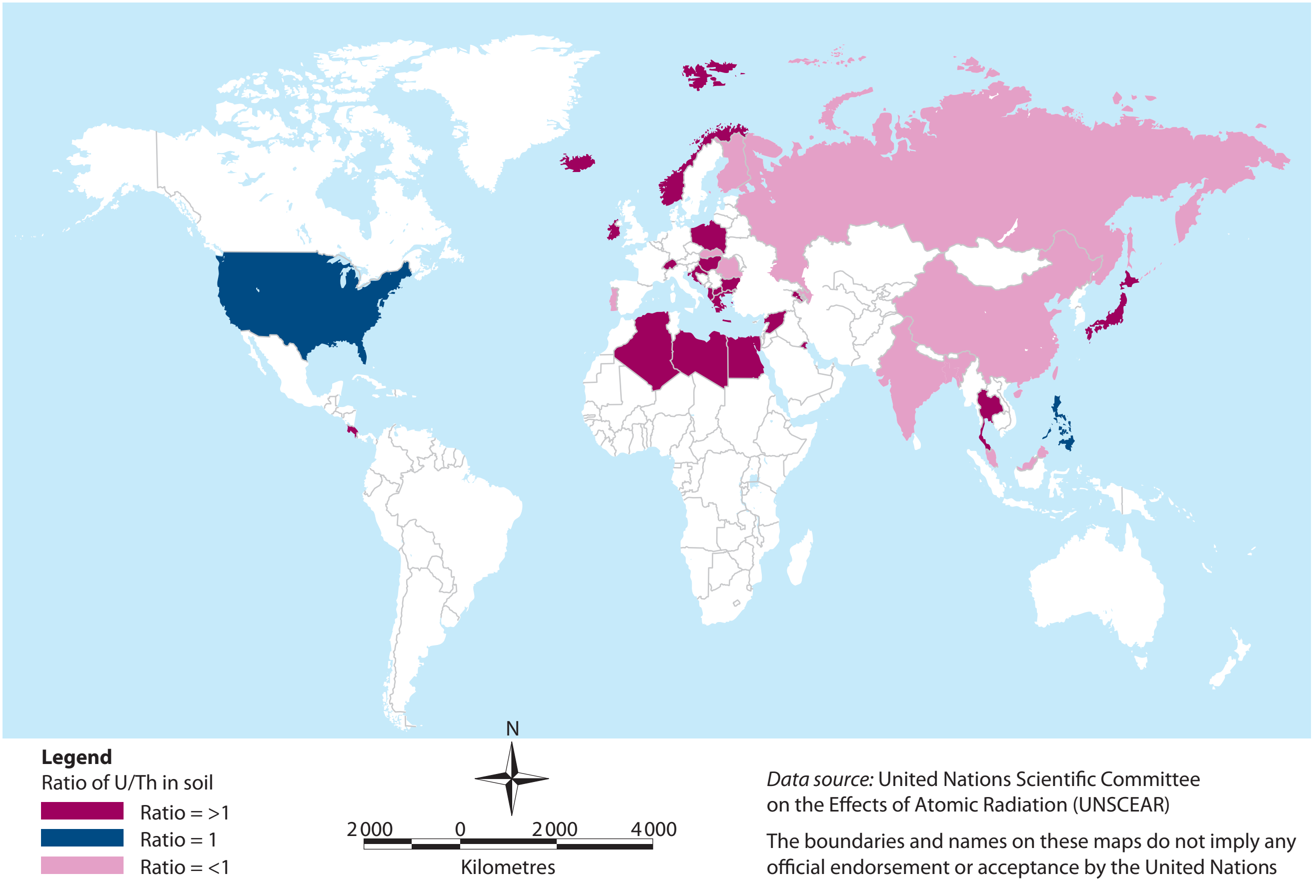


Figure IX. Reported ratios of ^{238}U/^{232}Th concentrations in soil
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources



Data source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

Figure X. Ranges of ^{238}U concentration in drinking water

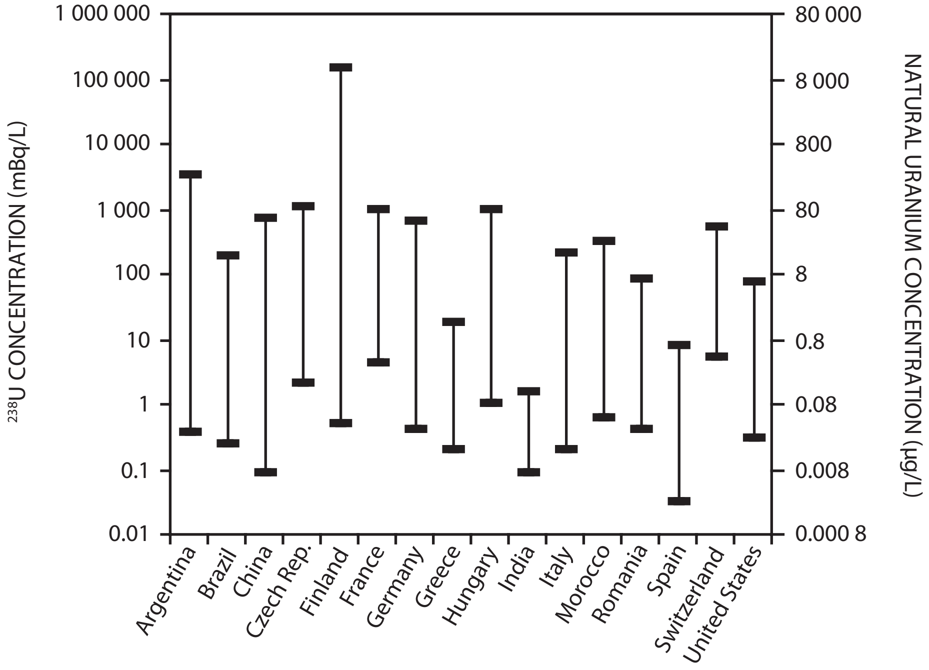


Figure XI. Cumulative frequency distribution of ^{238}U concentration in drinking water

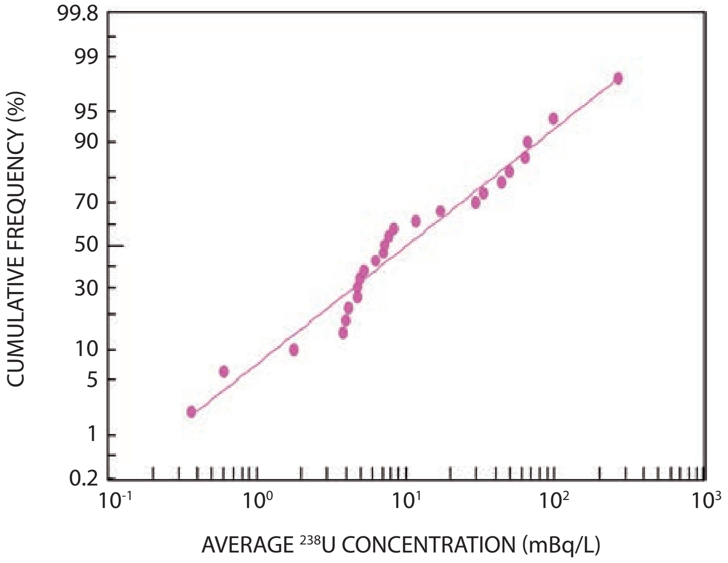


Figure XII. Cumulative frequency distribution of the concentrations in bone of radionuclides of the uranium and thorium series [U3]

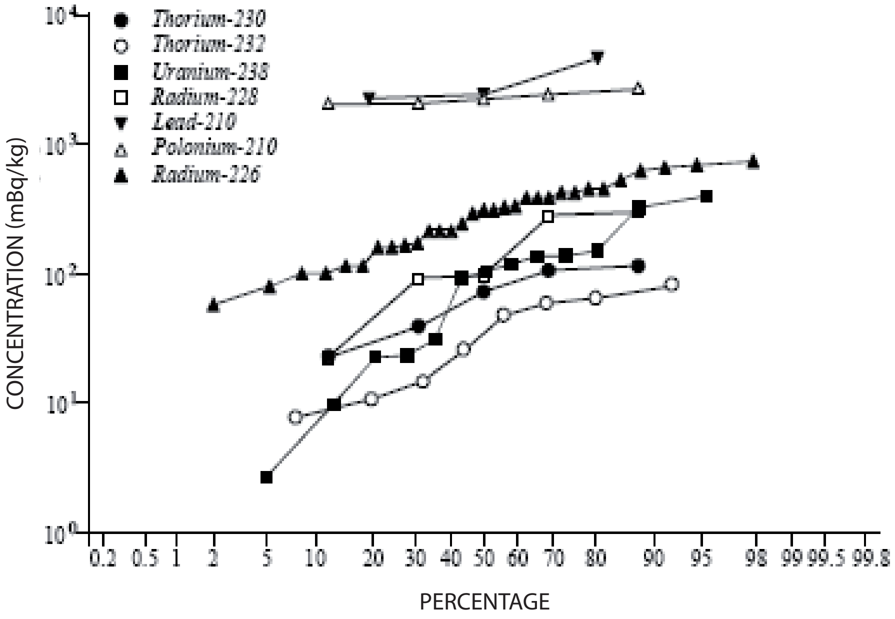


Figure XIII. Distribution of ^{210}Po in human body organs at steady state after chronic ingestion of radionuclides of the uranium and thorium series [C23, F8]

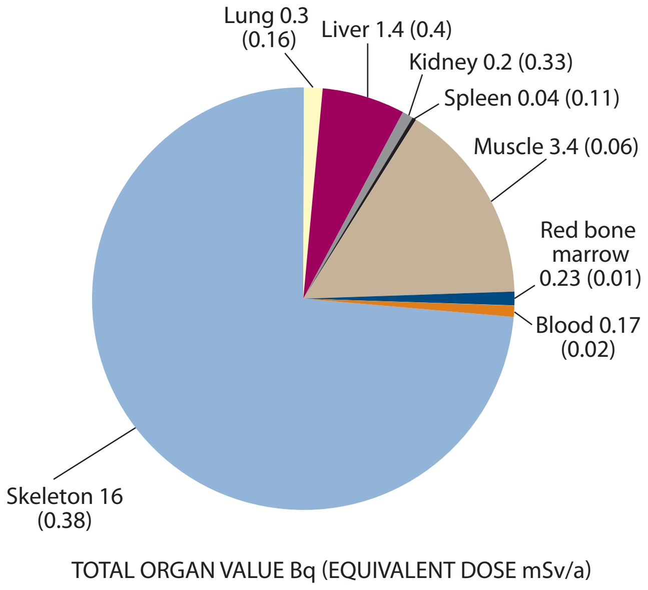


Figure XIV. Distribution of average radon concentrations in the indoor air of houses

Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources and reference [D14]

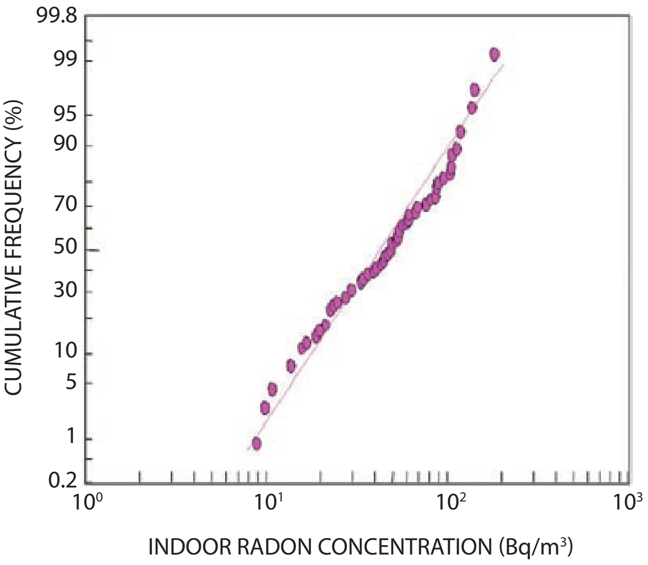


Figure XV. Total worldwide production of uranium (t) to 2003

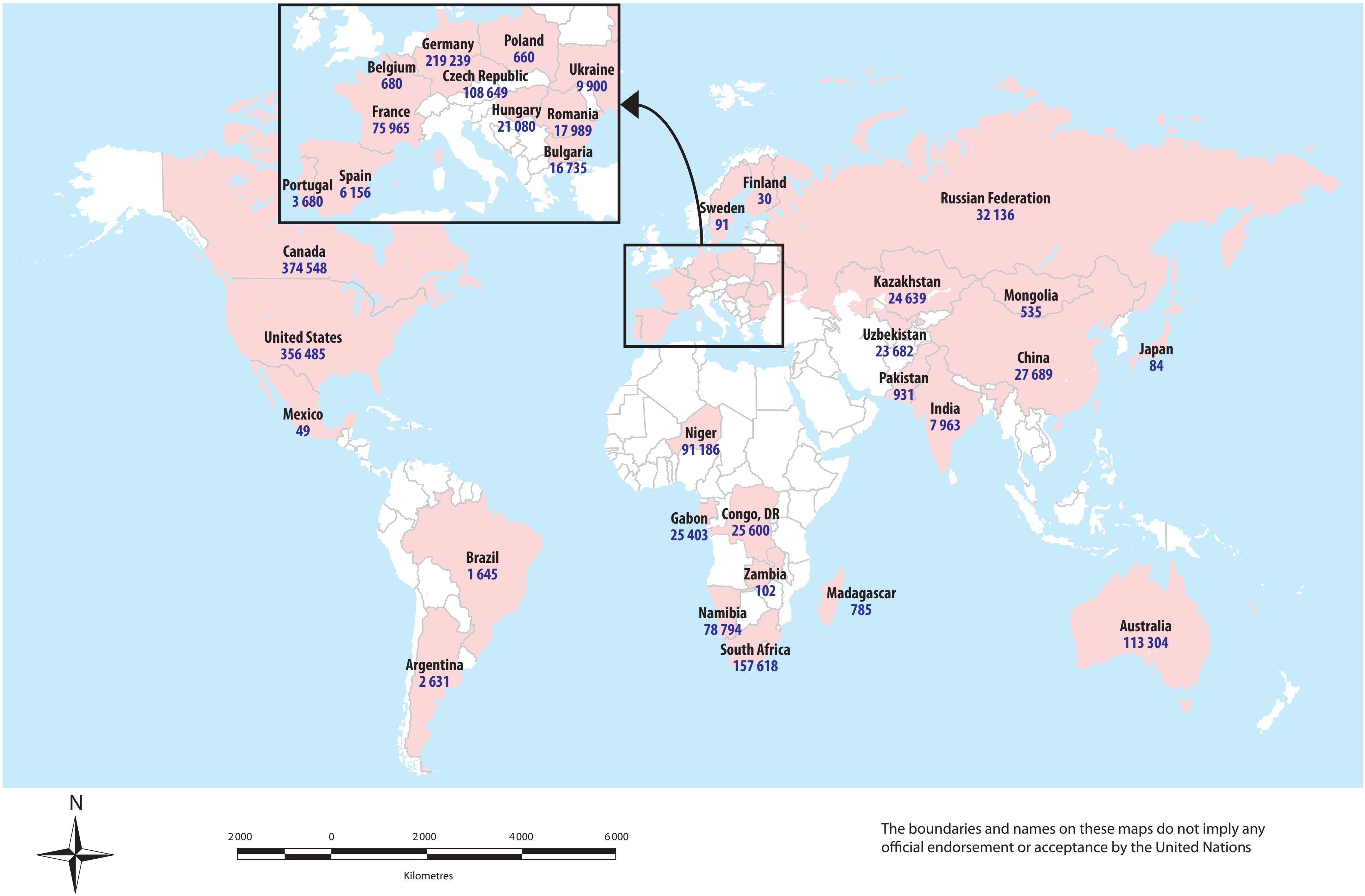


Figure XVI. Annual uranium production from 1990 to 2003 [O16, O17, O21]

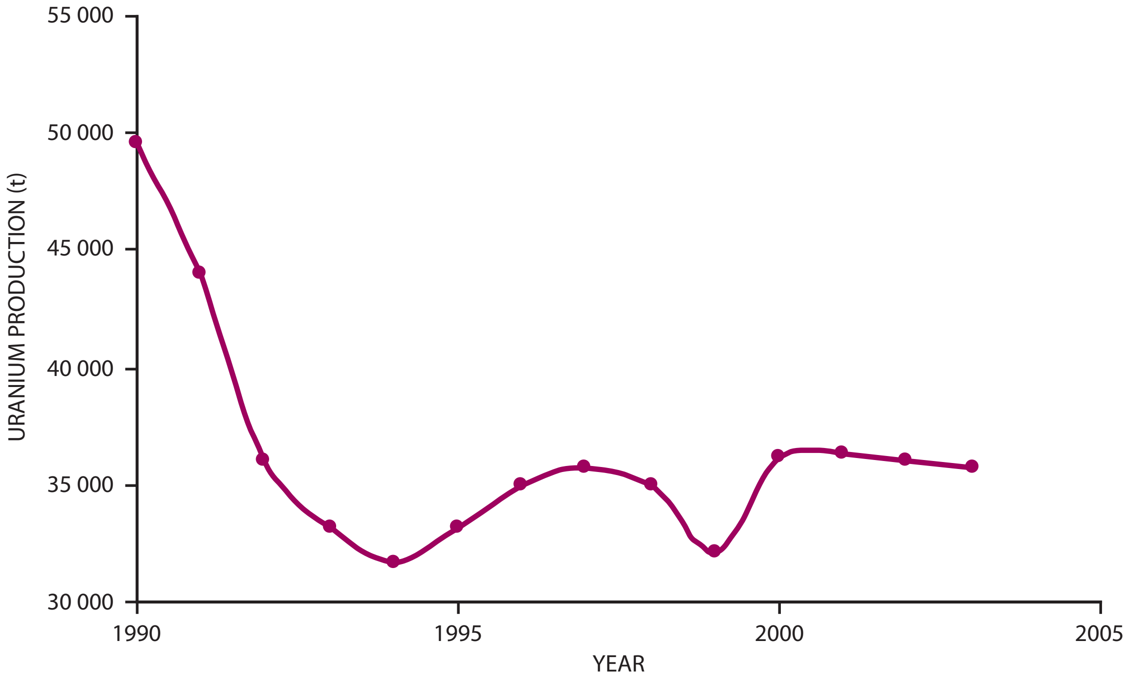


Figure XVII. Tailings from uranium mining and milling (10^6 t)

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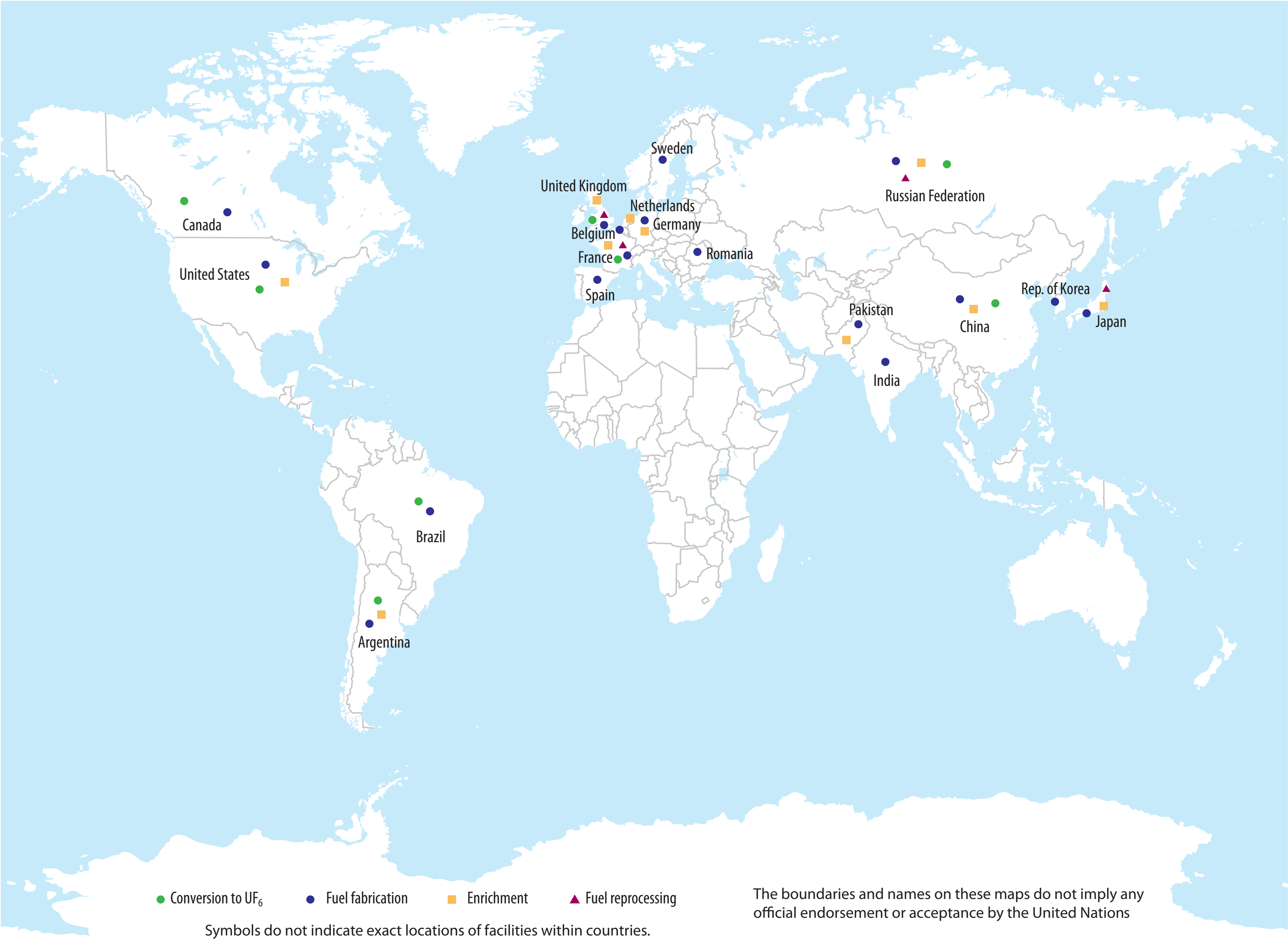
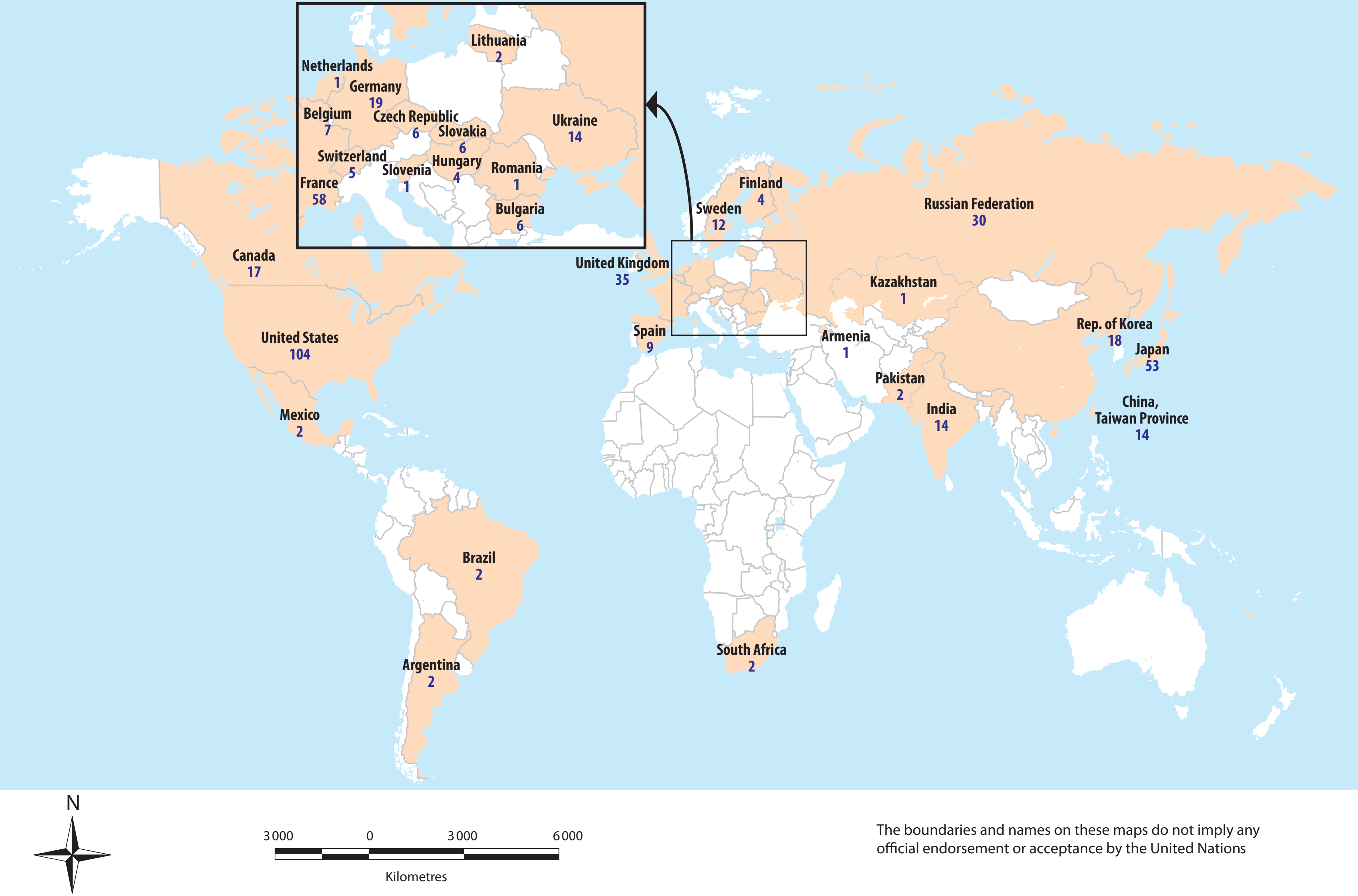
Figure XVIII. Countries with facilities for production of nuclear fuel for power reactors



Symbols do not indicate exact locations of facilities within countries.

The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

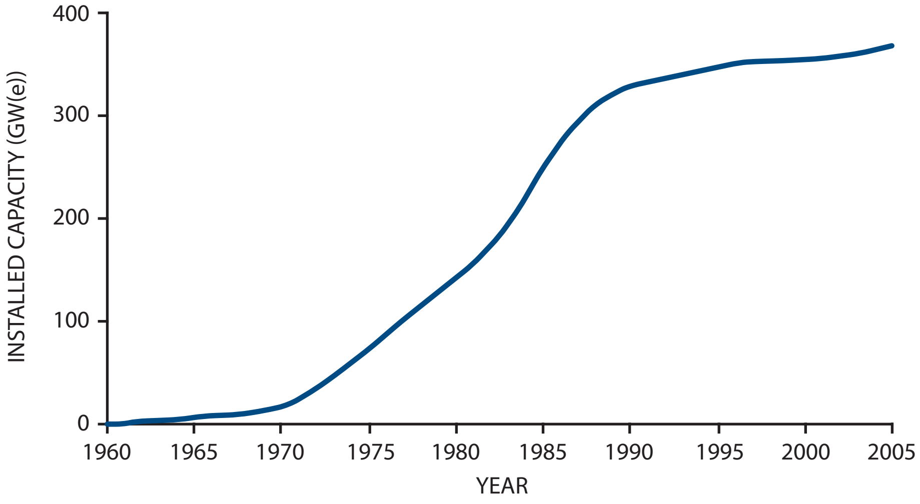
Figure XIX. Nuclear power reactors in the world, 1998–2002



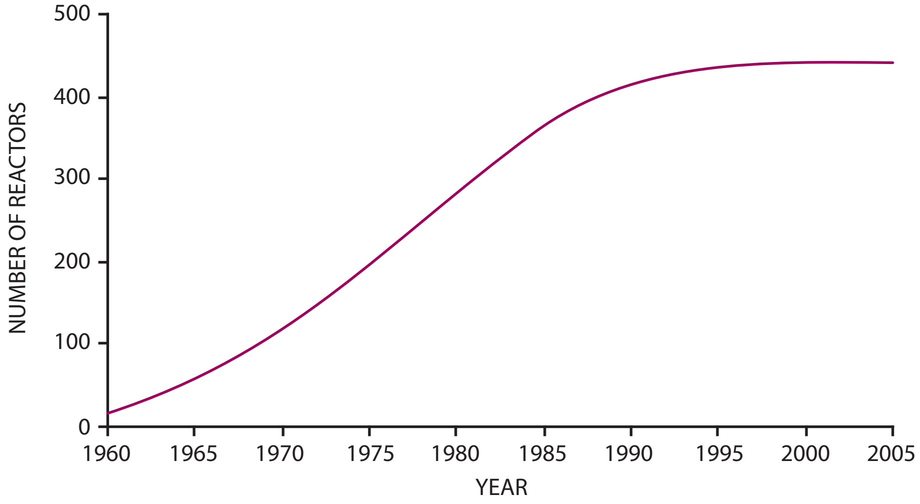
The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

Figure XX. Trends in nuclear energy generation

(a) Total installed electrical energy capacity worldwide



(b) Total number of nuclear power reactors worldwide



(c) Average electrical energy capacity per reactor unit

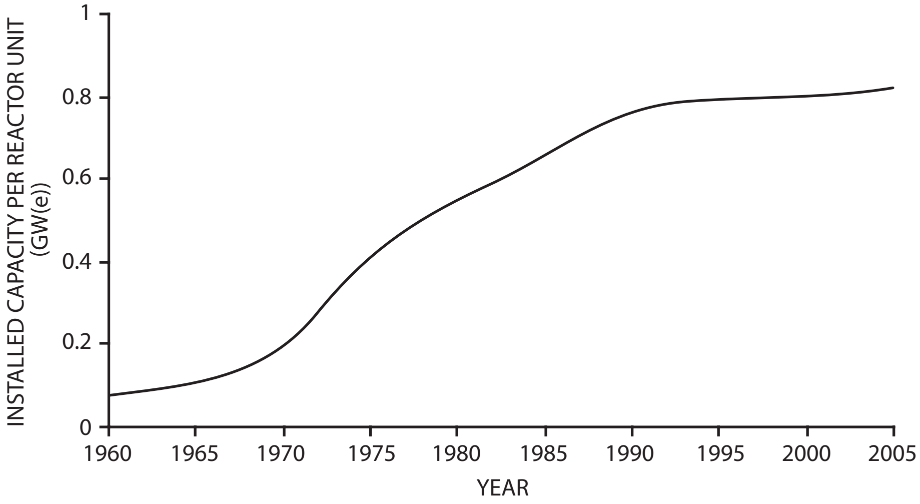


Figure XXI. Historical trends of energy generation by nuclear power reactors

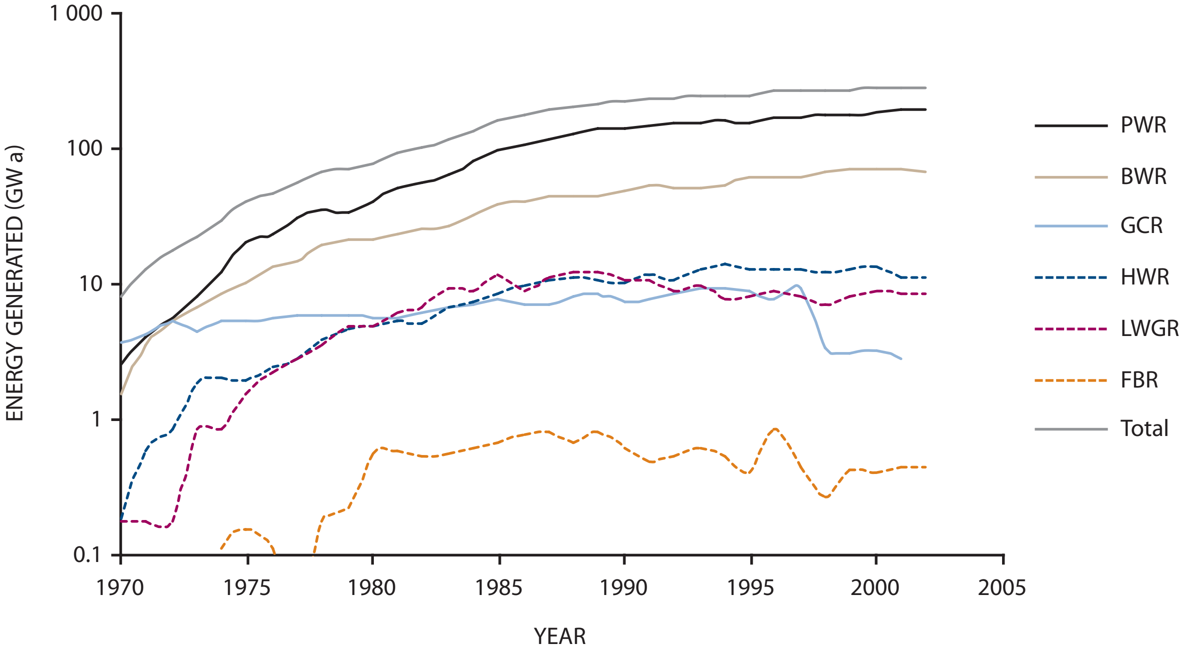


Figure XXII. Contribution of each type of reactor to the total nuclear energy generated in the periods 1970–1997 and 1998–2002

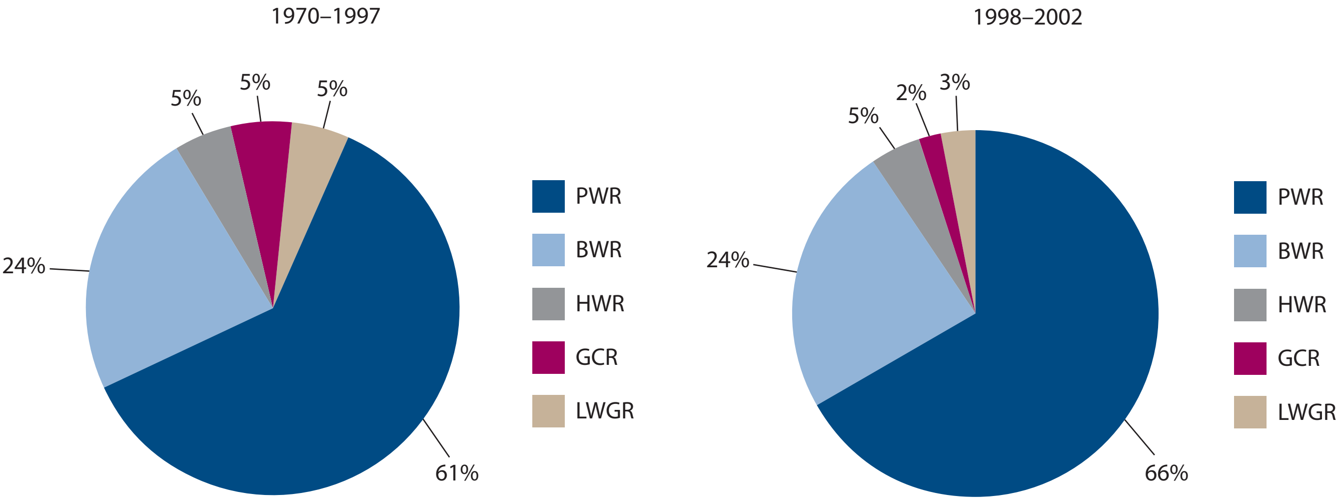


Figure XXIII. Normalized noble gas releases for different periods and types of reactor

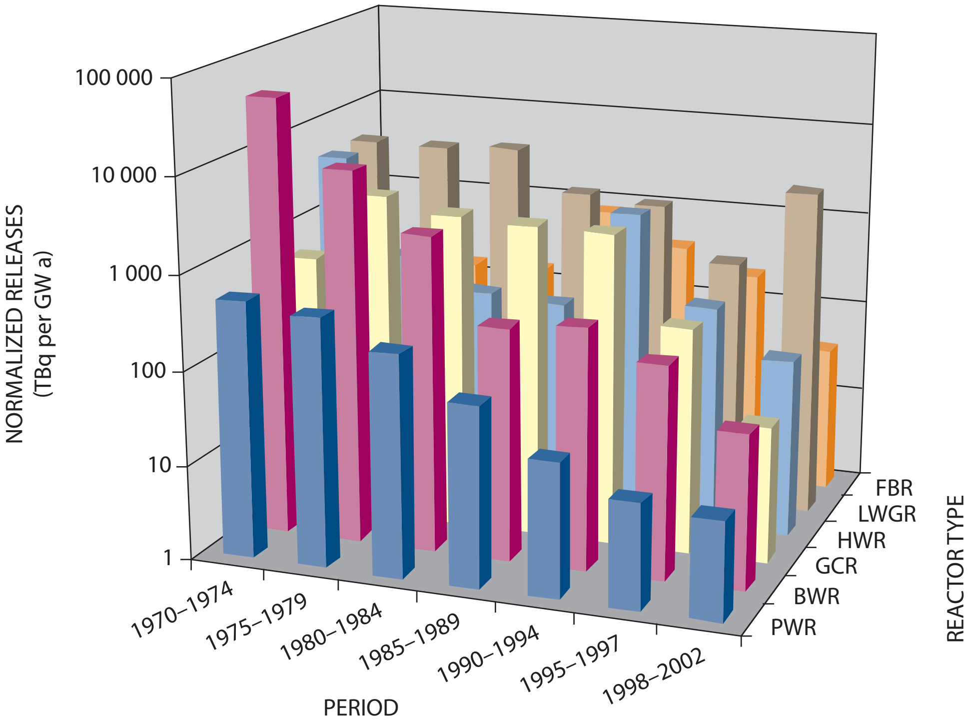


Figure XXIV. Number of nuclear fuel transports in Germany, including irradiated and non-irradiated fuel and waste, by road, rail, sea and air [B48]

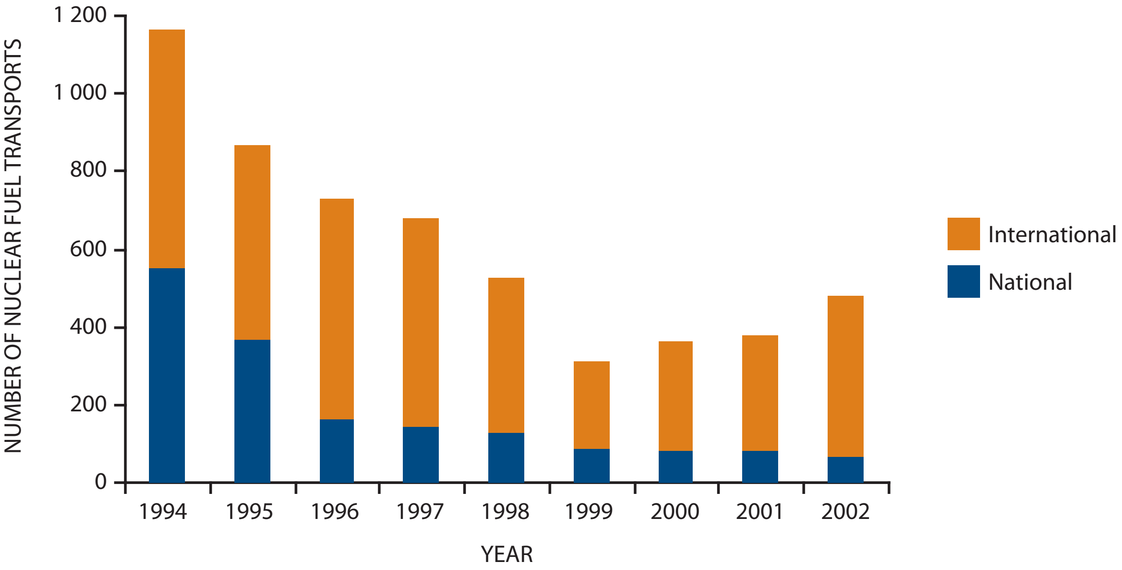
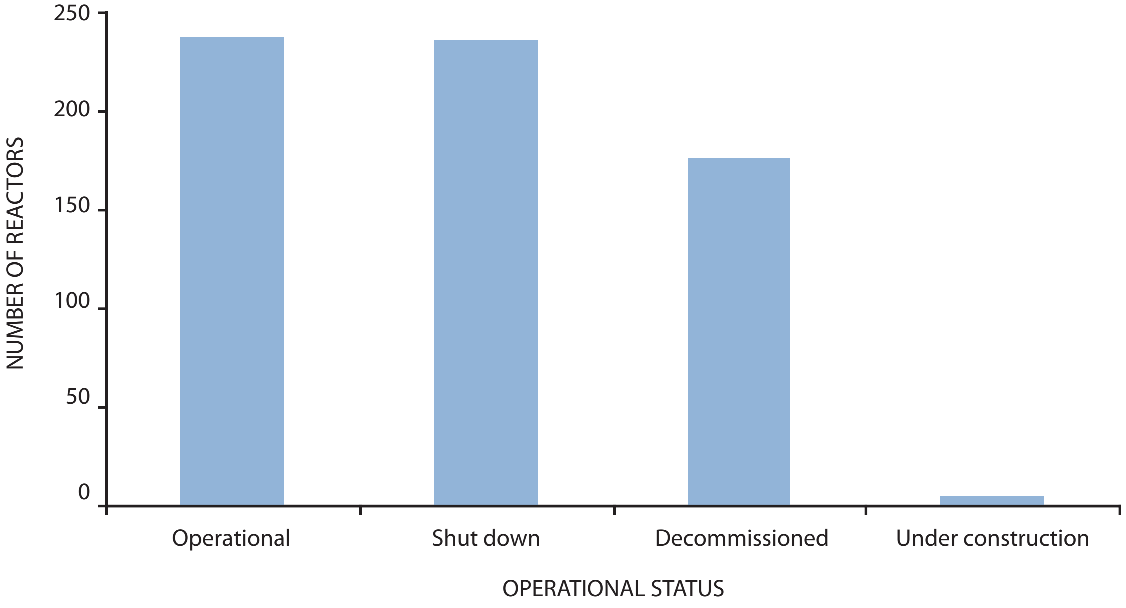


Figure XXV. Number of research reactors worldwide
Operational status (upper figure) and power range (lower figure)



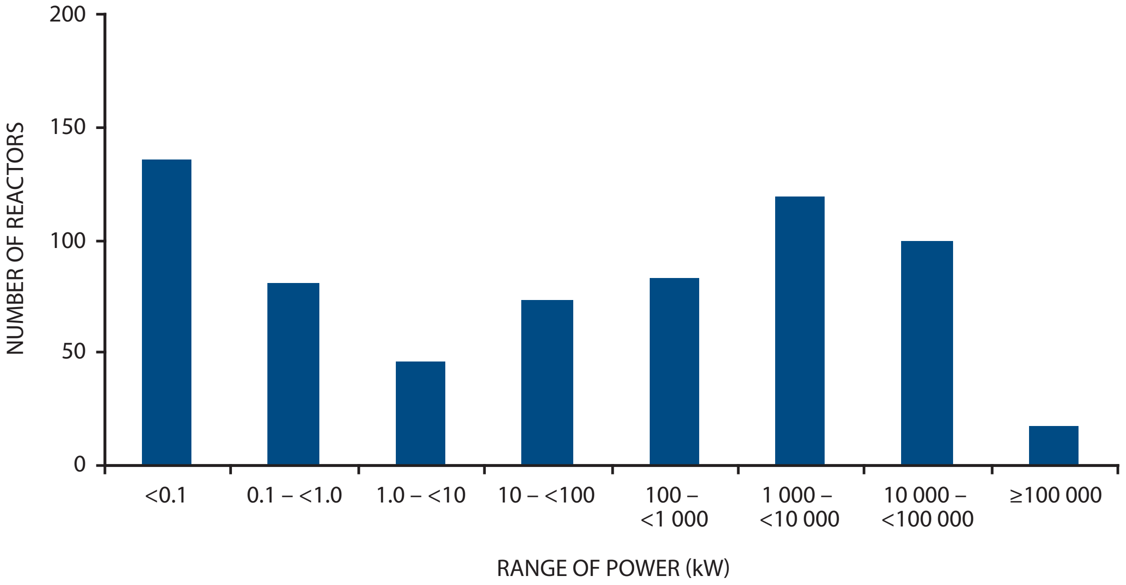
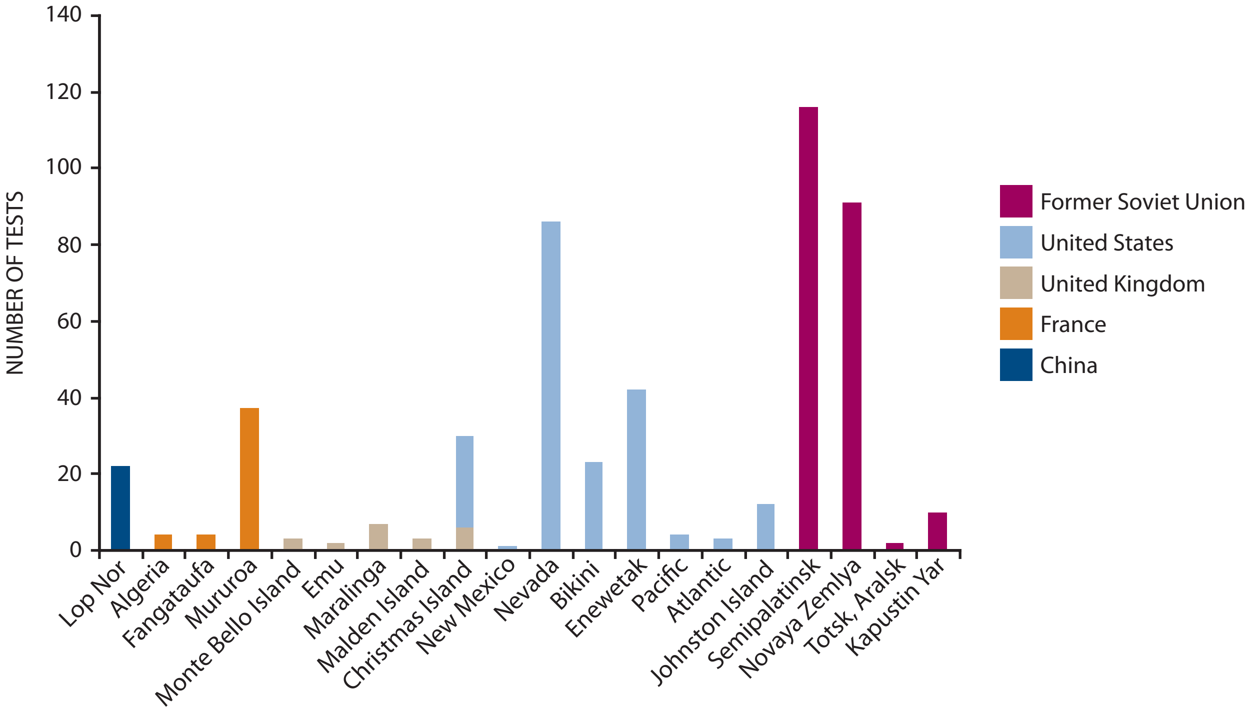


Figure XXVI. Number of tests and fission yields for different atmospheric layers for each nuclear test site

(a) Number of tests at each test site



(b) Fission yield at each test site

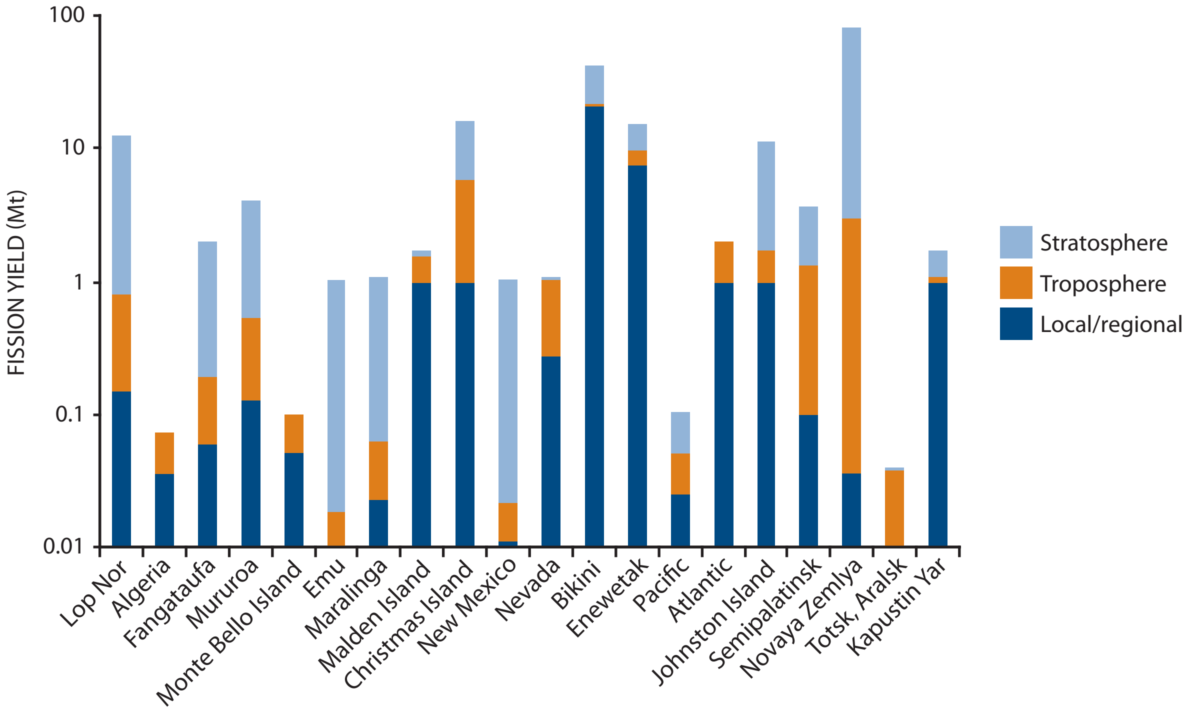


Figure XXVII. Worldwide average per caput effective doses from nuclear weapons tests

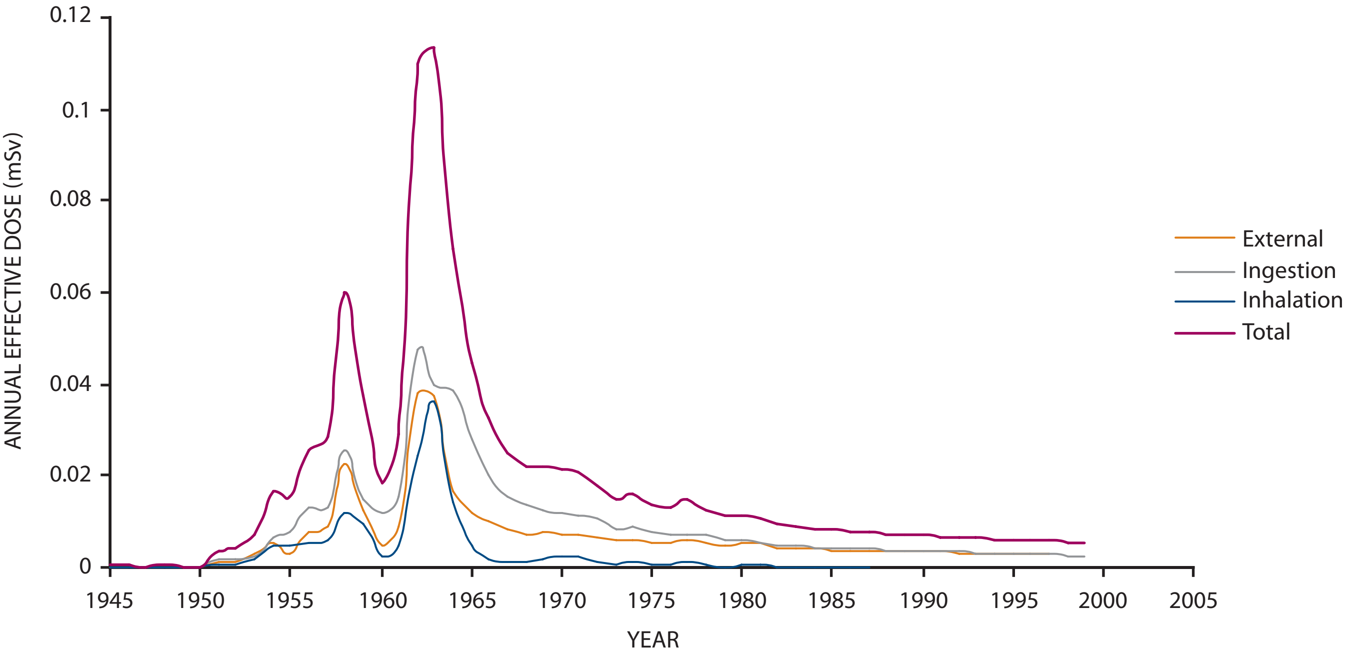
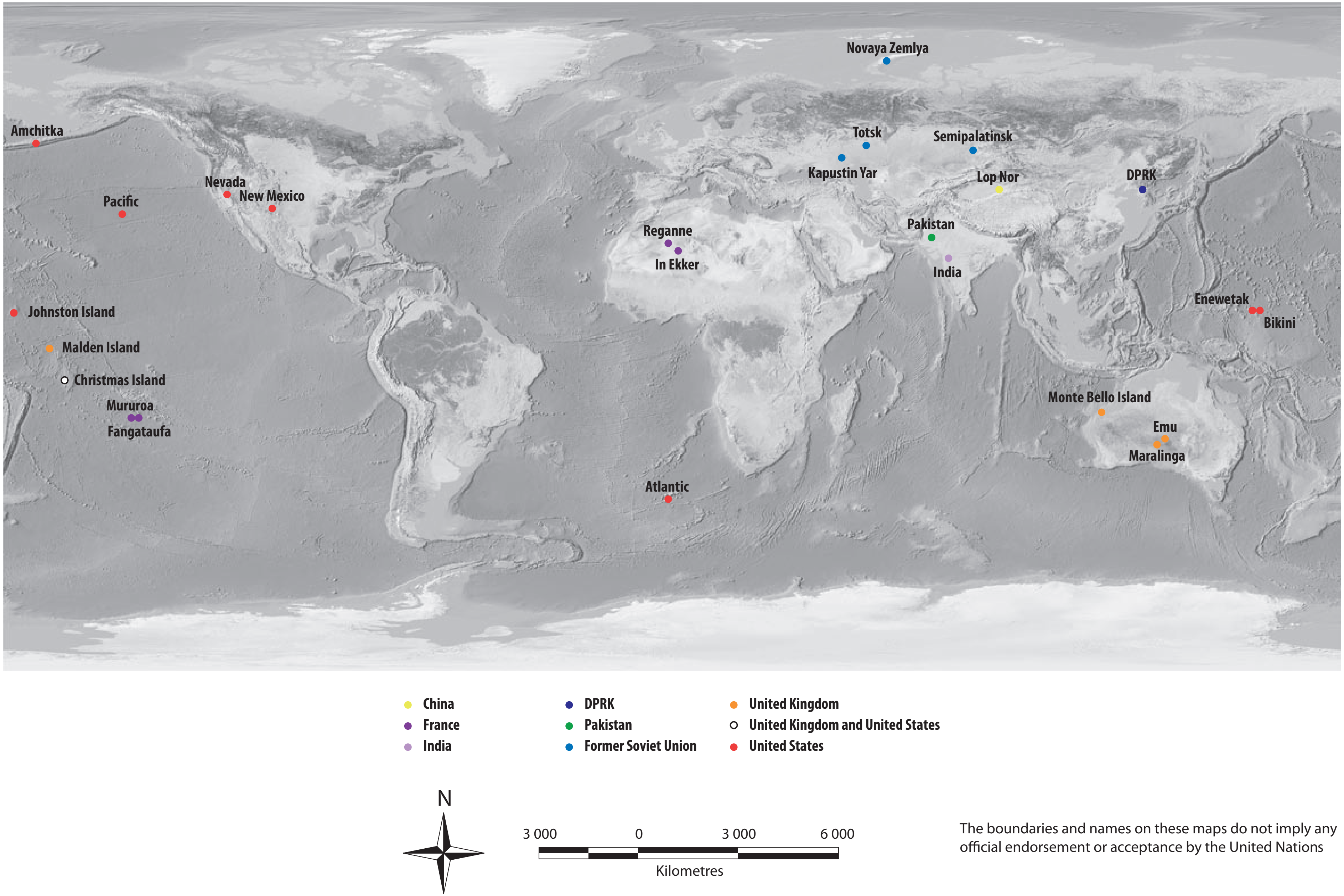


Figure XXVIII. Sites of nuclear weapons tests
Clean map from [C17]



The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

Figure XXIX. Number of nuclear tests performed by each country

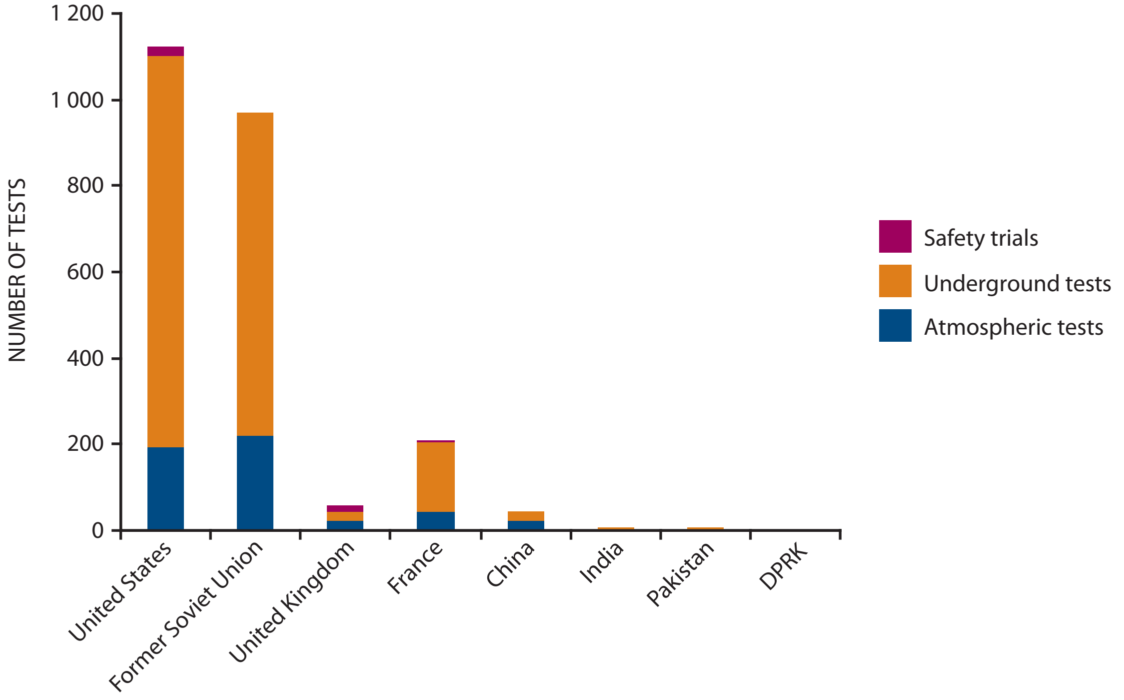


Figure XXX. Sites where radioactive waste has been dumped at sea [I11]

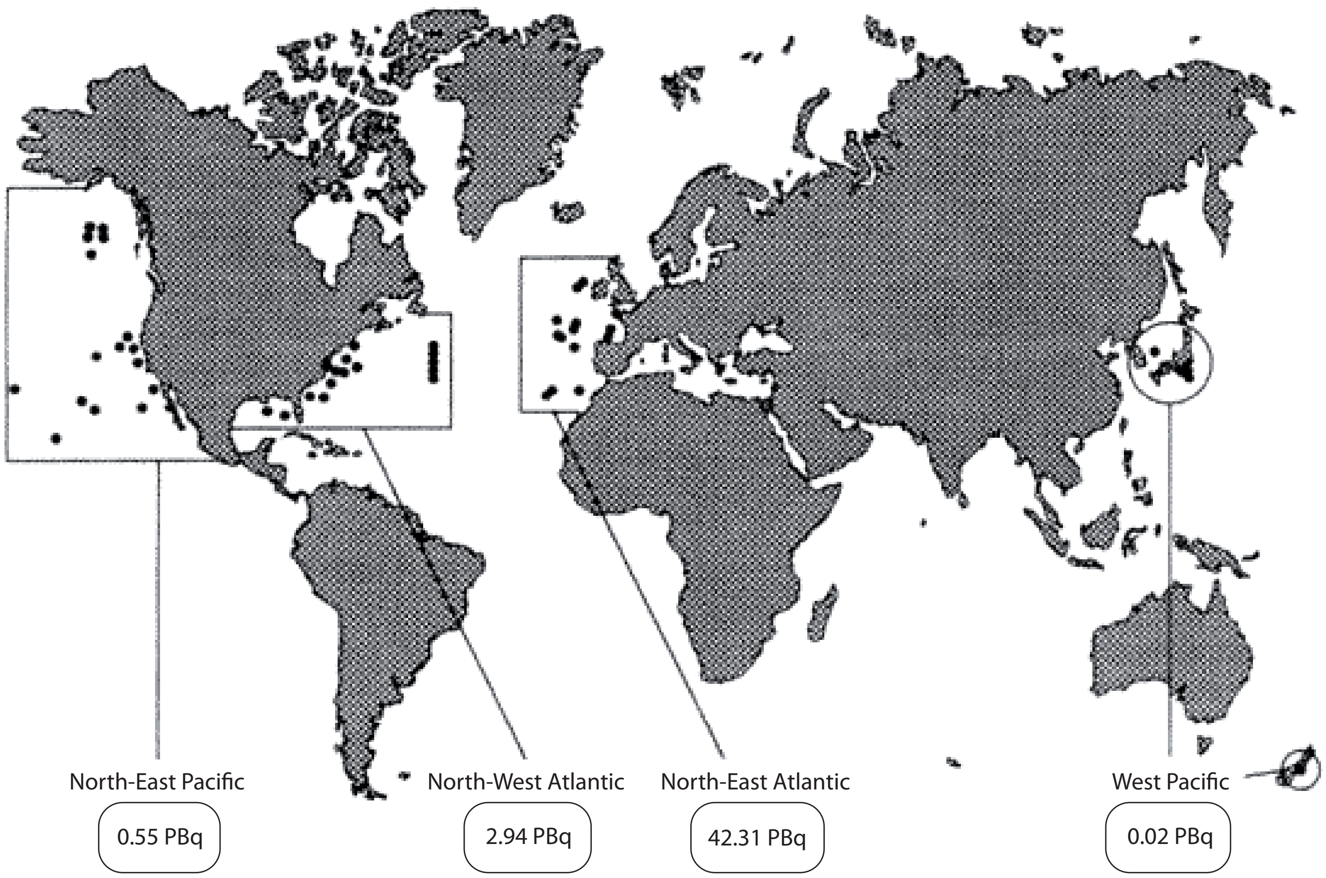


Figure XXXI. Locations where radioactive waste was dumped in the Kara Sea [I11]

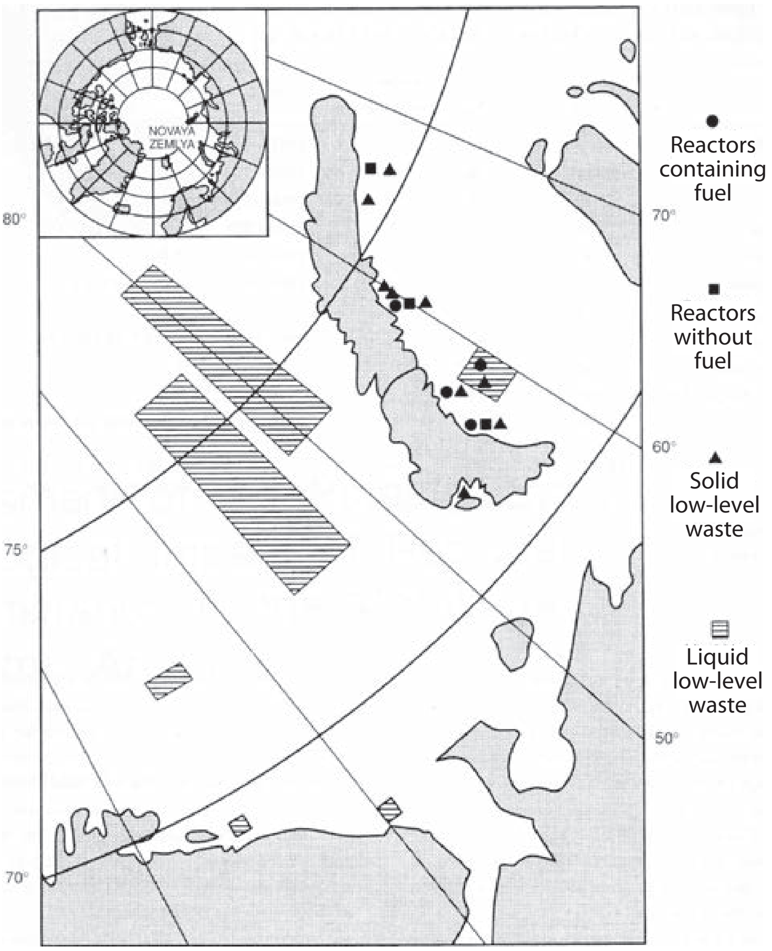


Figure XXXII. Spacecraft missions utilizing nuclear and/or radioactive material
RHU: radioisotope heating unit

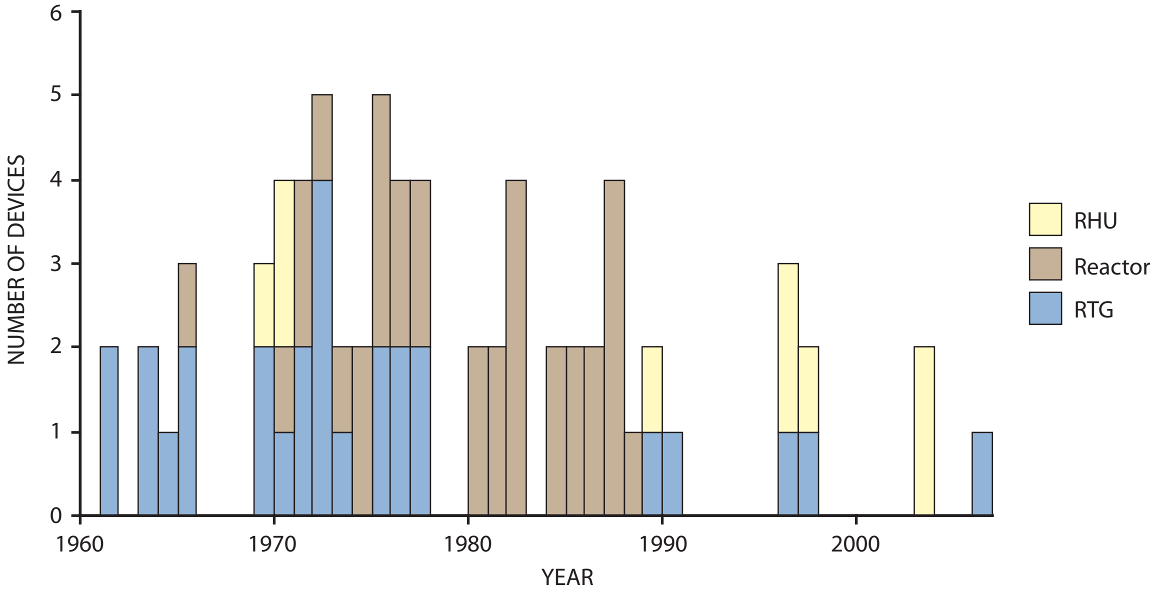


Figure XXXIII. Current status of devices utilizing nuclear and/or radioactive material in space: number of missions and number of devices

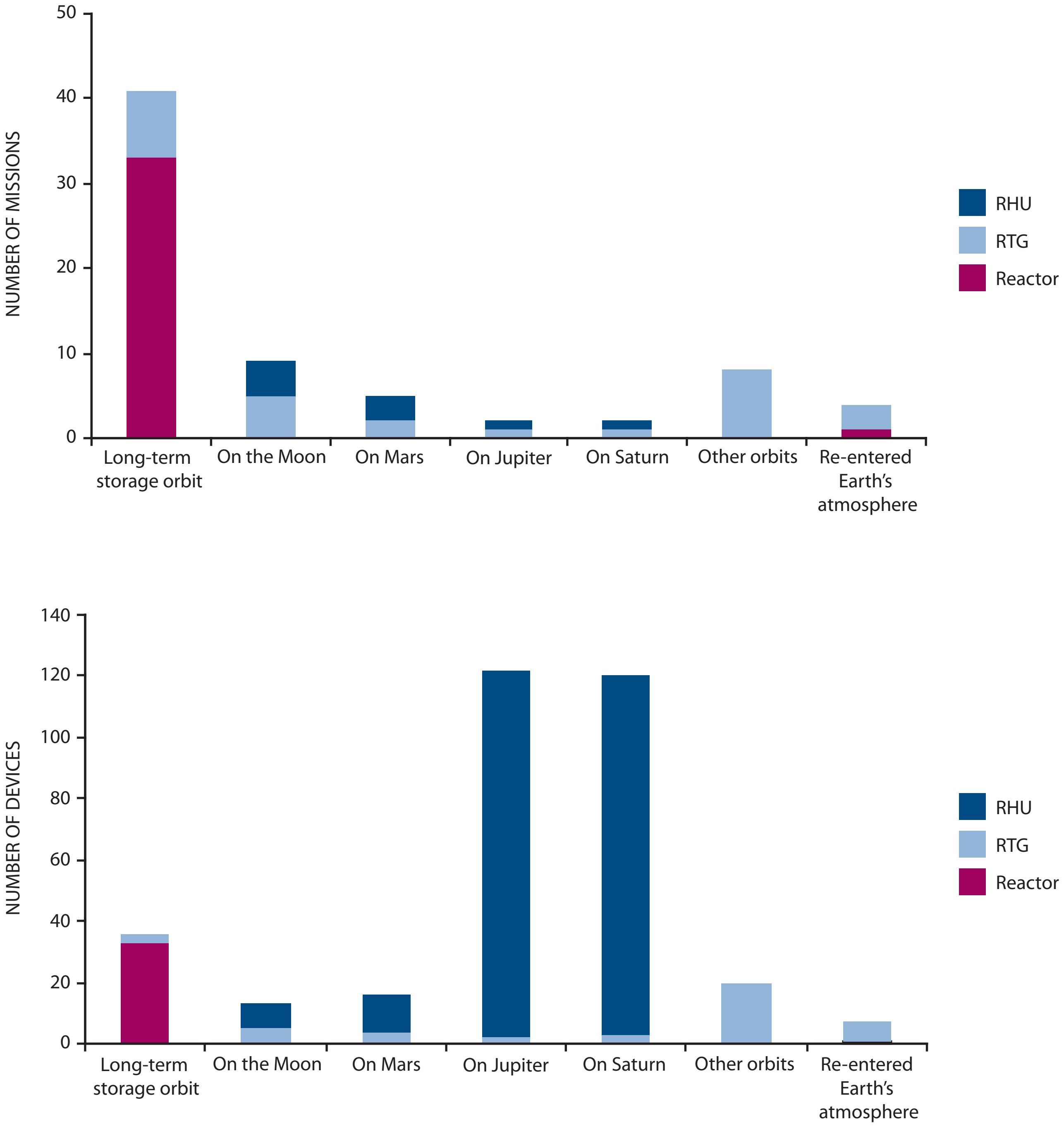
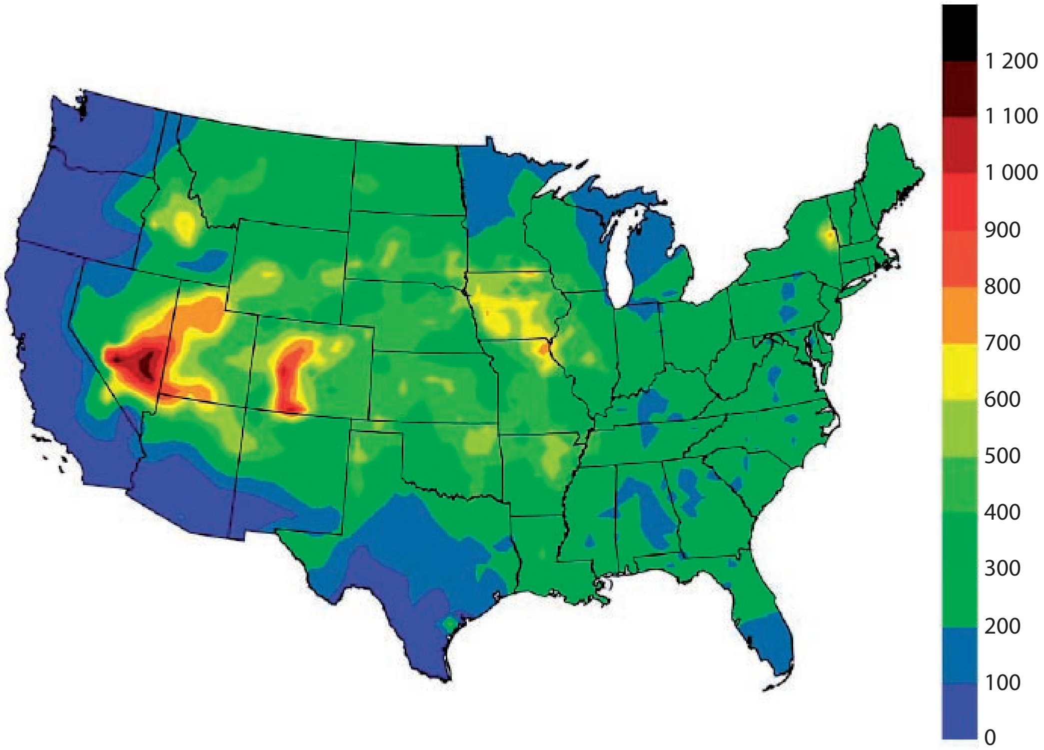


Figure XXXIV. Estimated ^{137}Cs deposition density (Bq/m^2) from NTS fallout (top figure) and from global fallout (bottom figure) across the continental United States [S23]



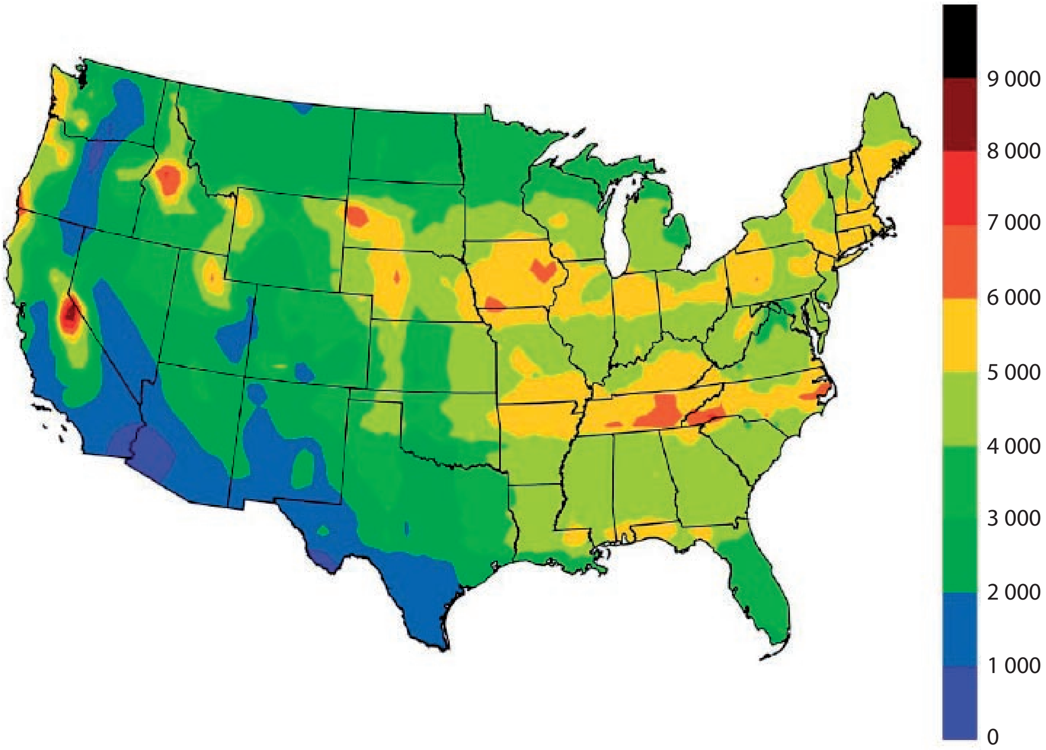


Figure XXXV. Sites of peaceful underground nuclear explosions in the former Soviet Union
Purposes of explosions: 1, obtaining seismic profiles; 2, creation of reservoirs in salt; 3, oil extraction; 4, creation of oil and gas inflow; 5, liquidation of oil wells; 6, burial of liquid toxic waste; 7, ore crushing; 8, creation of underground storage facilities in clay; 9, ground excavation; 10, ground loosening [V1]

Figure XXXVI. Estimated contributions to public exposure from different sources for different countries, and UNSCEAR estimates of worldwide average exposures

Figures for the United States from references [M23, N8], for Germany from [B49], for the United Kingdom from [W6]. Different distributions can be expected for other countries, as all countries considered here have a high level of development. For Germany, "Other" includes exposure due to fallout resulting from nuclear tests, to the Chernobyl accident and to releases from nuclear power plants

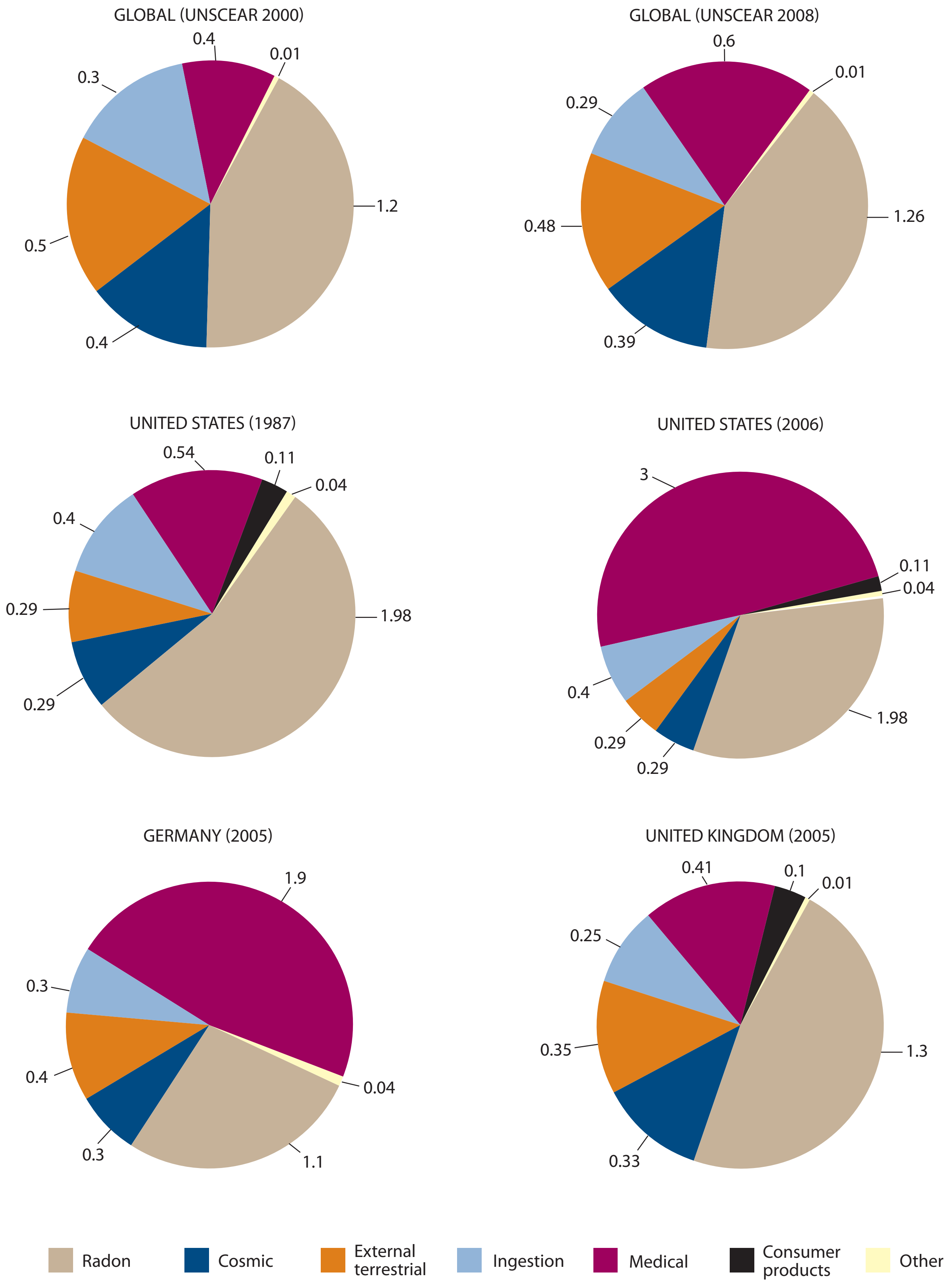


Figure XXXVII. Example of different dose distributions affecting public exposure in the United States

(a) Altitude and latitude effects on cosmic radiation dose [U26]; *(b)* external gamma exposure [U28]; *(c, d, e)* distributions of the natural terrestrial radionuclides Th, U and K, which contribute to ingestion and inhalation doses [U28]; *(f)* indoor radon, main contributor to public exposure from natural sources via inhalation [U28]; *(g)* doses from fallout resulting from nuclear tests [N6]; *(h)* location of nuclear power plants [U39]. All these source distributions would be combined with *(i)*, population distribution [U28]

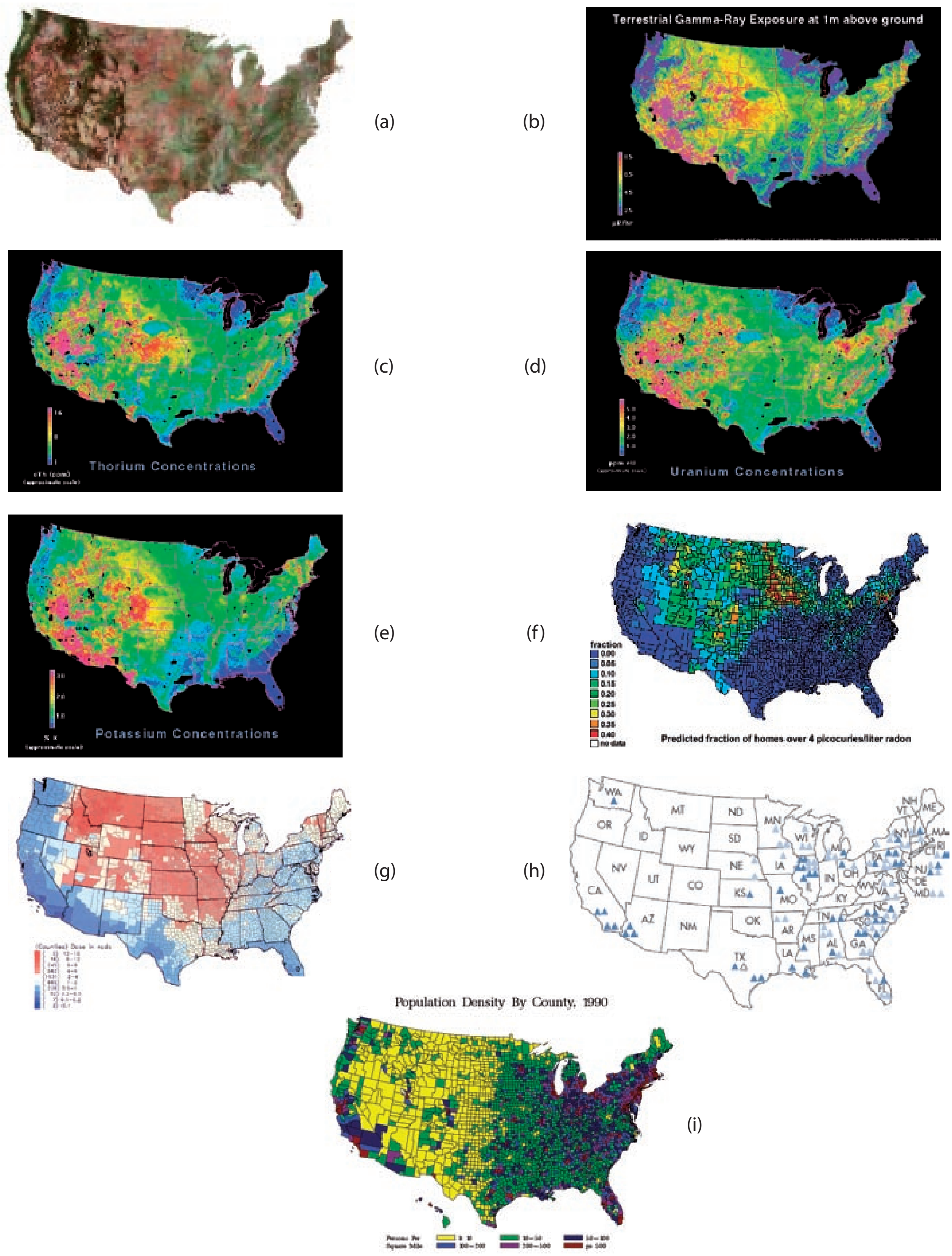


Figure XXXVIII. Worldwide trends in occupational exposure due to uranium mining
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

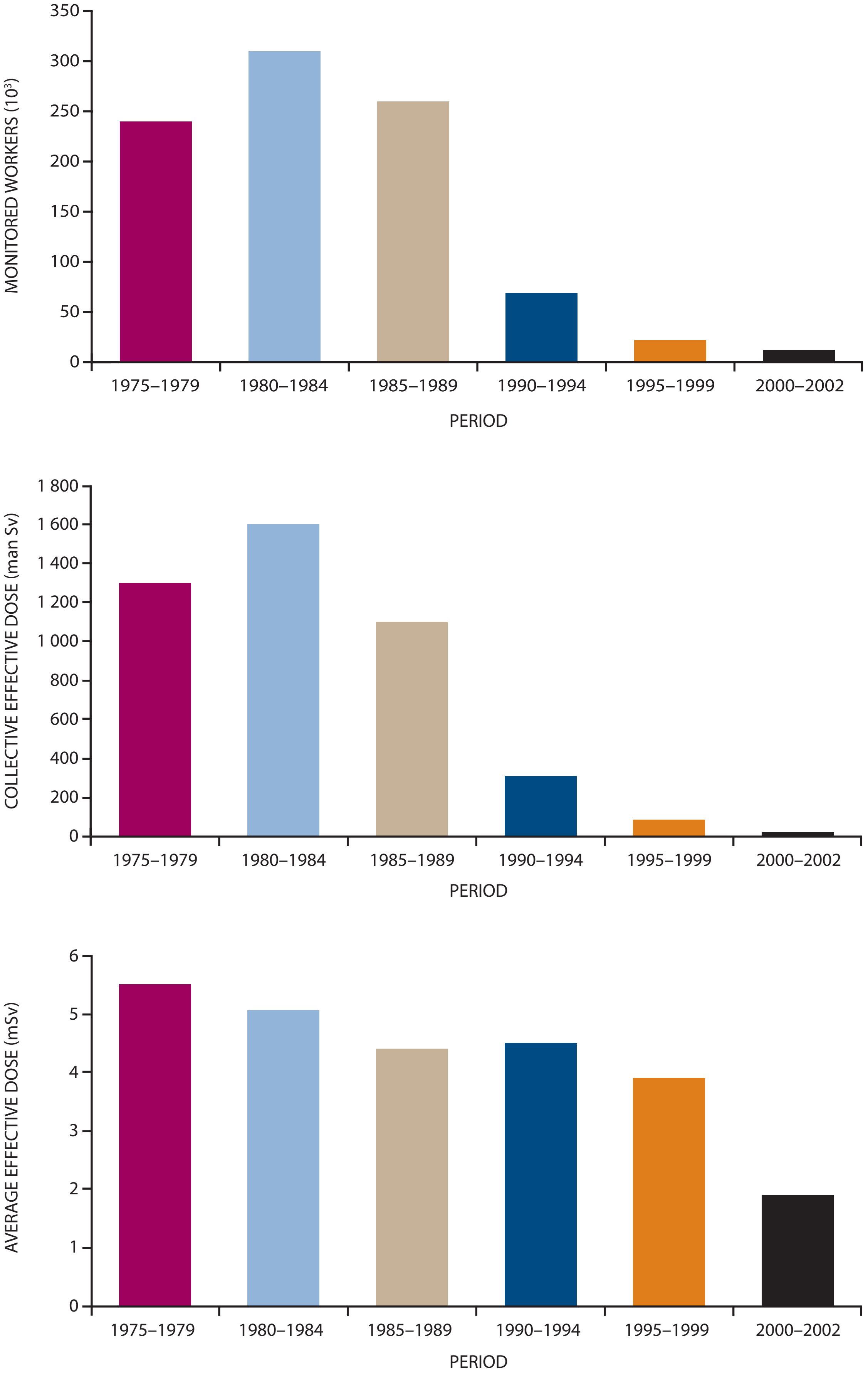


Figure XXXIX. Worldwide trends in occupational exposure due to uranium milling
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

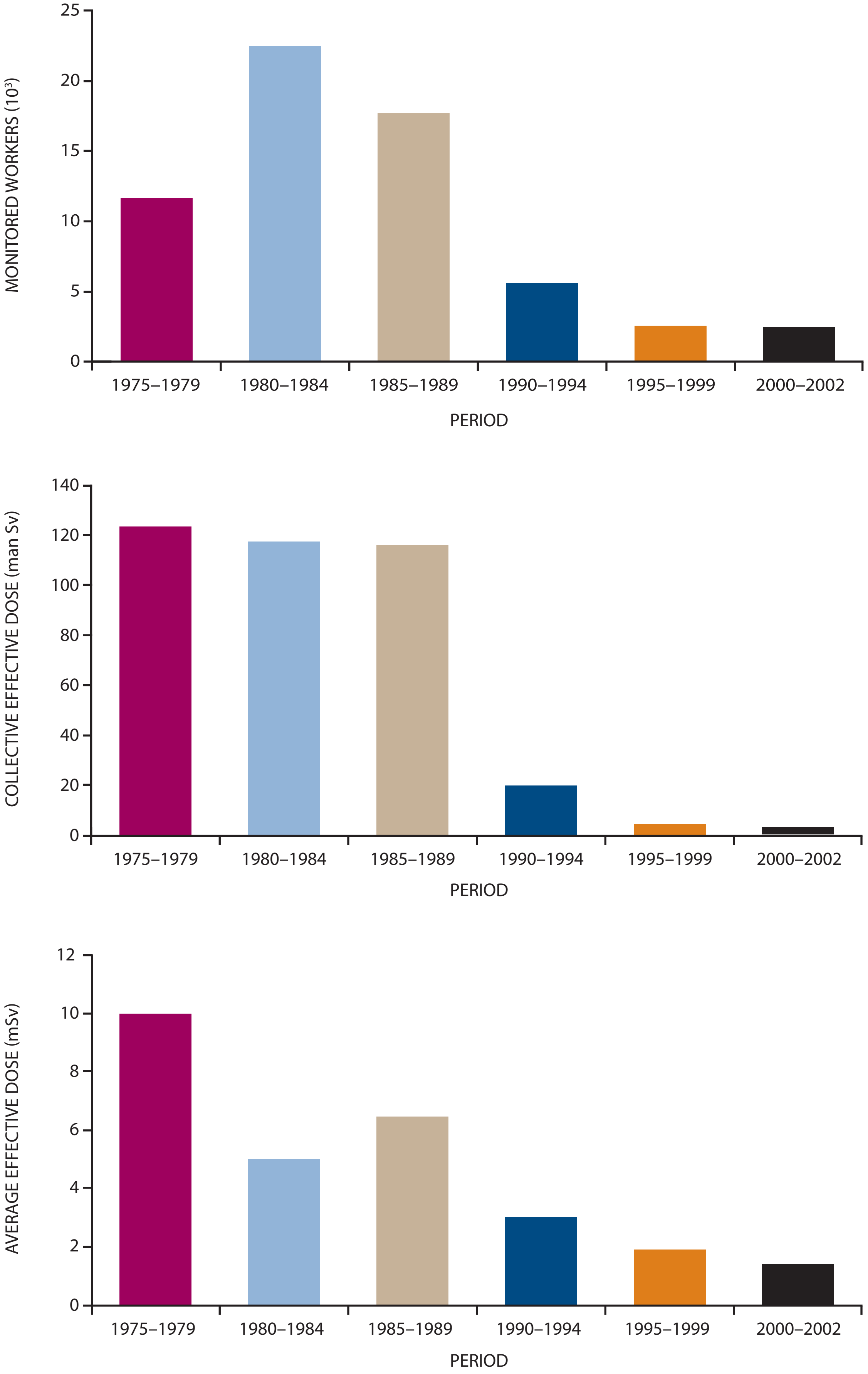


Figure XL. Worldwide trends in occupational exposure due to uranium enrichment and conversion
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

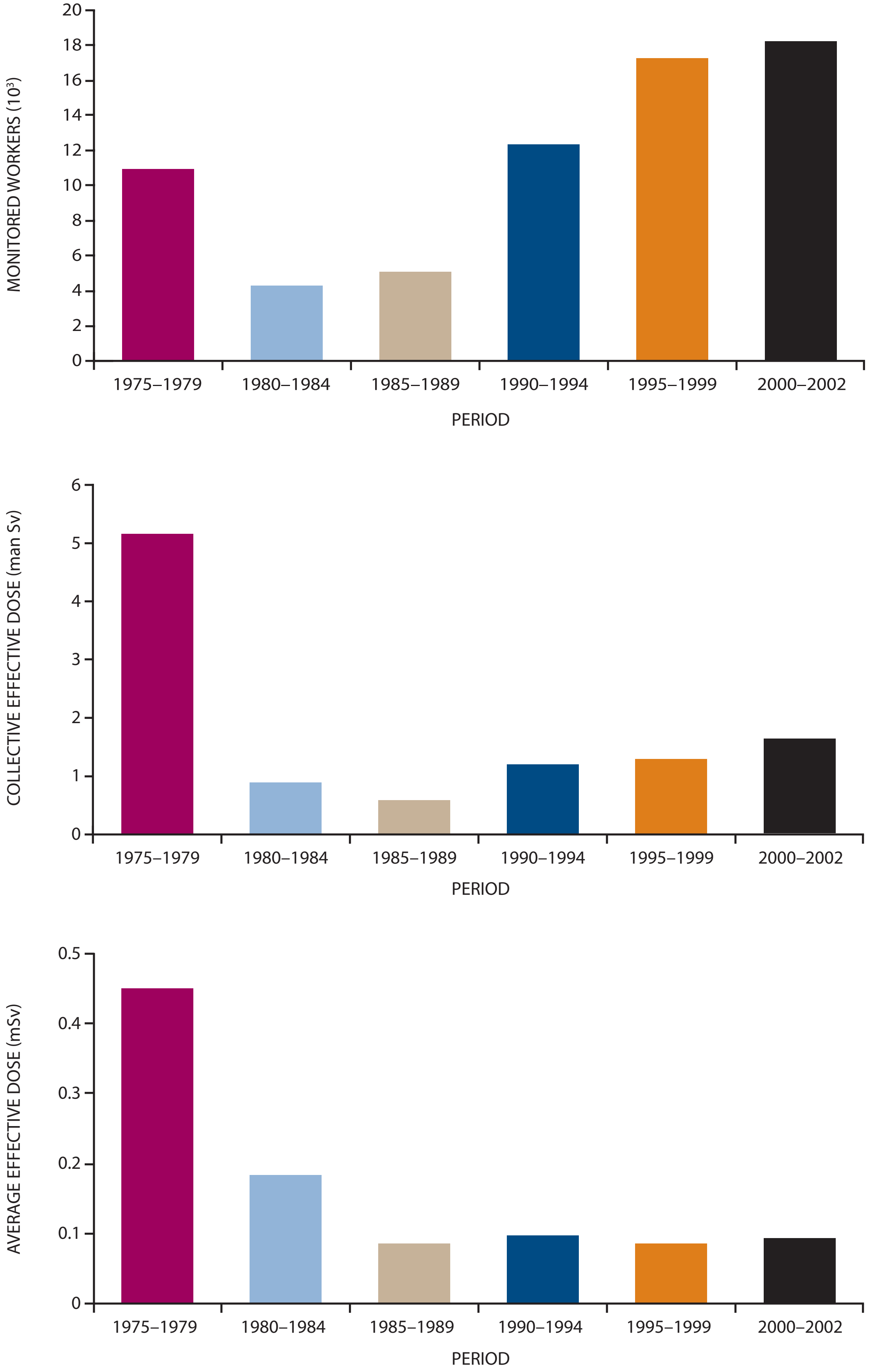


Figure XLI. Worldwide trends in occupational exposure due to nuclear fuel production
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

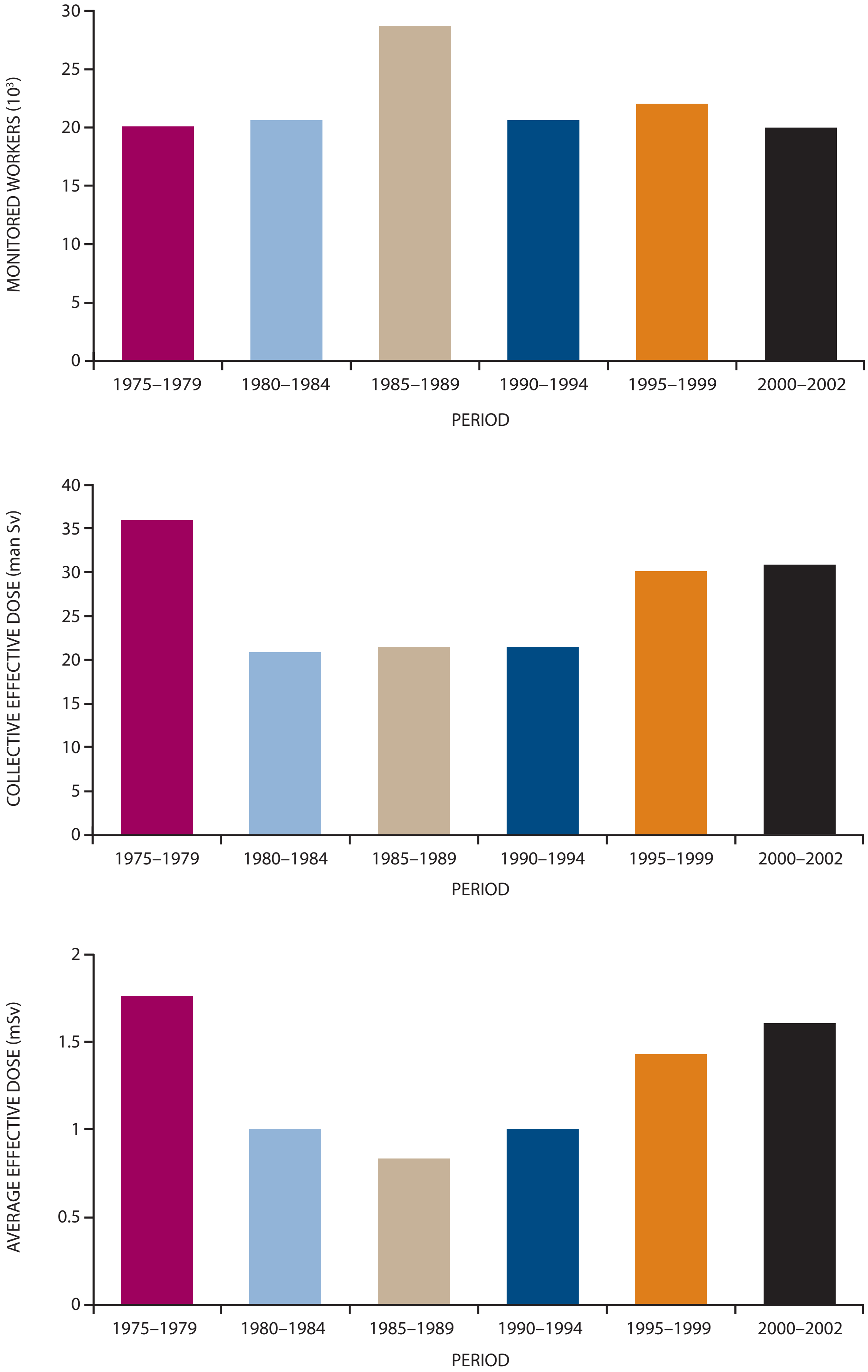


Figure XLII. Worldwide trends in occupational exposure due to reactor operation

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

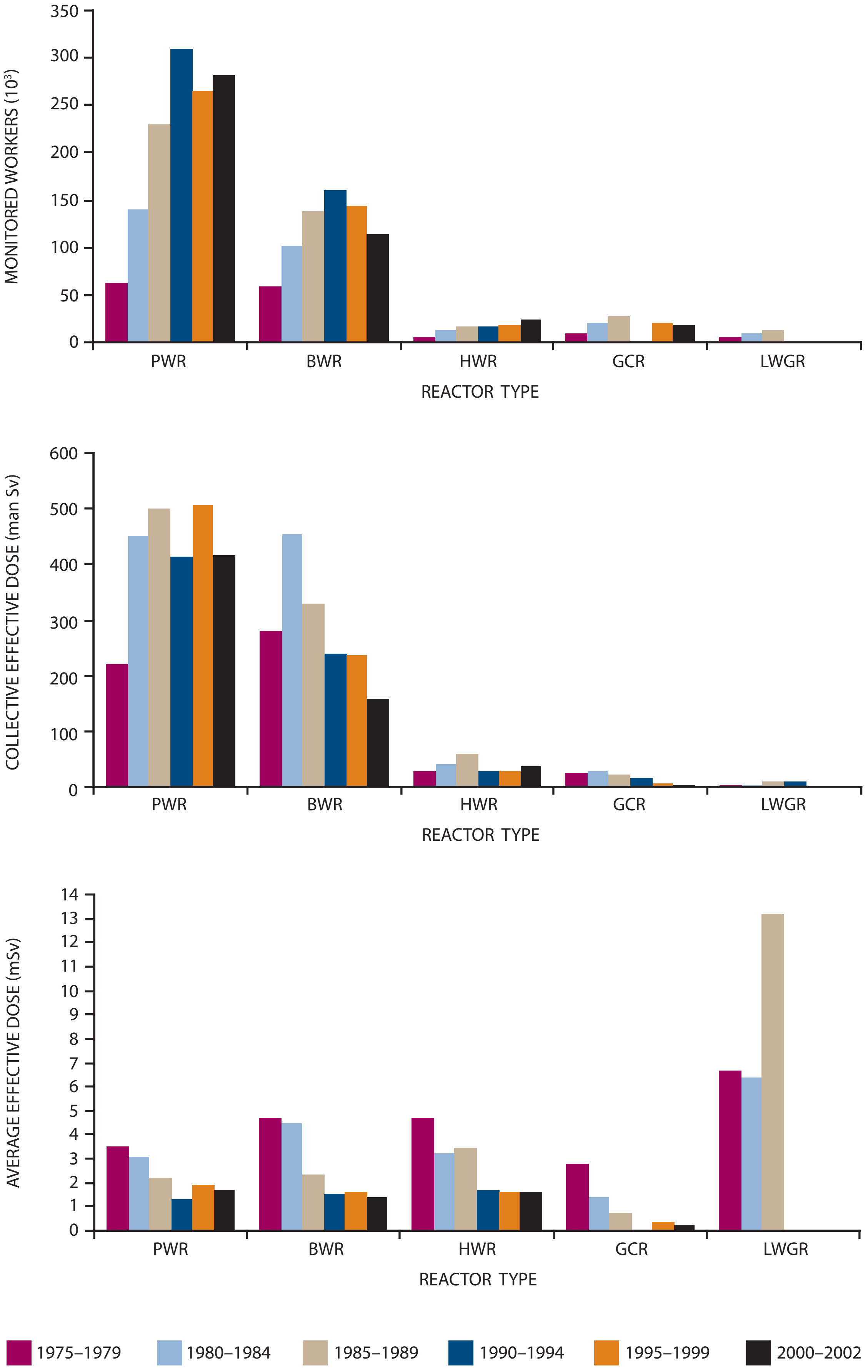


Figure XLIII. Worldwide trends in collective effective dose due to reactor operation, and in normalized collective effective dose per reactor and per unit electrical energy

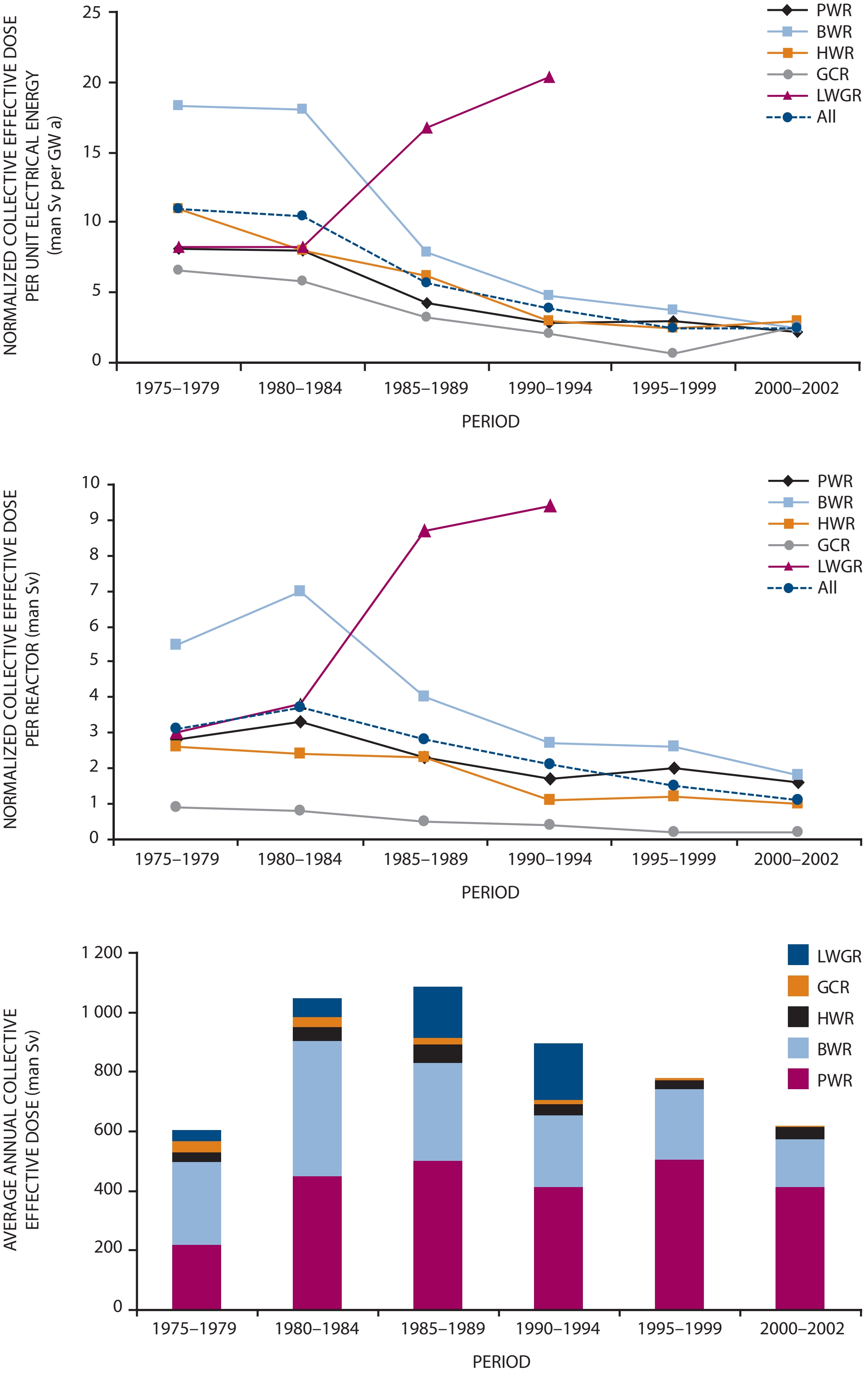


Figure XLIV. Worldwide trends in occupational exposure due to fuel reprocessing
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

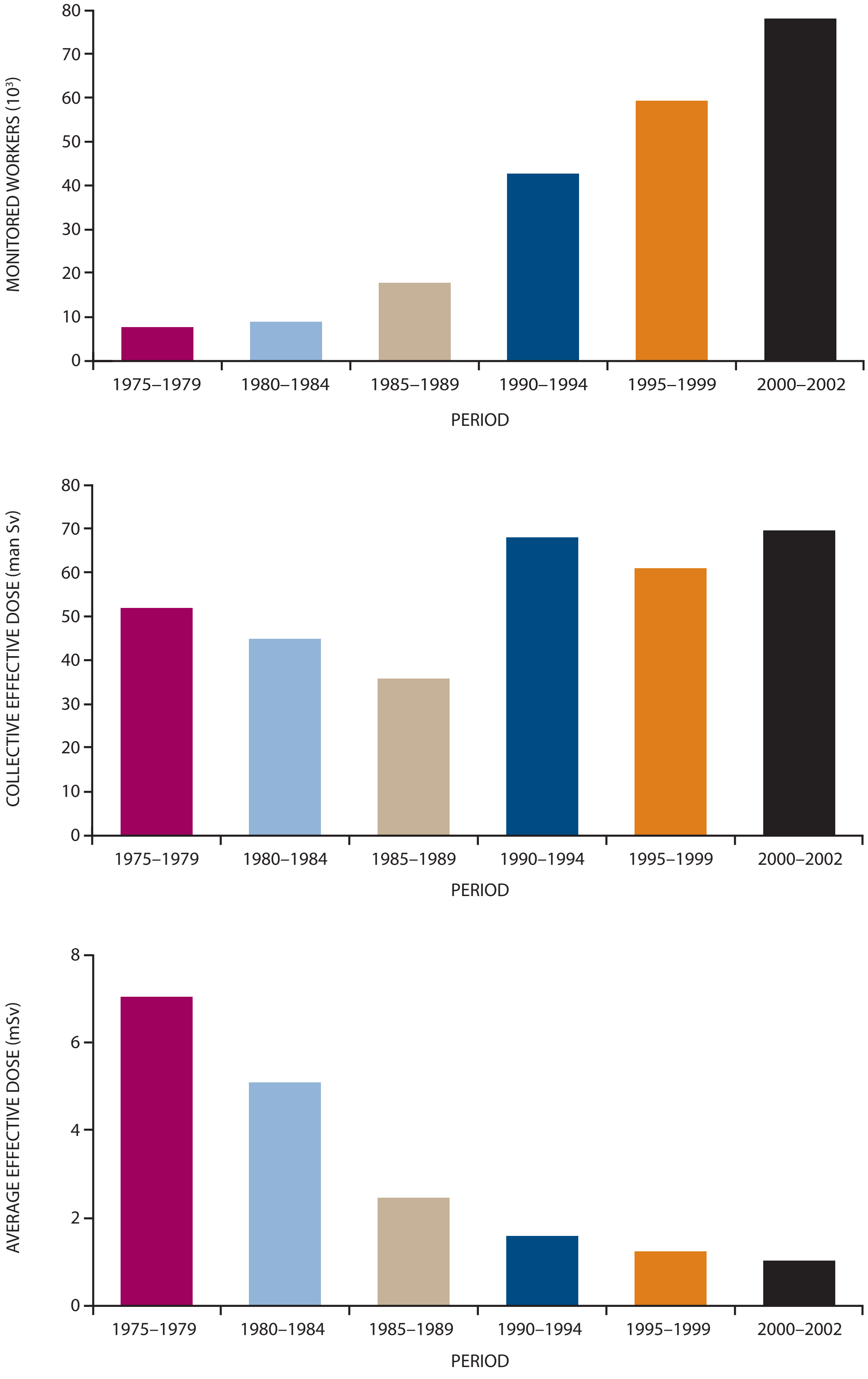


Figure XLV. Worldwide trends in occupational exposure due to research related to the nuclear fuel cycle
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

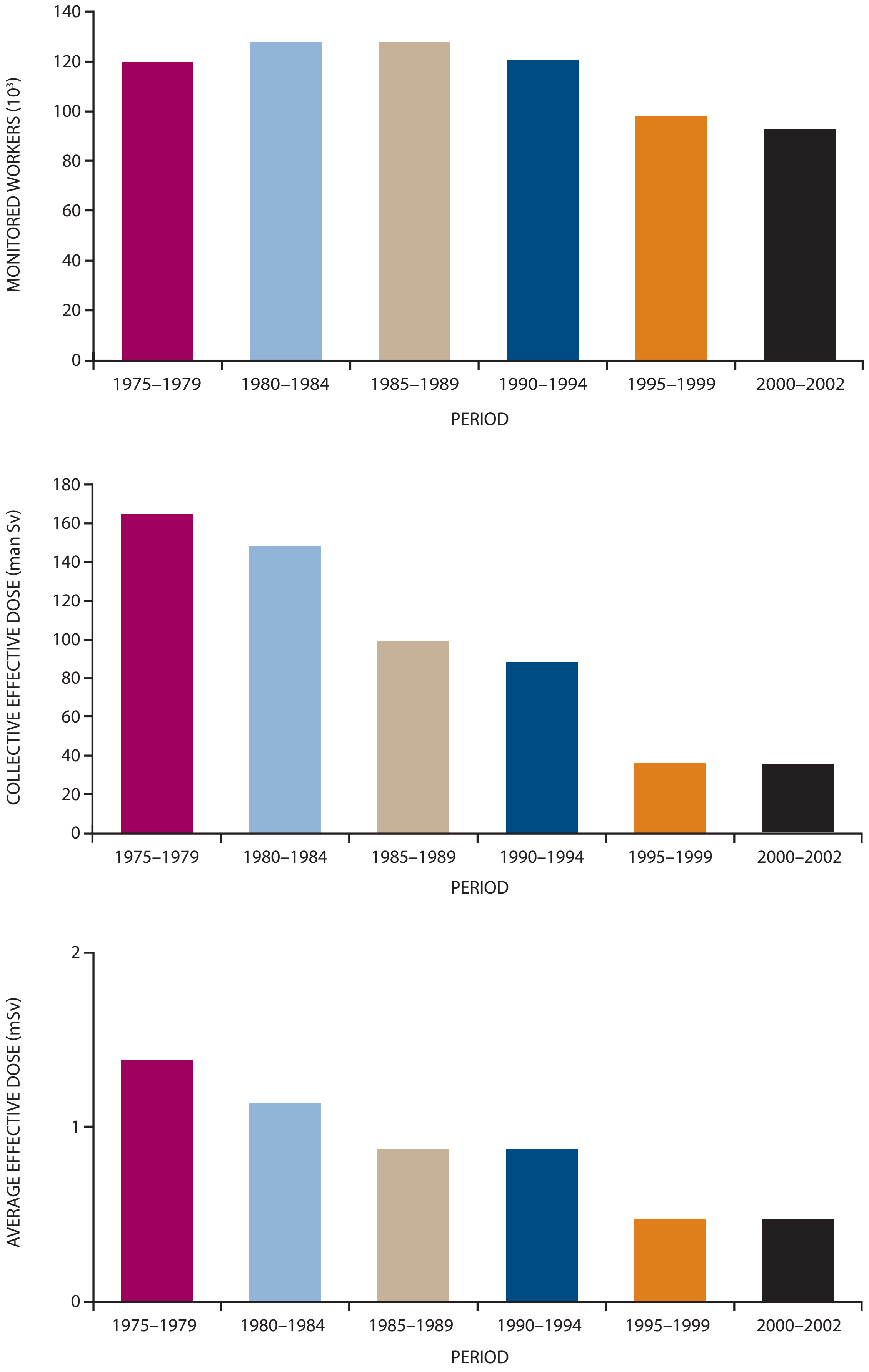


Figure XLVI. Worldwide trends in the number of monitored workers, and in collective effective doses and effective doses to workers for different practices of the nuclear fuel cycle

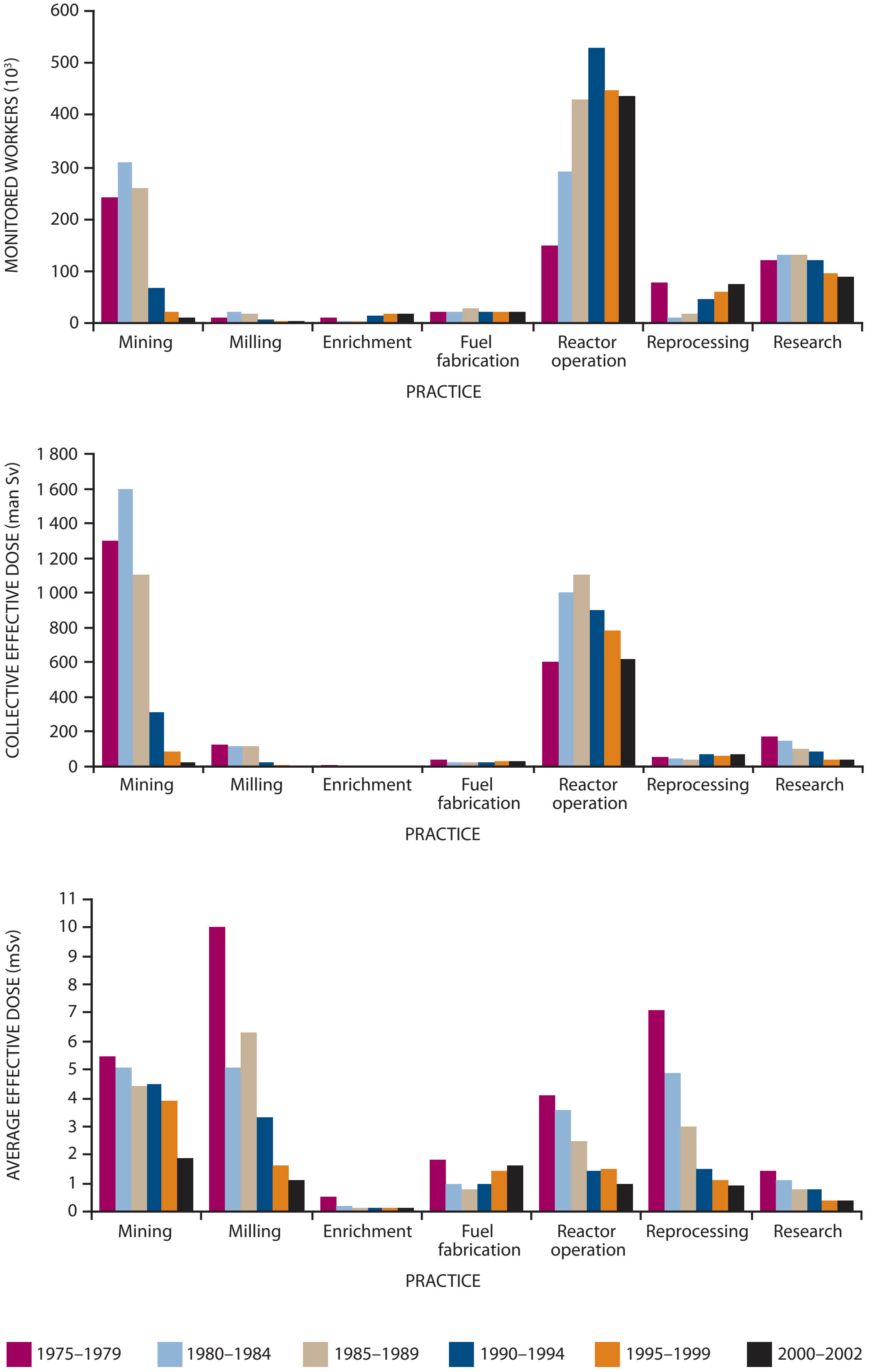


Figure XLVII. Worldwide trends in the number of monitored workers, and in collective effective doses and effective doses to workers in the nuclear fuel cycle

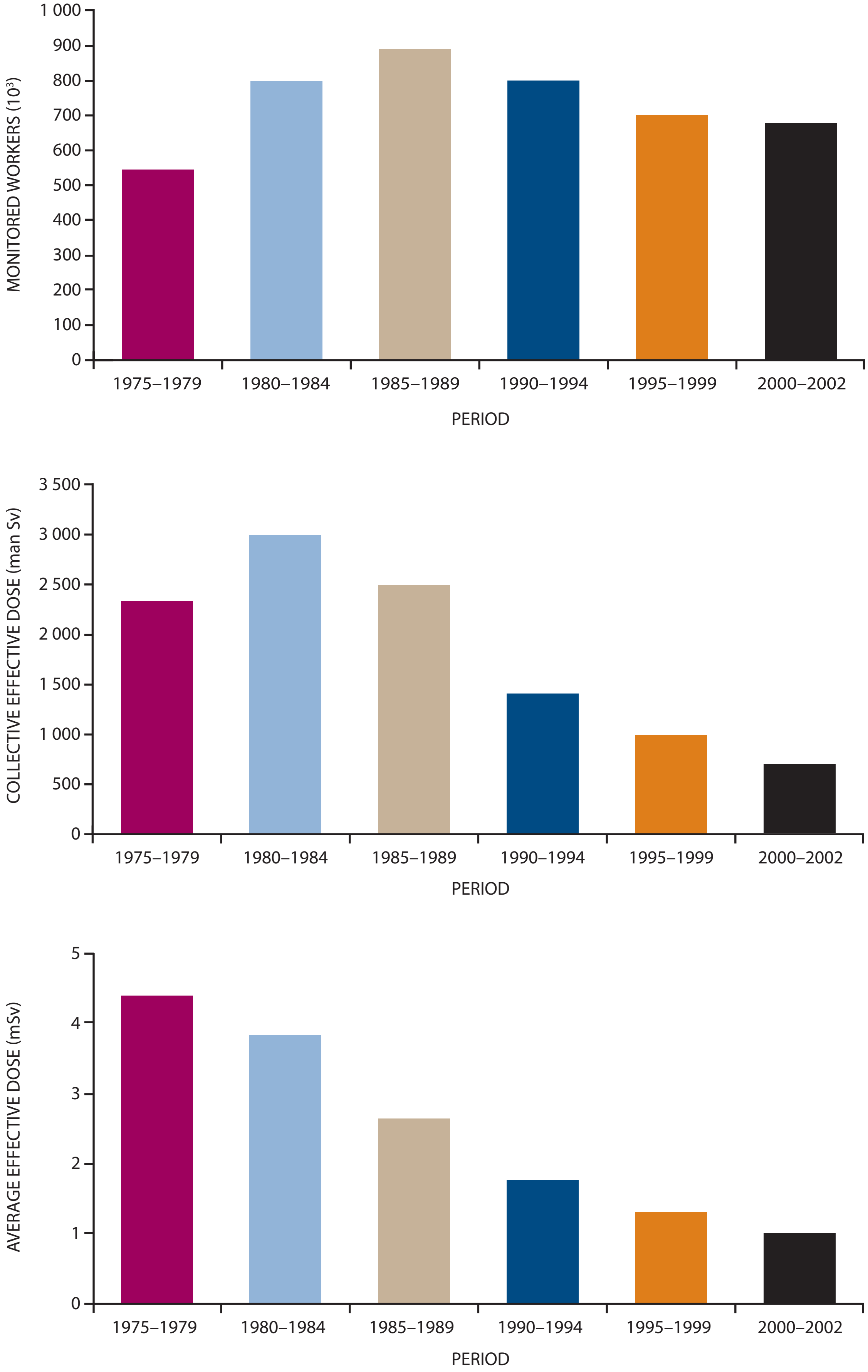


Figure XLVIII. Dose levels for *(a)* interventional radiologist and *(b)* interventional cardiologist
Average values of 83 procedures performed by ten specialists in six laboratories [V7]

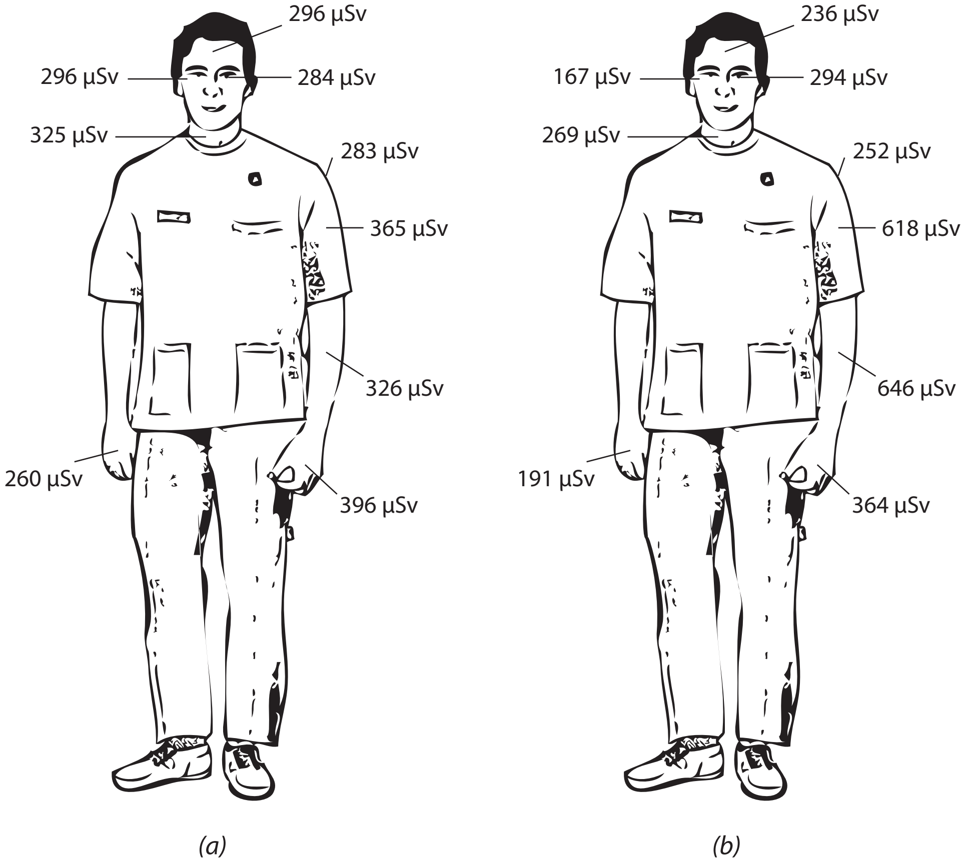


Figure XLIX. Worldwide trends in occupational exposure due to diagnostic radiology
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

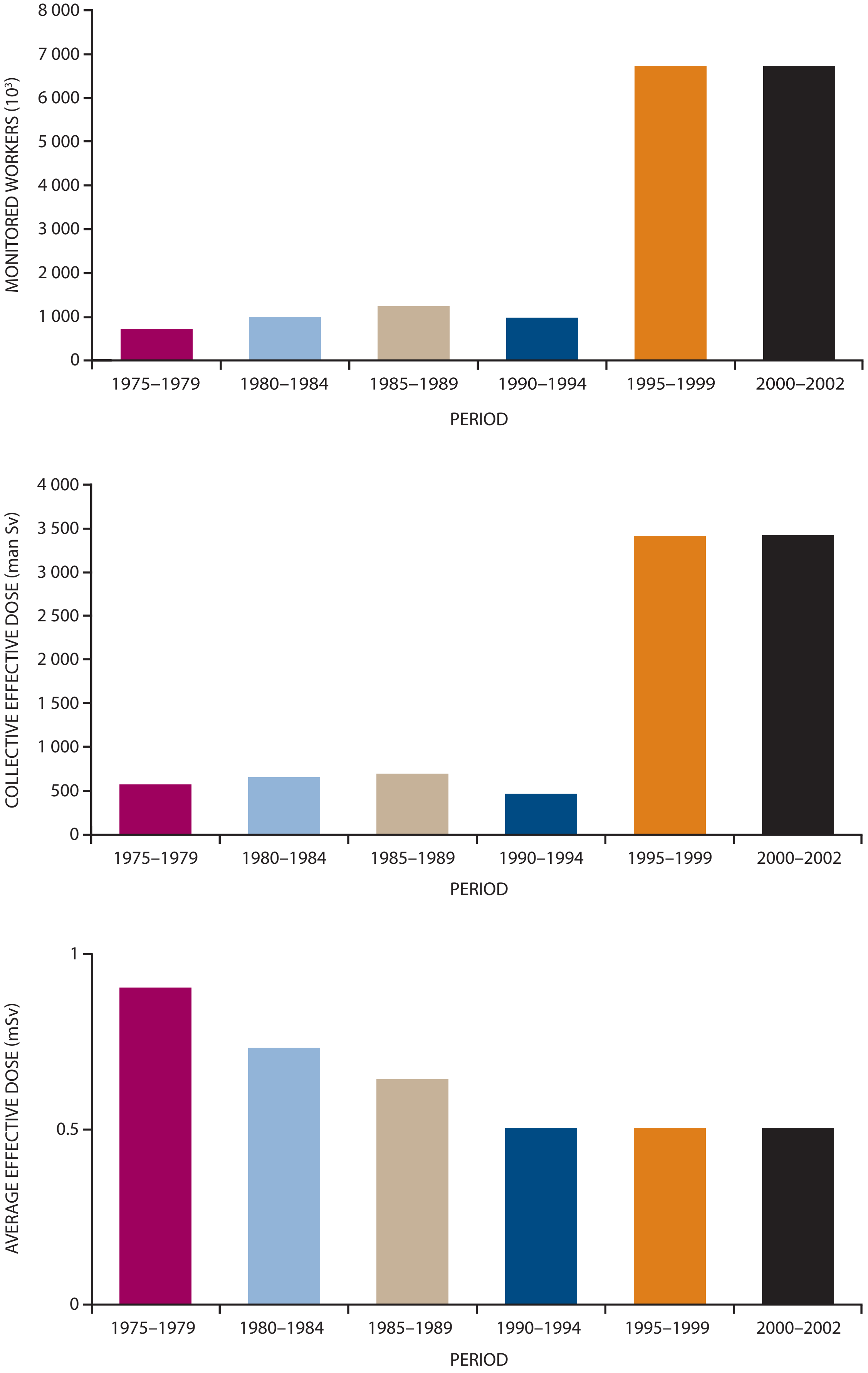
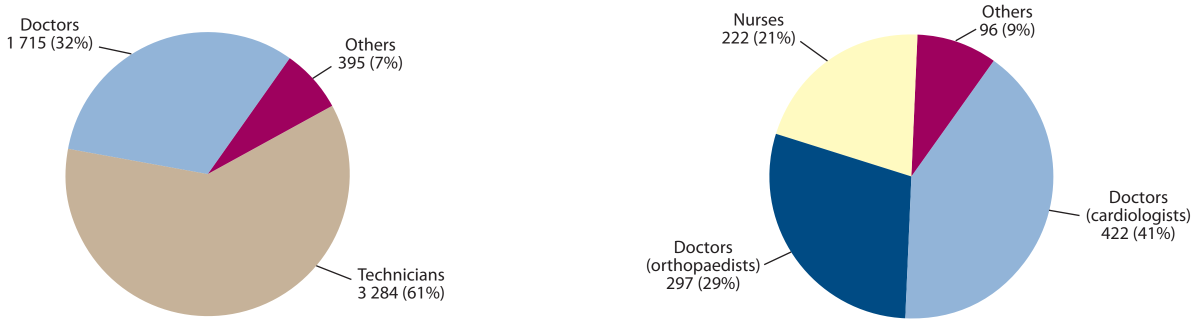


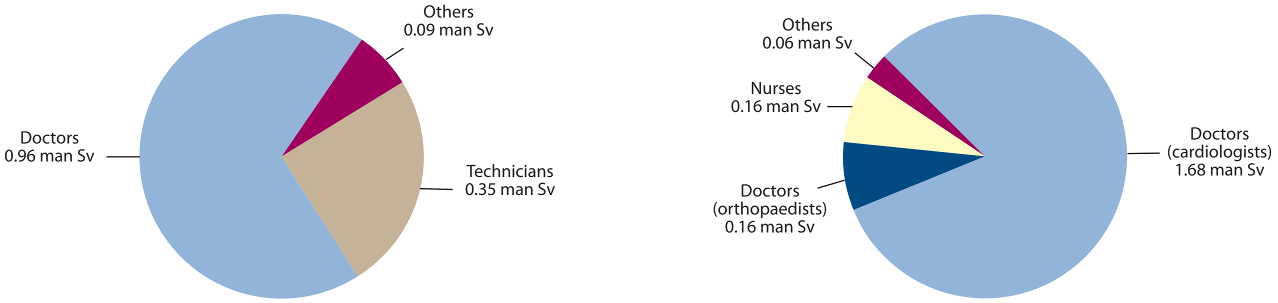
Figure L. Occupational exposures due to diagnostic radiology in Greece for various job categories

CONVENTIONAL PROCEDURES INTERVENTIONAL PROCEDURES

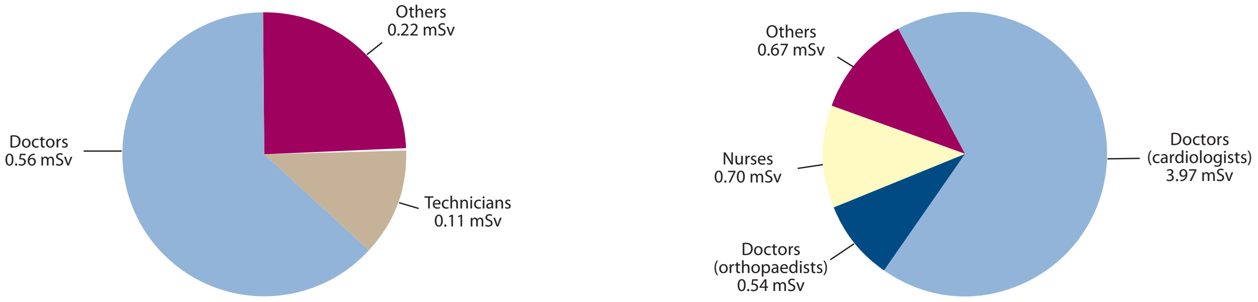
(a) Numbers of monitored workers for conventional and interventional procedures



(b) Collective effective doses for conventional and interventional procedures



(c) Average effective doses to monitored workers



(d) Average effective doses to measurably exposed workers

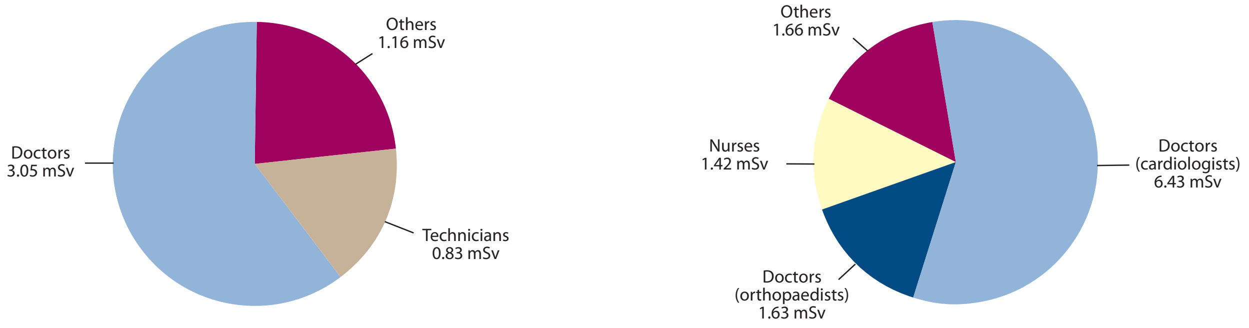


Figure LI. Worldwide trends in occupational exposure due to dental practice
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

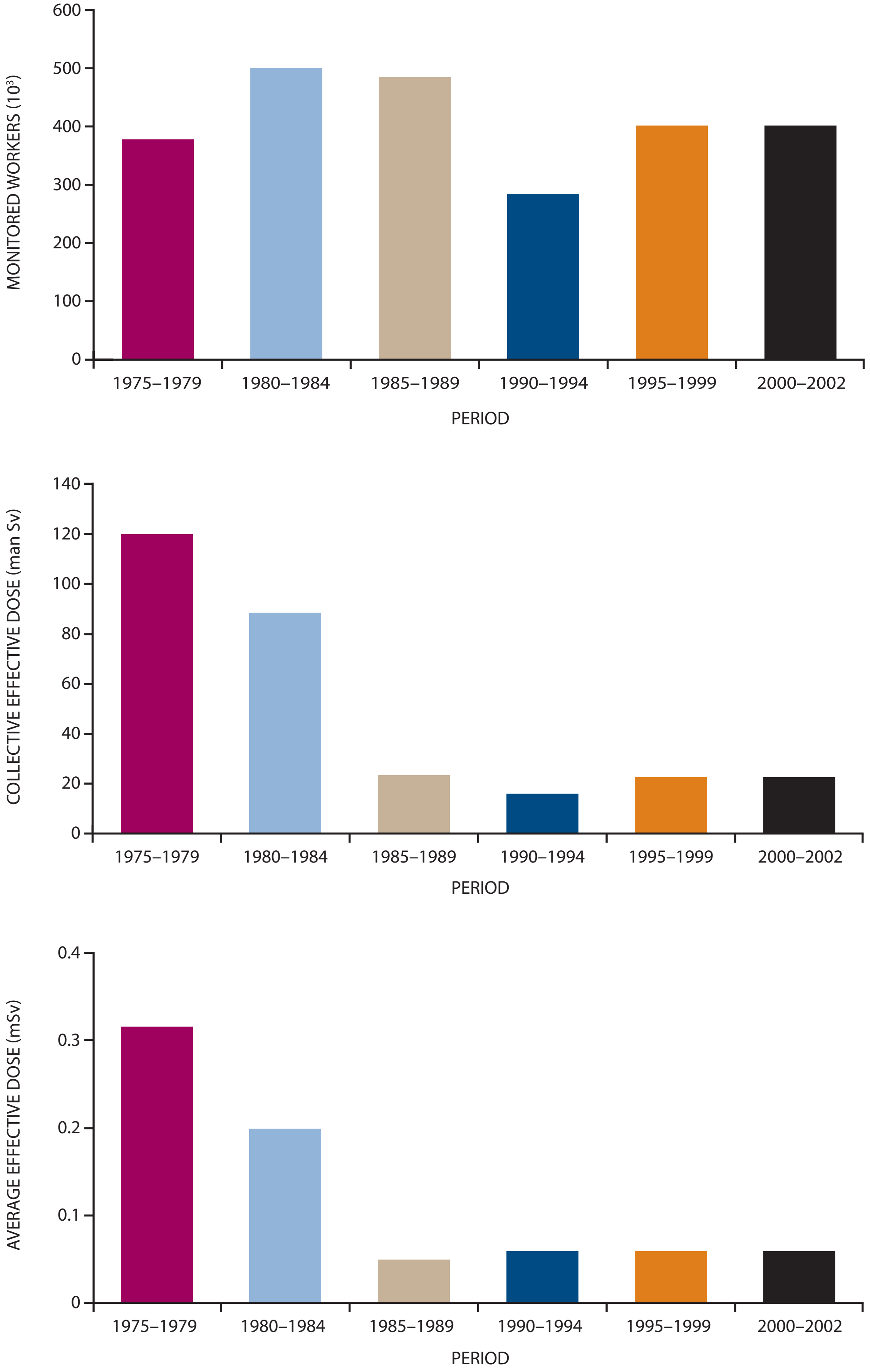


Figure LII. Worldwide trends in occupational exposure due to nuclear medicine
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

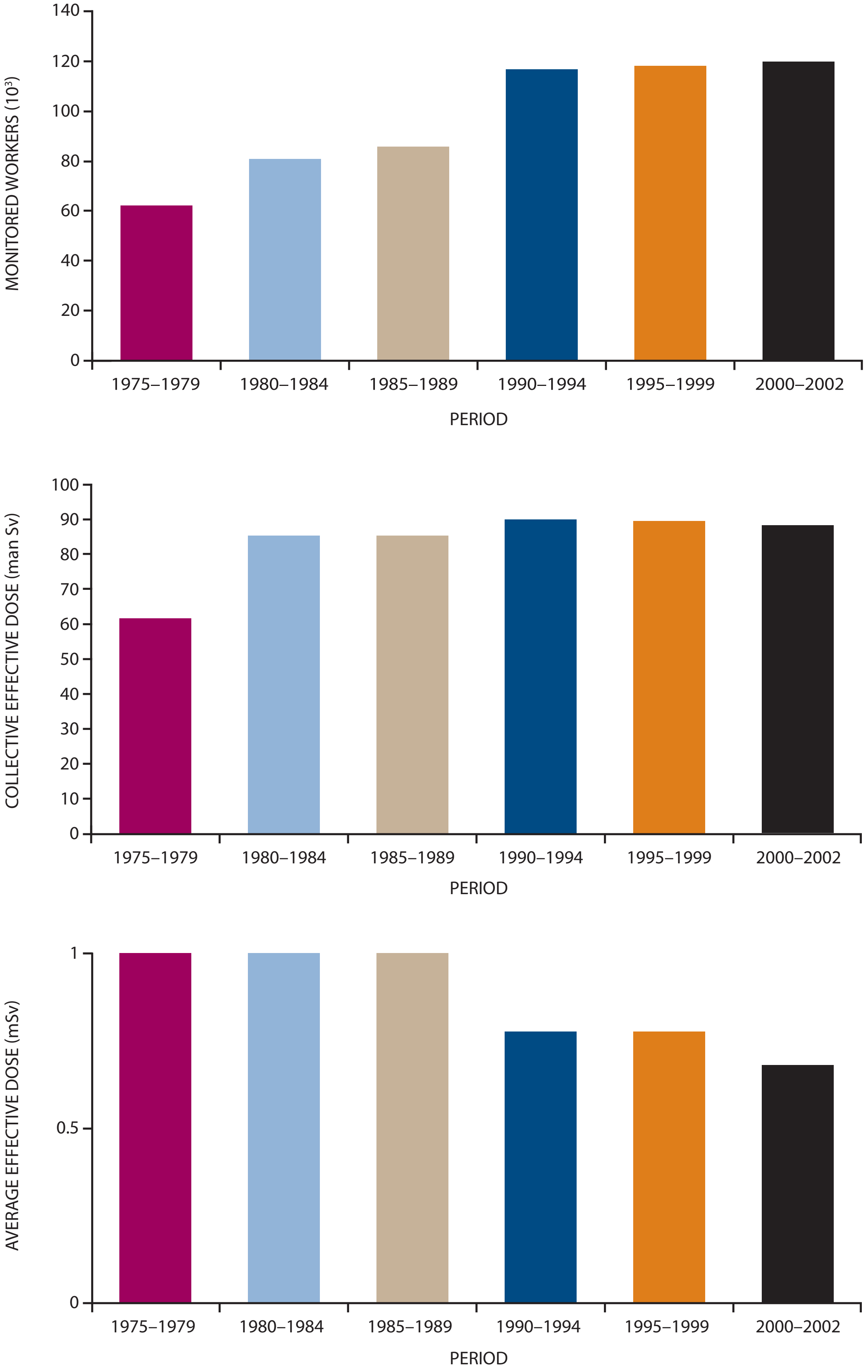
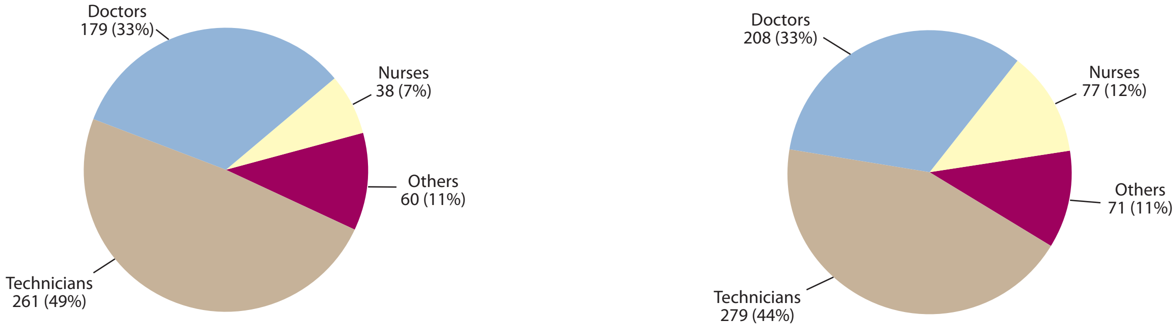


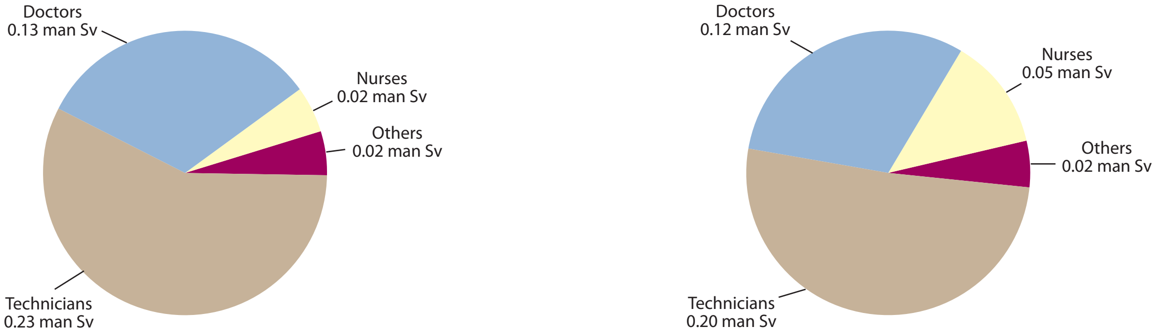
Figure LIII. Occupational exposures due to nuclear medicine in Greece for various job categories for the periods 1995–1999 and 2000–2002

(1995–1999) (2000–2002)

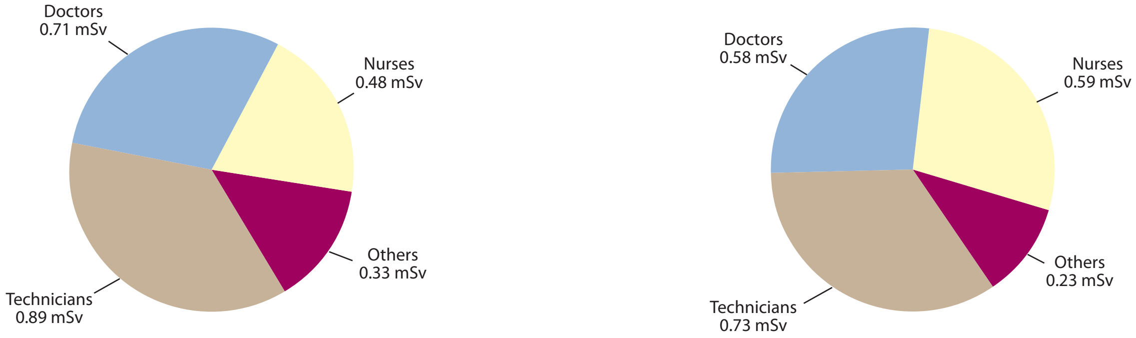
(a) Numbers of monitored workers



(b) Collective effective doses



(c) Average effective doses for monitored workers



(d) Average effective doses for measurably exposed workers

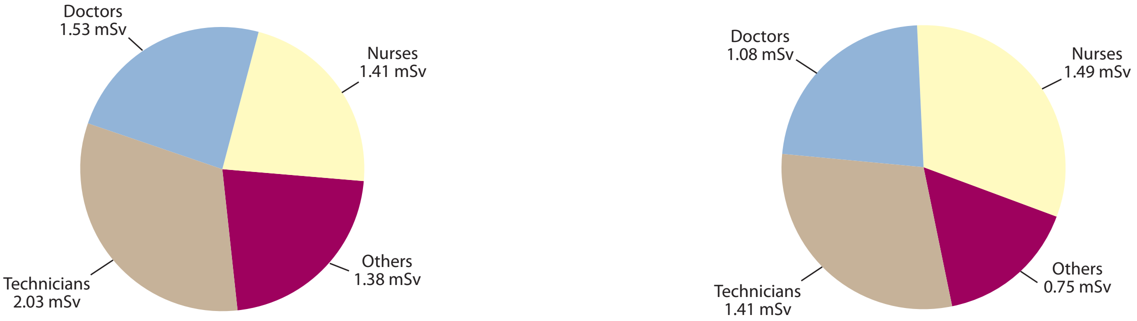


Figure LIV. Worldwide trends in occupational exposure due to radiotherapy

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

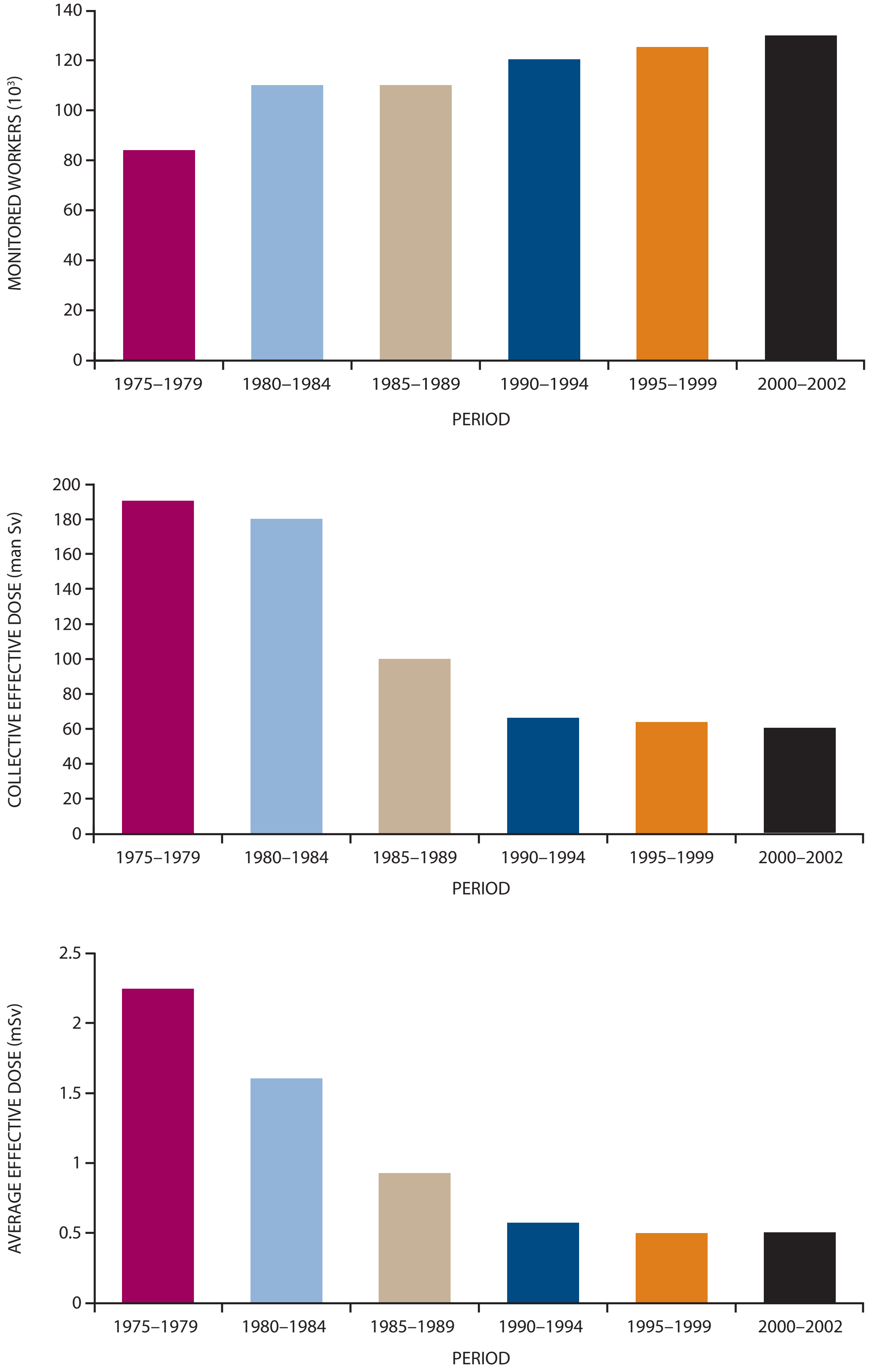


Figure LV. Worldwide trends in occupational exposure due to all medical uses of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

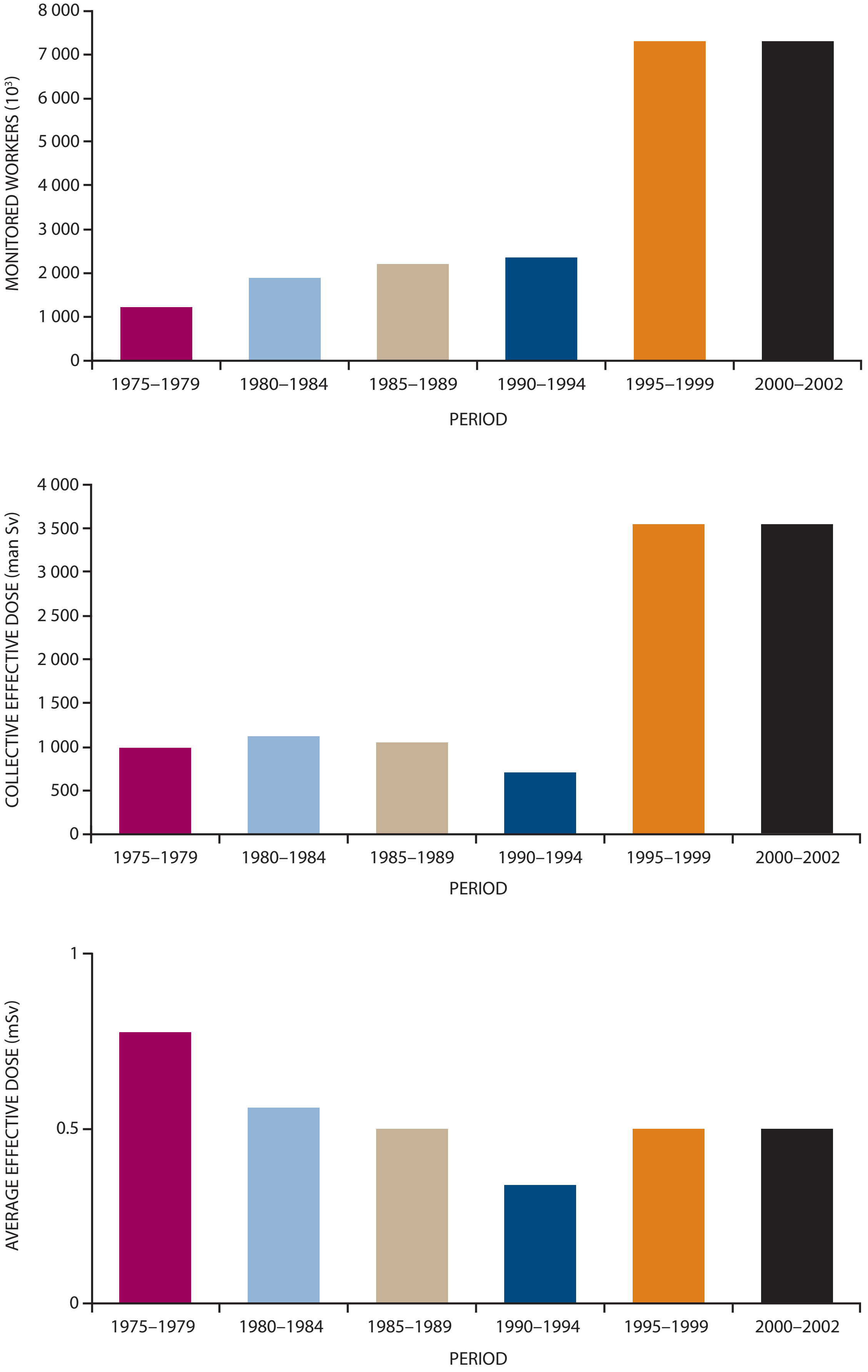


Figure LVI. Trends in occupational exposure due to industrial irradiation in China

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

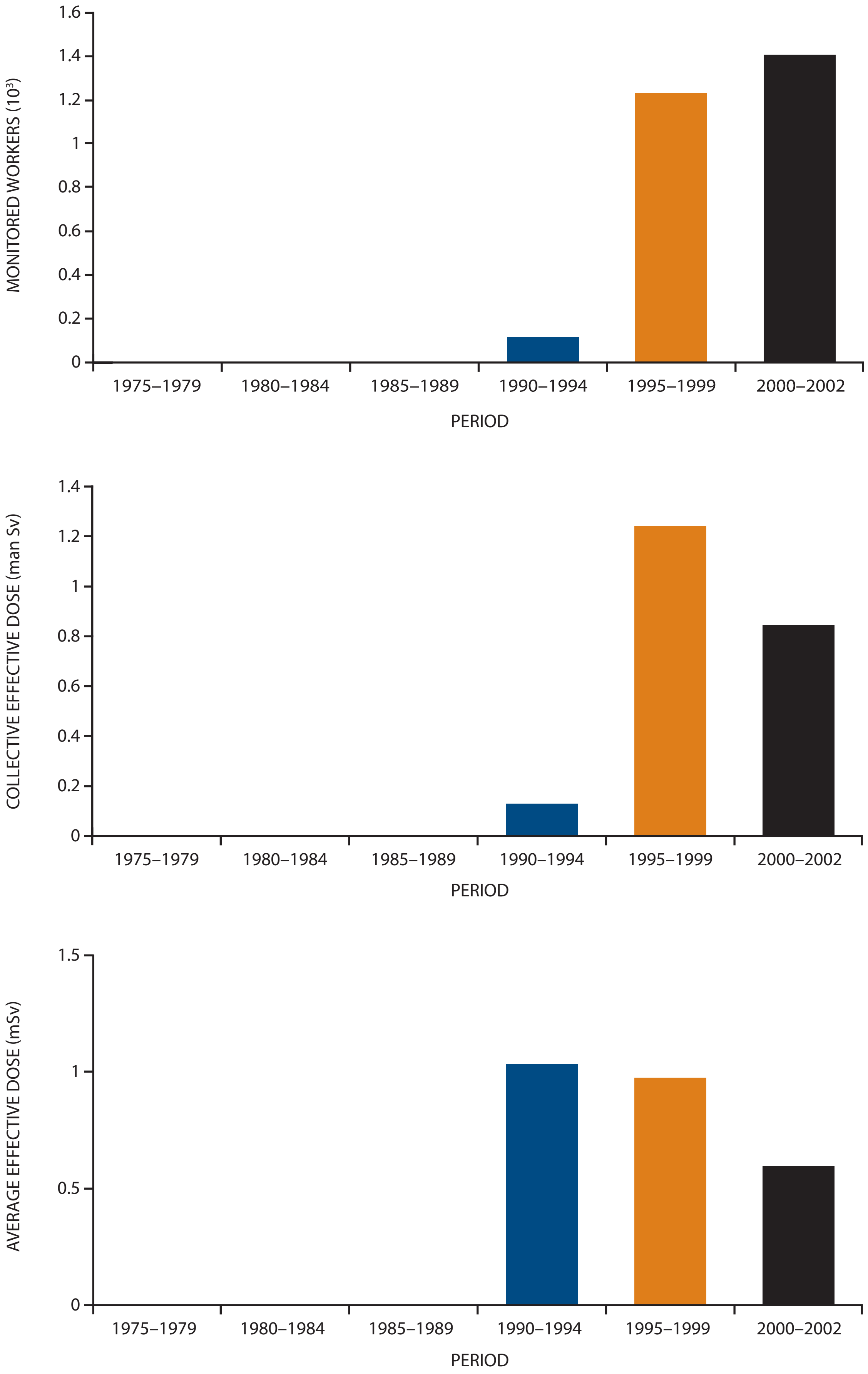


Figure LVII. Worldwide trends in occupational exposure due to industrial radiography

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

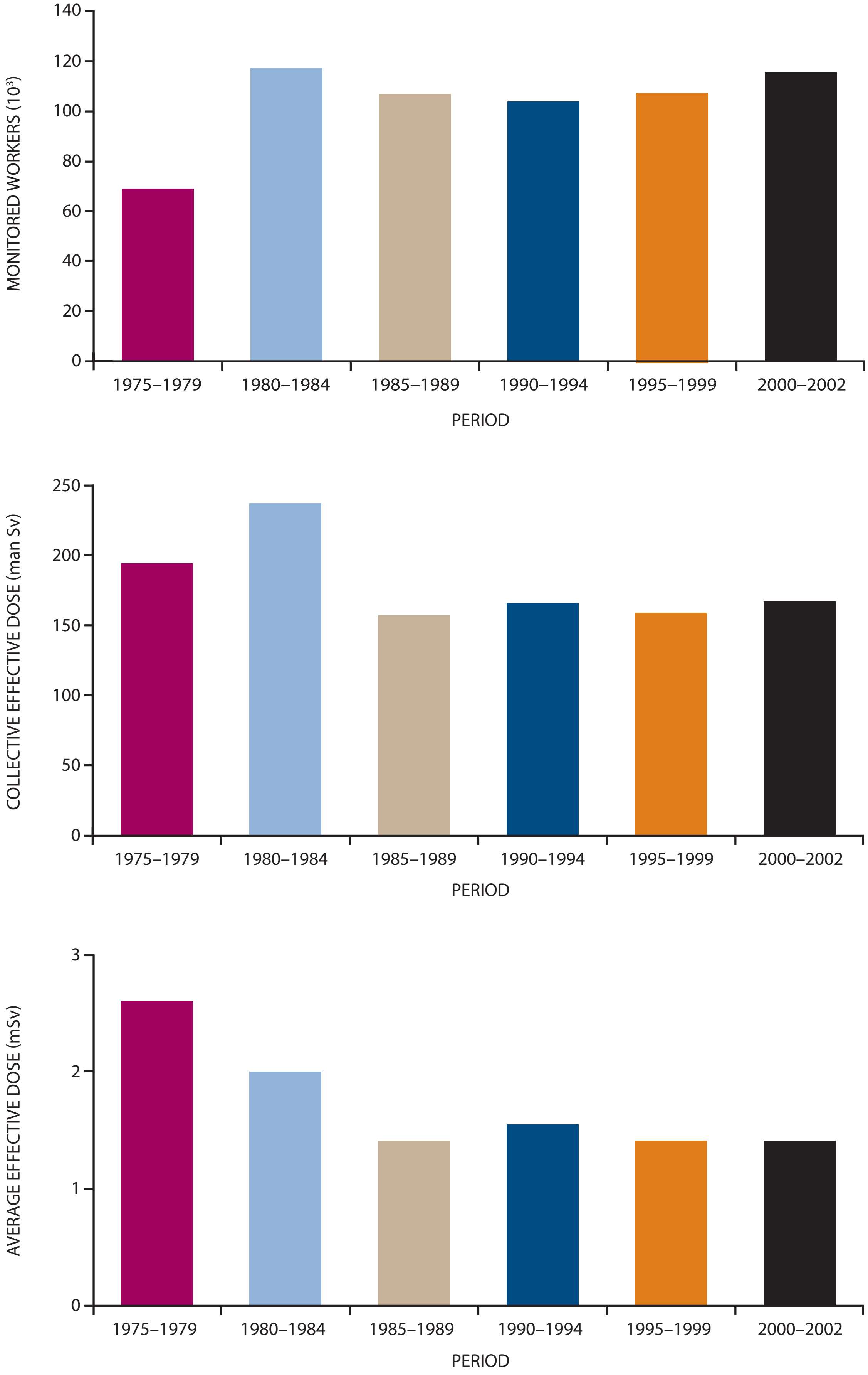


Figure LVIII. Trends in occupational exposure due to luminizing in Switzerland

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

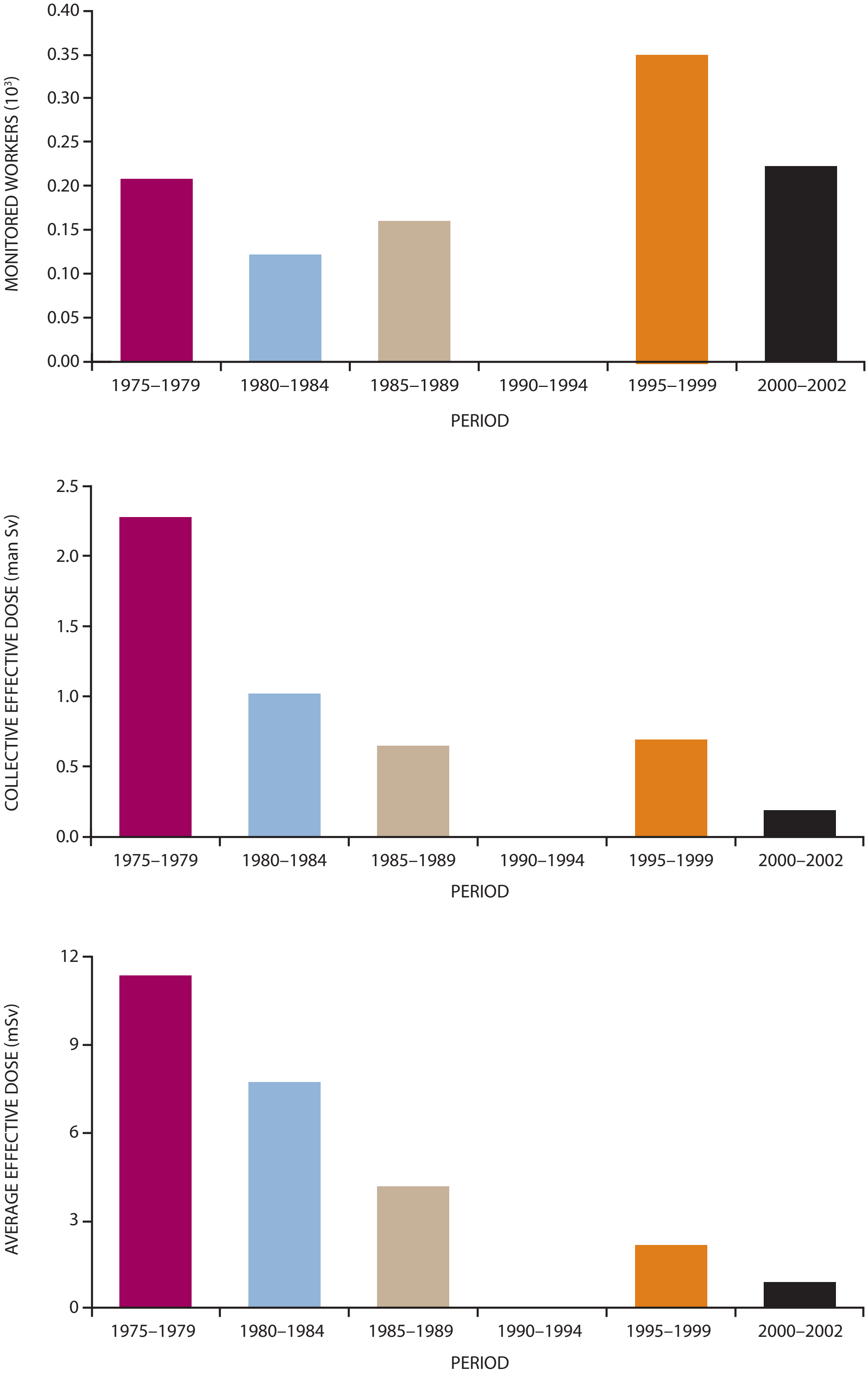


Figure LIX. Worldwide trends in occupational exposure due to radioisotope production
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

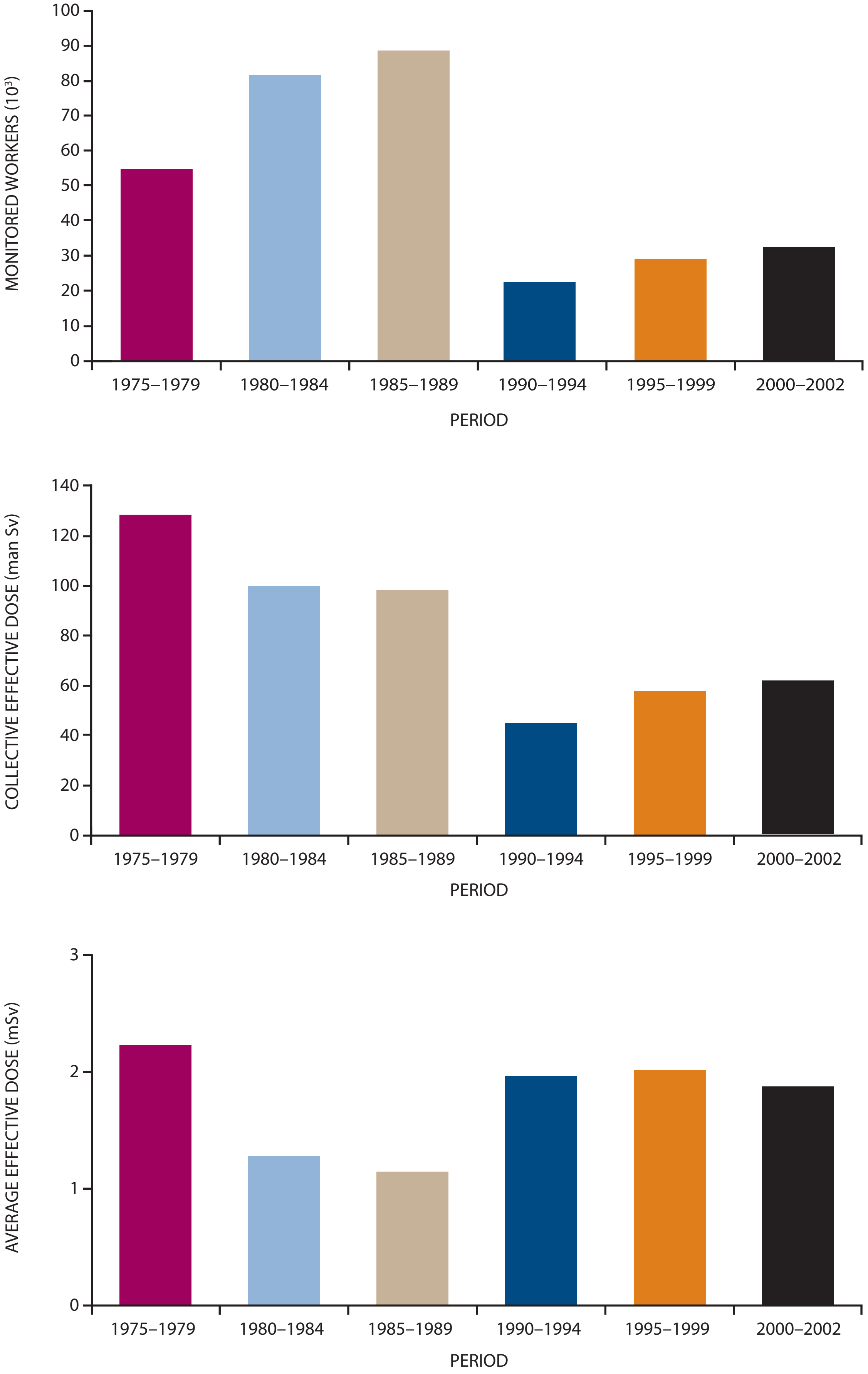


Figure LX. Trends in occupational exposure due to well logging in Canada

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

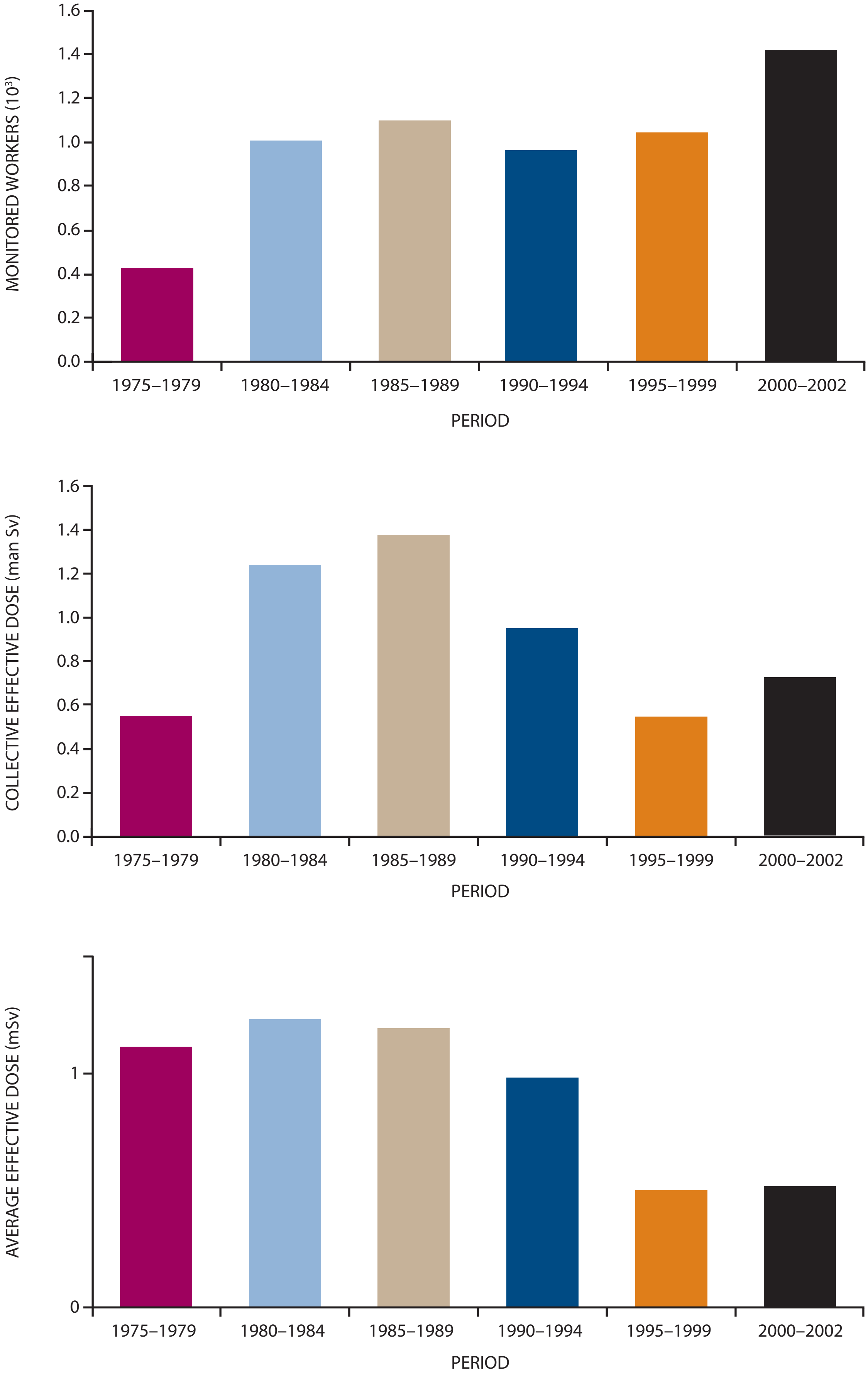


Figure LXI. Trends in occupational exposure due to accelerator operation in Canada
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

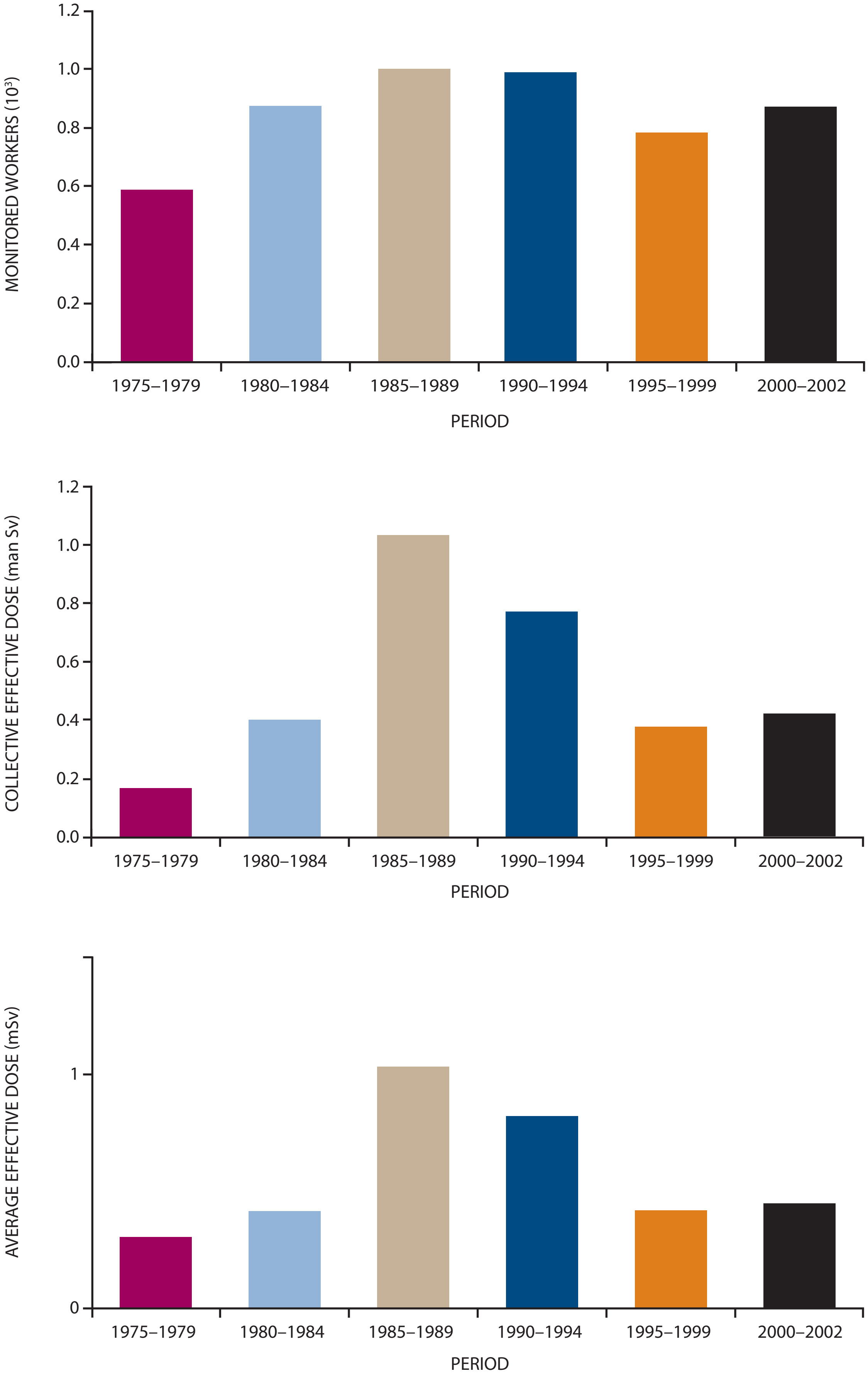


Figure LXII. Worldwide trends in occupational exposure due to all industrial uses of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

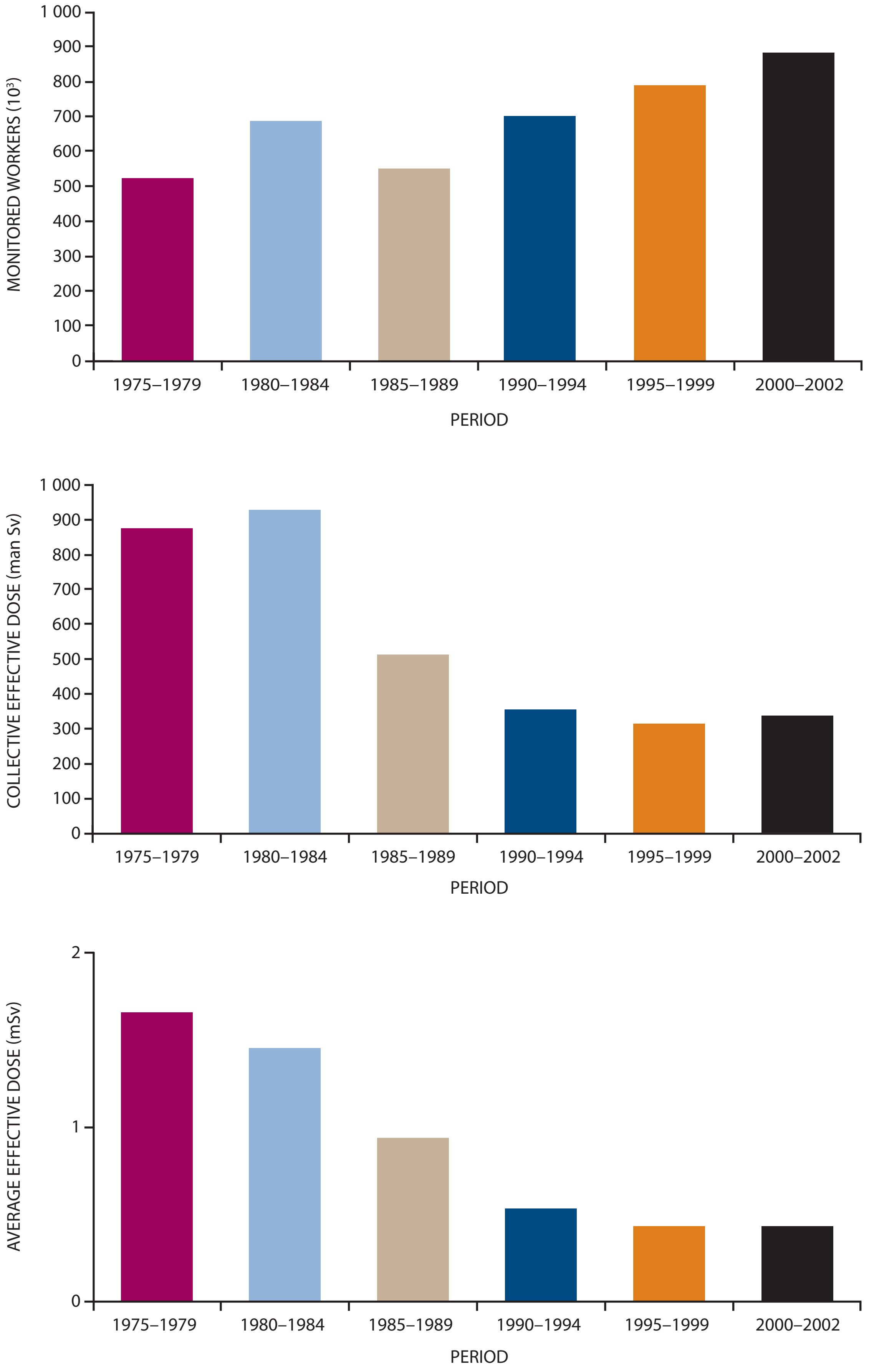


Figure LXIII. Worldwide trends in occupational exposure due to uses of radiation in educational establishments
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

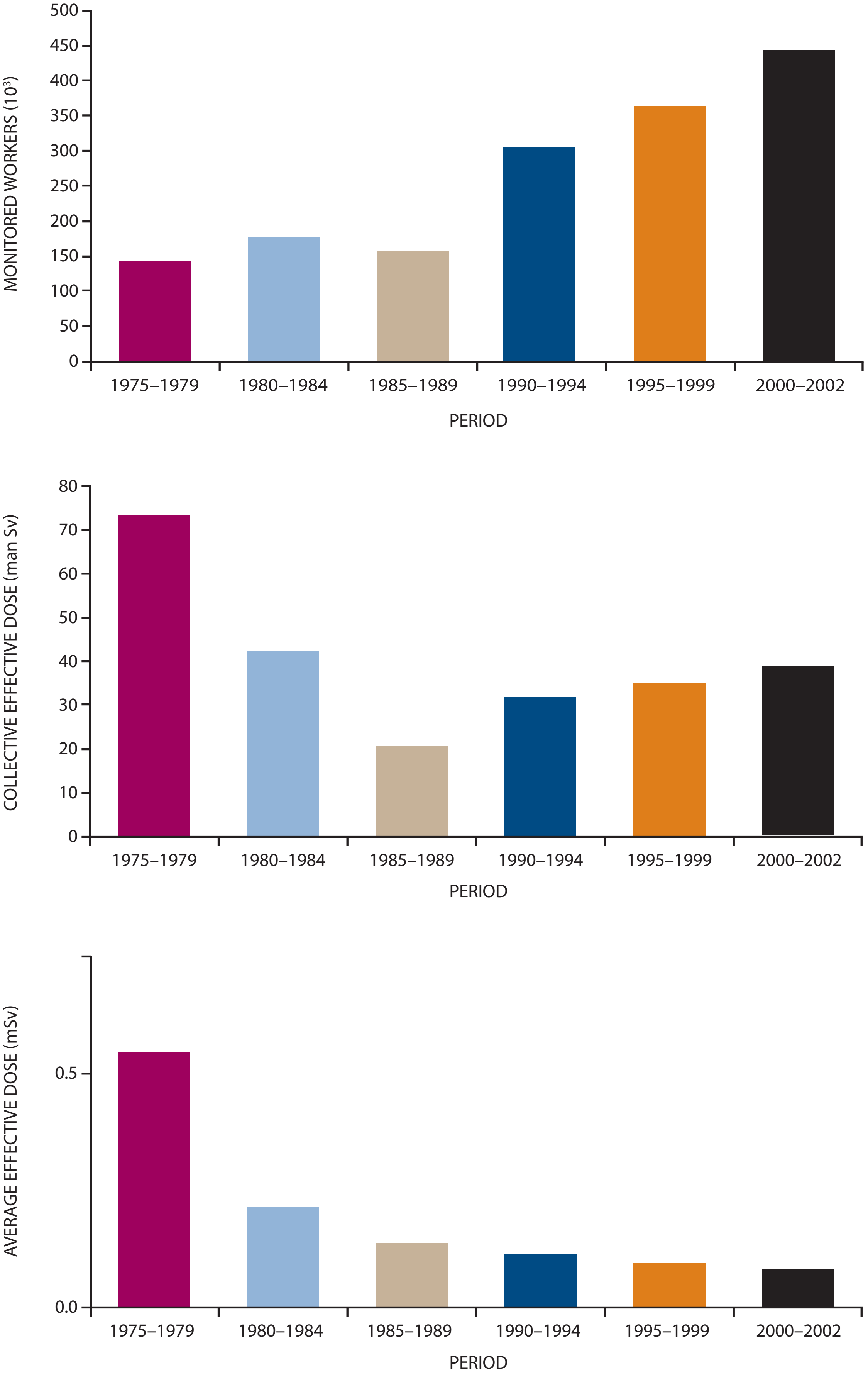


Figure LXIV. Worldwide trends in occupational exposure due to uses of radiation in veterinary medicine
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

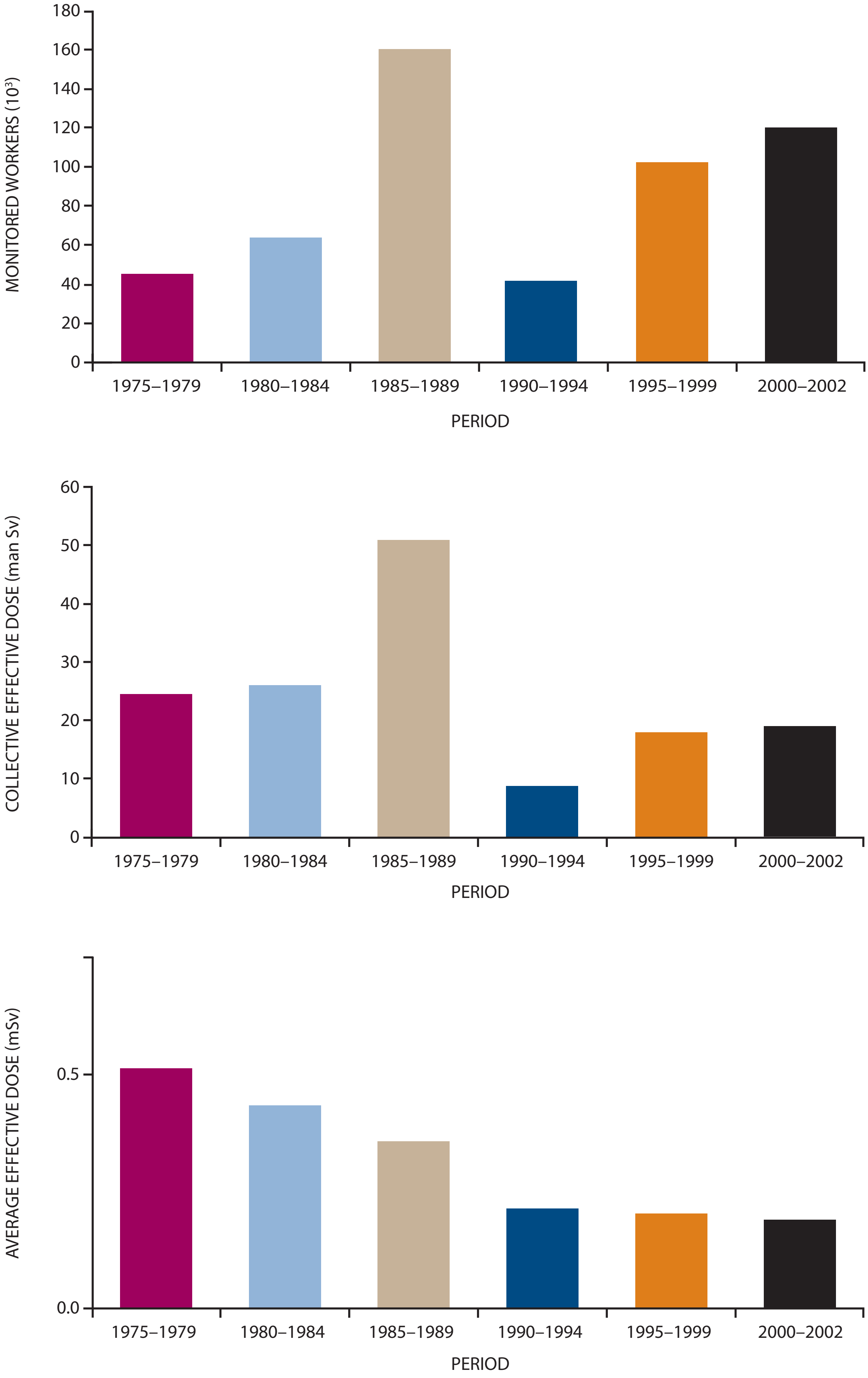


Figure LXV. Fraction of annual doses in three dose ranges for all companies participating in study of occupational doses due to transport in Canada [E2]

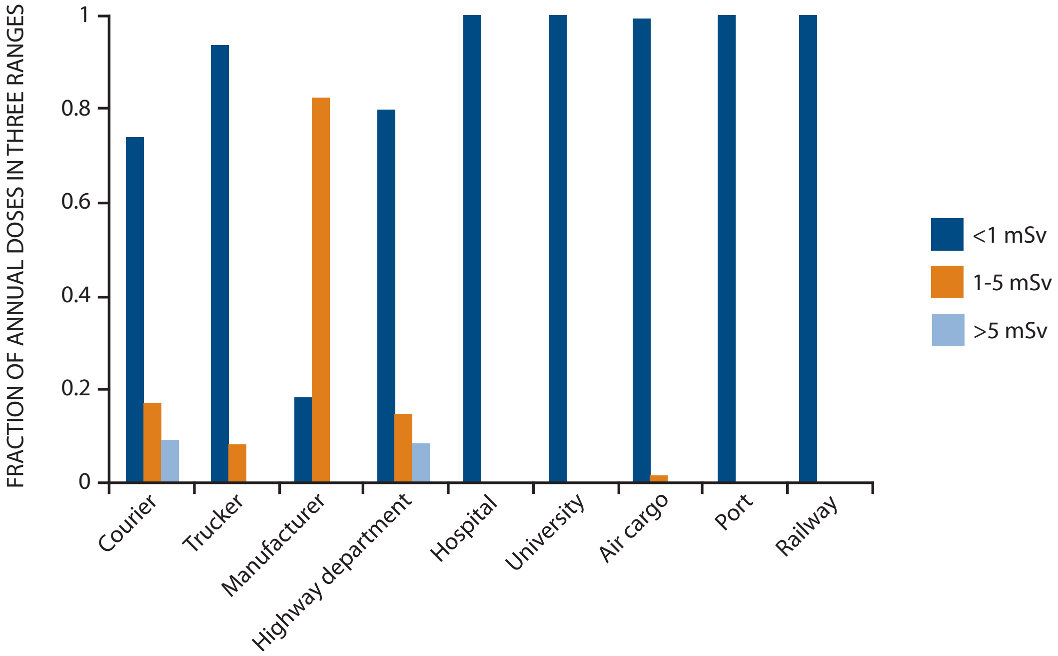


Figure LXVI. Worldwide trends in occupational exposure due to military activities
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

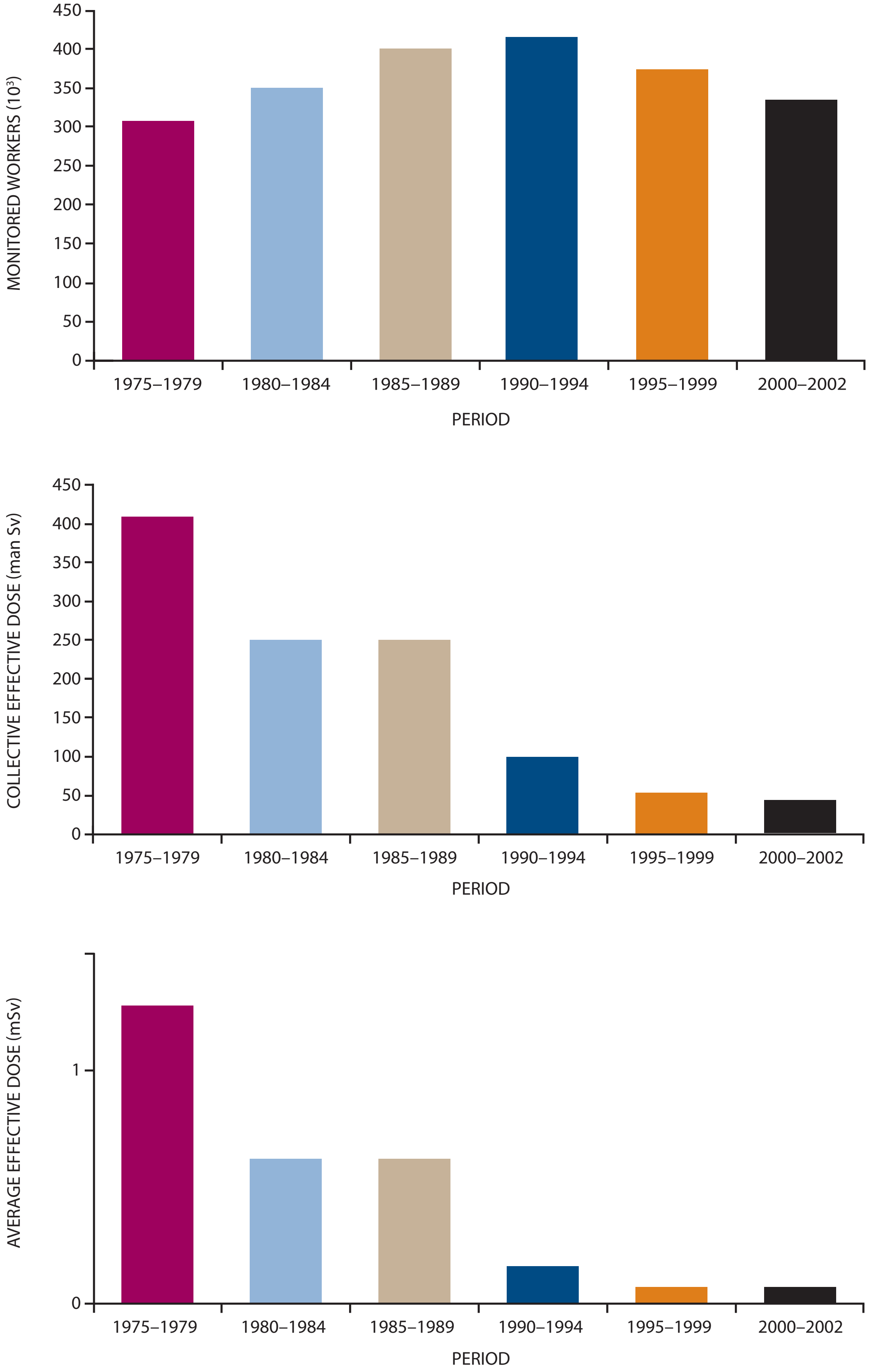


Figure LXVII. Worldwide trends in numbers of monitored workers, and in collective effective doses and effective doses to monitored workers

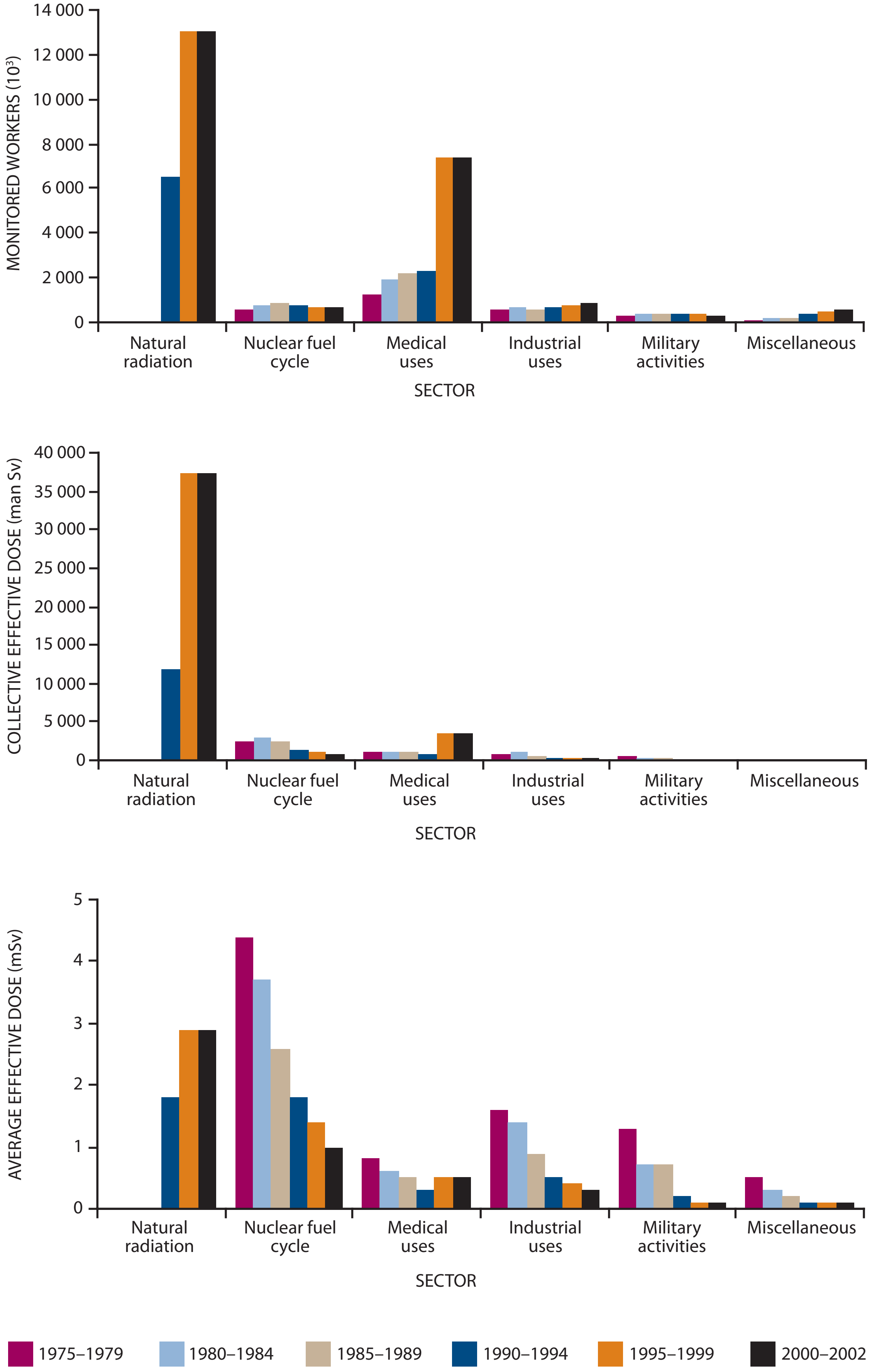


Figure LXVIII. Worldwide trends in occupational exposure due to natural sources of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

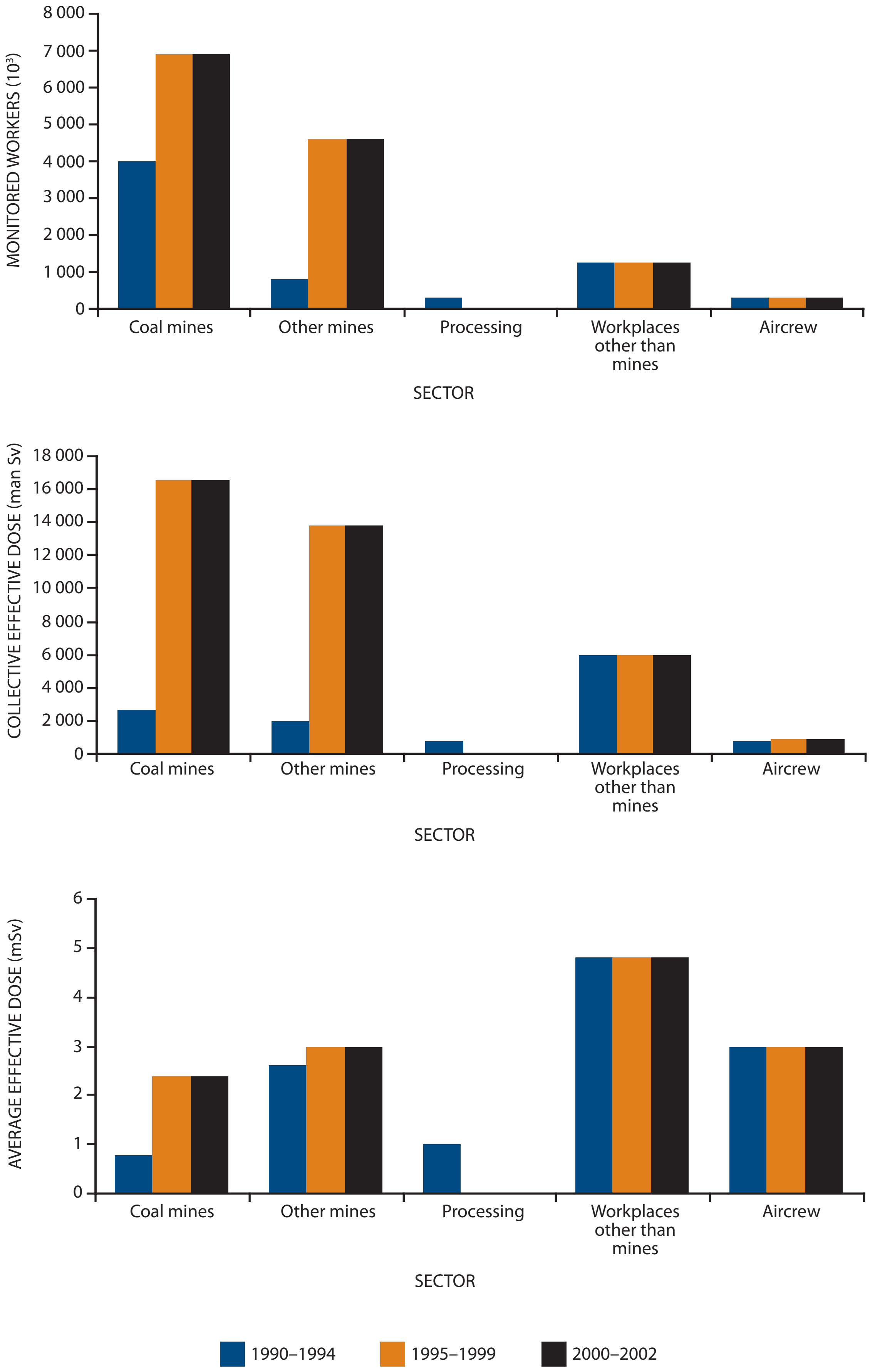


Figure LXIX. Worldwide trends in occupational exposure due to man-made sources of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

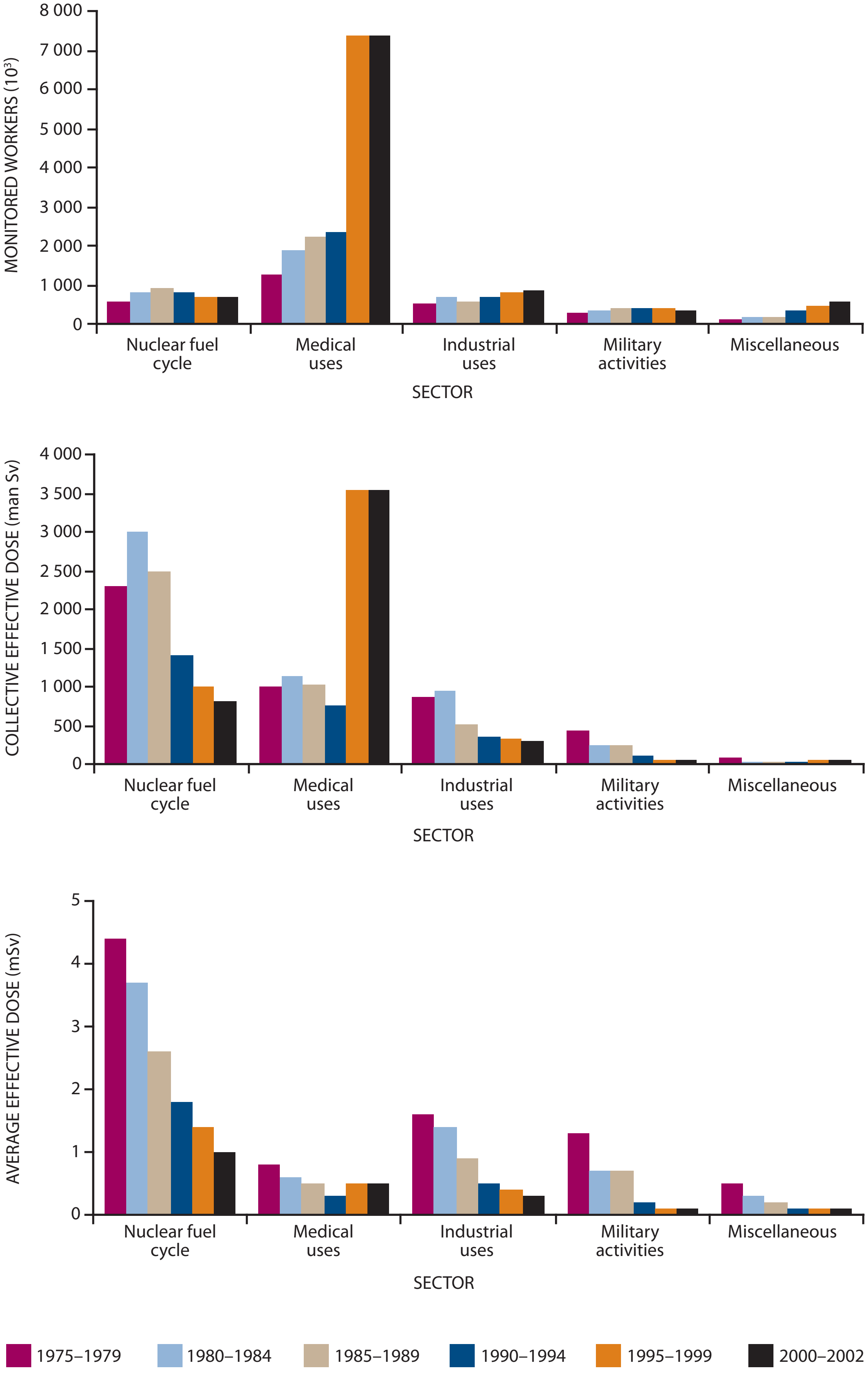


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Table A-1 Natural radionuclide content of soil

Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Population (10^{6})* [a]	*Concentration in soil (Bq/kg)*							
		^{40}K		*^{238}U*		*^{226}Ra*		*^{232}Th*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
Africa									
Algeria [U3]	28.78	370	66–1150	30	2–110	50	5–180	25	2–140
Egypt [U3]	63.27	320	29–650	37	6–120	17	5–64	18	2–96
Libya	1.5	270	265–282	10.5	8.7–12.8	8.8	8.3–9.4	9.5	7.6–9.7
Mauritius	1.22	28	0–55	8	1–22			12	1–32
North America									
Mexico		244	115–416						
United States [U3]	269.4	370	100–700	35	4–140	40	8–160	35	4–130
Central America									
Costa Rica	3.5	140	6–380	46	11–130	46	11–130	11	1–42
Cuba [J6]	11.2	328	20–2260			21.4	0.5–115	5	0.05–20
South America									
Argentina	35.22	654	559–773						
East Asia									
Bangladesh [C15, K5, R1, S8, S17, Y2]	57.08	1061	400–2168	52	18–95	51	18–98	79	28–167
China [U3]	1 232	440	9–1800	33	2–690	32	2–440	41	1–360
- Hong Kong Special Administrative Region [U3]	6.19	530	80–1100	84	25–130	59	20–110	95	16–200
- Taiwan Province		431	266–607	30	14–45	30	14–45	44	30–71
India [U3]	944.6	400	38–760	29	7–81	29	7–81	64	14–160
Japan [U3]	125.4	310	15–990	29	2–59	33	6–98	28	2–88
Kazakhstan	15.14		40–80		30–60				50–150
Indonesia	213.67	197	75–523			13.8	7–54	12.3	2–58
Malaysia [U3]	20.58	310	170–430	66	49–86	67	38–94	82	63–110
Philippines	75.9	212	33–585	14	2–53			14	1–63
Rep. of Korea [K16]	44.61	670	17–1500			39	6–140	57	5–204
Thailand [U3]	58.7	230	7–712	114	3–370	48	11–78	51	7–120

Region/country	*Population (10^6)[a]*	*Concentration in soil (Bq/kg)*							
		^{40}K		*^{238}U*		*^{226}Ra*		*^{232}Th*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
West Asia									
Armenia	3.64	360	310–420	46	28–70	51	32–77	30	29–60
Azerbaijan	8	120	60–180	26	26–50	25	15–35	33	10–56
Iran (Islamic Rep. of)	63.76	640	290–710			30	20–97	39	13–55
Iraq		469	146–518			16.8	0.5–35		
Kuwait	2.26	332	4–496	19	6–65	12	2–28	10	1.5–16
Syrian Arab Rep. [U3]	14.57	270	87–780	23	10–64	20	13–32	20	10–32
North Europe									
Denmark	5.2	460	240–610			17	8.5–29	19	8.1–30
Estonia [U3]	1.47	510	140–1120			35	6–310	27	5–42
Finland [A19]	5.2	640	300–1200	41	13–110	41	13–110	46	20–115
Iceland [E4]		140	40–240	10		8.5	2–15	6.5	0.5–11
Lithuania	3.45	536	241–800			41	10–96	21	10–46
Norway [U3]	4.35	850		50		50		45	
Sweden [M26, S15]	8.88		600–1180		10–1000		10–1000		2–100
West Europe									
Belgium [G10]	10.22	460	100–1000			32	6–70	33	6–53
Germany [U3]	81.92		40–1340		11–330	70	5–200		7–134
Ireland [M9]	3.92	418	11–1317	39	4–543	46	6–292	25	3–71
Luxembourg	0.41	620	80–1800			35	6–52	50	7–70
Netherlands [U3]	15.58		120–730		5–53	23	6–63		8–77
Portugal [U3]	9.81	840	220–1230	49	26–82	44	8–65	51	22–100
Spain [Q4, Q5, Q7, Q9]	39.67	578	31–2040			38	8–310	41	2–258
Switzerland	7.5	370	40–1000	26	9–80	37	17–140	25	4–65
United Kingdom [U3]	58.14		0–3200		2–330	37			1–180

Region/country	*Population (10^6)* [a]	*Concentration in soil (Bq/kg)*							
		^{40}K		*^{238}U*		*^{226}Ra*		*^{232}Th*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
East Europe									
Bulgaria [U3]	8.47	400	40–800	40	8–190	45	12–210	30	7–160
Czech Republic [W12]	10.3	613	262–1599			44	18–275	41	18–168
Hungary [U3]	10.05	370	79–570	29	12–66	33	14–76	28	12–45
Poland [B25]	38.12	410	123–1020	25.2	4.2–124	25.2	4.2–124	24.7	3.7–86
Romania [C20, C21, C22, I1]	21.83	490	250–1100	32	8–60	32	8–60	38	11–75
Russian Federation [U3]	148.1	520	100–1400	19	0–67	27	1–76	30	2–79
Slovakia [U3]	5.35	520	200–1380	32	15–130	32	12–120	38	12–80
Slovenia [A18]	2.02	374	15–1410			41	2–208	35	2–90
South Europe									
Albania [D9, T13]	3.4	348	91–665	34	2.5–141			18.3	0.8–61
Croatia	4.5	423	107–748	53	19–135	43	18–80	37	10–72
Cyprus [U3]	0.76	140	0–670			17	0–120		
Greece [A16, P13]	10.36	383	12–1570	45	10–190	29	1–310	28	1–193
Montenegro [V24]	0.6	246	78–480			29.3	7–166	23.7	9–74
The former Yugoslav Republic of Macedonia		456	0–699	36.9	11.5–92.7	23.4	0–31.7	25	19.8–37.9
Oceania									
New Zealand	4.1	370	<40–740			23	<4–56	29	<4–63

[a] When not provided by the country, the information was taken from reference [C17].

Table A-2 Activity concentration in building materials

Country/region	*Activity concentration (Bq/kg)*				*Comments*	*Reference*
	^{226}Ra	*^{232}Th*	*^{40}K*	*Other nuclides*		
Sand						
Australia	3.7	40.7	44.7			[A23]
Bangladesh	14.2	25	158.4			[C16]
Brazil, SP	24.1		454	45.5 (^{228}Ra)		[V19]
Brazil, ES	10.2	12.6	51			[M3]
Brazil, RN	14.3	180	809			[M3]
China	25	35	850			[a]
Cuba	16.7	15.6	188			[F11]
Cuba	44	22	99		White cement	[F11]
Czech Republic	13.3	13	284			[V22]
Germany	15	16	380			[B49]
Greece	1–4	3	1–37			[L21]
Italy	18	22	530			[R15]
Jordan	25.1	14.6	188.1			[A23]
Lithuania	15	8	426			
Malaysia	70.3	33.3	425.5			[A23]
Malaysia		13	750	60 (^{238}U)		[I2]
Mexico	22.2	22.8				[A23]
Netherlands	8.1	10.6	200			[A23]
Pakistan	27	40.63	566.9			[A23]
Rep. of Korea	29	56.4	1008			[L4]
Romania	6.8	21.8	507	2.0 (^{137}Cs)		[P4]
Romania	25	20	176			[B40]
Spain	7–30	2.9–28	12–31			[M2]
Cement						
Australia	51.8	48.1	114.7			[A23]
Austria	26.7	14.2	210			[A23]
Bangladesh	62.3	59.4	329			[C16]
Belgium	62	76				[A23]
Brazil, SP	70.5		151	26.4 (^{228}Ra)		[V18]
China	50	30	140			[a]
- Taiwan Province	33		279.9			[I3]
Cuba	22.8	10.6	467			[F12]
Czech Republic	26.5	20.7	306			[V22]
Finland	40.2	19.9	251			[A23]
Germany	15.1	22.9	325			[A23]
Greece	29–218	11–30	172–553			[L21, P5]
Italy	42	66	369			[R15]
Jordan	43.21	11.23	265.12		Fuhais	[A23]
Jordan	45.07	11.42	226.4		South	[A23]
Jordan	49.1	13.47	111.91		White	[A23]
Lithuania	31	13	172			
Malaysia	81.4	59.2	303.5			[A23]
Malaysia		23	862	51 (^{238}U)		[I2]
Mexico	26	52.6				[A23]
Netherlands	27	19	230			[A23]
Norway	29.6	18.5	259			[A23]
Pakistan	36.5	28.1	214.9			[A23]
Rep. of Korea	34.5	19.4	241			[L4]
Romania	5.7	13.4	198	4.4 (^{137}Cs)		[P4]
Romania	64	27	281			[B40]

Country/region	*Activity concentration (Bq/kg)*				*Comments*	*Reference*
	^{226}Ra	*^{232}Th*	*^{40}K*	*Other nuclides*		
Romania	178	206	133		With Al industry waste	[B40]
Spain	48.3	32.3	316.3			[M11, Q3]
Sudan	16.6	13.2	107.2		Atbra	[S7]
Sudan	24	13.6	91.9		Rabak	[S7]
Sudan	19.5	12.3	101.1		Seabulk	[S7]
Sudan	25.9	16.8	176.3		Jordanian	[S7]
Sudan	19.8	10.6	90.6		Indonesian	[S7]
Concrete						
Australia	15	41	200			[A23]
Bangladesh	36.6	49.4	250			[C16]
Brazil, ES	21.9	25.3	42			[M3]
Brazil, RN	7.1	9.9	360		Phosphate area	[M3]
China - Taiwan Province	43		358			[A23]
Cuba	24.5	12	595			[F12]
Czech Republic	21.1	17.4	404			[V22]
Czech Republic	46.1	45.1	348		Aggregate concrete	[V22]
Czech Republic	66.7	55.3	444		Slag concrete	[V22]
Germany	30	23	450			[B49]
Greece	7–85	1–11	23–330			[L21, P2, P5, S9]
Italy	22	16	237			[R15]
Jordan	38	6	138			[A23]
Lithuania	32	17	426			[P10]
Malaysia	85	52	322			[A23]
Netherlands	14	16	130			[A23]
Norway	28	36	650			[A23]
Pakistan	27	21	240			[A23]
Rep. of Korea	26.4	39.1	596			[L4]
Romania	69	77	918			[B40]
Romania	106	91	477		With cinder (coal)	[B40]
Romania	118	556	615		With Al industry waste	[B40]
Sweden	47	80	577			[A23]
United Kingdom	22	42				[A23]
United States	27	11	350			[A23]
Tiles						
Brazil, SP	46		468	53.0 (^{228}Ra)		[V18]
Brazil, ES	56.3	99.1	413			[M3]
Brazil, RN	51.1	95.6	944		Phosphate area	[M3]
Czech Republic	63	54.7	452		Ceramic tiles	[V22]
Germany	50	55	560			[B49]
Greece	52–98	26–46	251–758			[P5]
Italy	43	36	689			[R15]
Malaysia		13	328	24 (^{238}U)	Roof asbestos	[I2]
Malaysia		51	7541	241 (^{238}U)	Red clay brick	[I2]
Rep. of Korea	58.1	55.6	625			[L4]
Romania	48.1	58.1	792	2.9 (^{137}Cs)		[P4]
Spain		68	507		Porcelain tile	[S14]
Spain		76	490		Superwhite porcelain	[S14]
Blocks						
Brazil, SP	48.4		475	54.3 (^{228}Ra)	Ceramic block	[V19]
Brazil, SP	24.2		767	55.7 (^{228}Ra)	Concrete block	[V19]
Brazil, SP	9.9		26.6	26.4 (^{228}Ra)	Calcareous silicon	[V19]
Nigeria	47±21	52±21	353±222			[F1]

Country/region	*Activity concentration (Bq/kg)*				*Comments*	*Reference*
	^{226}Ra	*^{232}Th*	*^{40}K*	*Other nuclides*		
Bricks						
Bangladesh	29.5	52	292			[C16]
Brazil, ES	46.8	119.9	322			[M3]
Brazil, RN	50.7	69.4	728			[M3]
Brazil, RN	91	116			Phosphate area	[M3]
Brazil, SP	36		325	55.8 (^{228}Ra)	Ceramin brick	[V19]
China	55	65	600			[a]
Cuba	57	12	785			[F12]
Czech Republic	45.2	46.8	611		Clay brick	[V22]
Germany	50	52	700			[B49]
Greece	25–93	35–65	539–1058			[L21, P2, P5, S9]
Italy	29	26	711			[R15]
Lithuania	40	32	754			[P10]
Malaysia		24	740	30 (^{238}U)	Cement brick	[I2]
Pakistan	46.1	62	744.5			[K9]
Rep. of Korea	29.1	40.7	785			[L4]
Rep. of Korea	36.4	48.3	736		Red brick	[L4]
Romania	50	52	652			[A23]
Romania	33.3	79.8	698			[B40]
Romania	139	57	196		Brick (coal cinder)	[B40]
Romania	47.5	65.6	669	3.8 (^{137}Cs)	Red brick	[P4]
Romania	7.9	12.5	264	3.1 (^{137}Cs)	ACC brick	[P4]
Ceramic						
Italy		52–66	520–890	50–79(^{238}U)	Glazed tile; porcelain	[B47]
Spain	55–73	44–60	292–747			[M2]
Romania	51	45	725			[B40]
Granite						
China - Taiwan Province		81	1 322	36 (^{238}U)		[I3]
Germany	100	120	1000			[B49]
Italy	89	94	1126			[R15]
Rep. of Korea	53.1	86.4	1081			[L4]
Spain	85.5	45.1	1028			[M11, Q3]
Marble						
China - Taiwan Province	16.43	22	133			[A23, I3]
Germany	24	5	90			[B49]
Greece	80.8	33.7	483.1			[A23]
Italy	4	1	8			[R15]
Jordan	308.9	6.6	59.2		Dabbah	[A23]
Jordan	19.3	11.9	93.3		Ajloun	[A23]
Jordan	20.1	11.4	85		Azraq	[A23]
Pakistan	16	20	248			[A23]
Other						
Bangladesh	25.3	54.7	228.4		Gravel	[C16]
Bangladesh	2	39.7	241.5		Mortar	[C16]
Bangladesh	254.5	21.4	120.8		Phosphogypsum	[C16]
Bangladesh	43.9	65.4	1383.7		Lime	[C16]
Brazil, SP	38.6		1064	77 (^{228}Ra)	Aggregate	[V19]
China	50	80	900		Gravel	[a]
China	25	7	55		Lime	[a]
Czech Republic	29.8	22.7	367		Stone	[V22]
Czech Republic	19.8	12.4	246		Mortar	[V22]
Czech Republic	13.9	9.6	112		Plaster	[V22]
Czech Republic	40.9	23.9	144		Clay	[V22]
Czech Republic	12.5	6.3	126		Lime	[V22]

Country/region	*Activity concentration (Bq/kg)*				*Comments*	*Reference*
	^{226}Ra	*^{232}Th*	*^{40}K*	*Other nuclides*		
Czech Republic	12.1	10.3	187		Gypsum	[V22]
Italy	8	3	160		Natural gypsum	[R15]
Italy	209	349	1861		Tuff	[R15]
Italy	160	130	420		Fly ash	[R15]
Rep. of Korea	271	<ld	16.8		Phosphogypsum	[L4]
Rep. of Korea	6.47	<ld	112		Wood	[L4]
Romania	118	86.7	673	2.7 (^{137}Cs)	Coal fly ash	[P4]
Romania	54	23	113		Phosphogypsum	[G8]
Romania	10.5	9.8	180	9.6 (^{137}Cs)	Tufa	[P4]
Romania	<6.7	2.1	75	9.3 (^{137}Cs)	Wood	[P4]
Romania	41	40	199		Natural gypsum	[B40]

[a] Provided by the Chinese delegation to UNSCEAR; typical values for the country.

Table A-3 Activity concentration of naturally occurring radionuclides in drinking water (mBq/L)

Country	*Location*	*Origin*	^{238}*U*		^{232}*Th*		^{226}*Ra*		^{228}*Ra*		^{210}*Pb*		^{210}*Po*	
			Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
Africa														
Morocco [H3]	Countrywide	Wells	66	4.5–309			1	1.0–25	5	1.0–17.3				
	Countrywide	Mineral springs	5.3	0.6–8.5			651	9.1–3696	91.5	2.4–620				
	Countrywide	Tap water	4.8	2.5–15.7			7.3	0.46–46	1.9	<0.4–12				
North America														
United States [U3]	Countrywide			0.3–77	0.05			0.4–1.8		0–0.5		0.1–1.5		
Central America														
Cuba [E8]	Camaguey	Public supply					27							
South America														
Argentina [B35, S25]	Countrywide	Private wells		0.37–3100			2.24	<0.3–22						
	Countrywide	Bottled water	7.2	0.5–47			1.3	<0.3–2.4						
Brazil [A11, G11, G12]	Countrywide	Mineral water					27	8.0–83	97	12–385	66	20–102		
	Countrywide	Underground water	29.7	0.25–186			14	1–3790	45	2–3800	40	9–980		
East Asia														
China [U3]	Countrywide			0.1–700		0.04–12		0.2–120						
India [A22, U3]	Goa	Potable water										2.19–11.48		1.66–7.04
	Countrywide			0.09–1.5										
North Europe														
Finland [S6, U3]	Countrywide			0.5–150000				10–49000		18–570		0.2–21000		0.2–7600
	Countrywide	Groundwater	4.2				0.44				0.43		0.22	
			0.61				0.04				0.08		0.04	

Country	*Location*	*Origin*	^{238}*U*		^{232}*Th*		^{226}*Ra*		^{228}*Ra*		^{210}*Pb*		^{210}*Po*	
			Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
West Europe														
France [U3]	Countrywide			4.4–930		0–4.2		7–700						
Germany [B48, G6]	Countrywide		5	0.4–600	0.1	0.1–4	5	0.5–32	3	0.5–23	1.5	0.2–170	0.5	0.1–40
	Enhanced natural radiation area	Springs and wells		<10–30				30–30200		410–7700		<200–300		60–80
Italy [B22, B37, D8, F13, J4, R20]	Countrywide	Tap water		0.2–199				<1.2–23		1.5–12				0.13–5.9
[B36, D7, F13, J4, R21]	Countrywide	Mineral water		<0.5–119				0.5–126		0.1–44				< 0.04–24
Portugal [U3]							27	<3–2 185			18.5	2–392		
Spain [D15]	Countrywide	Public supply	4	0.028–7.6	2.03	0.01–9.6	1.75	1.3–2.2	<84.5		18.7	0.23–59	3.63	1.8–19.3
	Countrywide	Bottled water					86.7	2–600						
Switzerland [U3]	Countrywide			<5–500				5–200		5–300				
United Kingdom [U3]	Countrywide							0–180				40–200		
East Europe														
Czech Republic [V21]	Countrywide	Public supply	45	<2–1080			28	40–302				<40–346	9	<2–71
Hungary [S46]	Countrywide	Public supply	100	1–934			43	8–238						
Poland [U3]	Countrywide		7.3		0.06			1.7–4.5			1.6		0.5	
Romania [B38, U3]	Countrywide			0.4–37		0.04–9.3		0.7–21				7.0–44		7.0–44
	Crucea/Grinties	Drinking water		1.8–78.7		2.0–10.4		0.3–120						
Russian Fed. [S19]	Komi Rep.	Water supply					7.4	2.6–23.4	12.6	2.4–34	26.9	2.3–67.9	2.72	1.2–7.1
South Europe														
Greece [K7]	Attiki	Lakes used for public supply		0.19–17.27										

Table A-4 Nuclear power plants operating in the period 1998–2002

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
Argentina	Atucha-1	HWR	1974	335
Argentina	Embalse	HWR	1984	600
Armenia	Armenia-2	WWER	1980	376
Belgium	Doel-1	PWR	1974	392
Belgium	Doel-2	PWR	1974	433
Belgium	Doel-3	PWR	1975	1006
Belgium	Doel-4	PWR	1985	985
Belgium	Tihange-1	PWR	1975	962
Belgium	Tihange-2	PWR	1982	1008
Belgium	Tihange-3	PWR	1985	1015
Brazil	Angra-1	PWR	1985	626
Brazil	Angra-2	PWR	2001	1275
Bulgaria	Kozloduy-1	WWER	1974	408
Bulgaria	Kozloduy-2	WWER	1975	408
Bulgaria	Kozloduy-3	WWER	1980	408
Bulgaria	Kozloduy-4	WWER	1982	408
Bulgaria	Kozloduy-5	WWER	1987	953
Bulgaria	Kozloduy-6	WWER	1991	953
Canada	Bruce A-3 [a]	HWR	1977	750
Canada	Bruce A-4 [a]	HWR	1978	750
Canada	Bruce B-5	HWR	1984	790
Canada	Bruce B-6	HWR	1984	841
Canada	Bruce B-7	HWR	1987	790
Canada	Bruce B-8	HWR	1987	790
Canada	Darlington-1	HWR	1990	881
Canada	Darlington-2	HWR	1989	881
Canada	Darlington-3	HWR	1992	881
Canada	Darlington-4	HWR	1993	881
Canada	Gentilly-2	HWR	1982	635
Canada	Pickering A-4	HWR	1973	515
Canada	Pickering B-5	HWR	1982	516
Canada	Pickering B-6	HWR	1983	516
Canada	Pickering B-7	HWR	1984	516
Canada	Pickering B-8	HWR	1985	516
Canada	Point Lepreau	HWR	1982	635
China	Qinshan 3-1	HWR	2002	650
China	Guangdong-1	PWR	1993	944
China	Guangdong-2	PWR	1994	944
China	Lingao-1	PWR	2002	938
China	Lingao-2	PWR	2002	938
China	Qinshan-1	PWR	1991	288
China	Qinshan 2-1	PWR	2002	610
China	Qinshan 2-2	PWR	2004	610
China - Taiwan Province	Chinshan-1	BWR		
China - Taiwan Province	Chinshan-2	BWR		
China - Taiwan Province	Kuosheng-1	BWR		
China - Taiwan Province	Kuosheng-2	BWR		
China - Taiwan Province	Maanshan-1	PWR	1984	
China - Taiwan Province	Maanshan-2	PWR	1985	

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
Czech Republic	Dukovany-1	WWER	1985	412
Czech Republic	Dukovany-2	WWER	1985	412
Czech Republic	Dukovany-3	WWER	1987	412
Czech Republic	Dukovany-4	WWER	1987	412
Czech Republic	Temelin-1	WWER	2000	950
Czech Republic	Temelin-2	WWER	2002	950
Finland	Olkiluoto-1	BWR	1978	840
Finland	Olkiluoto-2	BWR	1979	840
Finland	Loviisa-1	WWER	1977	488
Finland	Loviisa-2	WWER	1980	488
France	Belleville-1	PWR	1987	1310
France	Belleville-2	PWR	1988	1310
France	Blayais-1	PWR	1981	910
France	Blayais-2	PWR	1981	910
France	Blayais-3	PWR	1983	910
France	Blayais-4	PWR	1983	910
France	Bugey-2	PWR	1978	910
France	Bugey-3	PWR	1978	910
France	Bugey-4	PWR	1979	880
France	Bugey-5	PWR	1979	880
France	Cattenom-1	PWR	1986	1300
France	Cattenom-2	PWR	1987	1300
France	Cattenom-3	PWR	1990	1300
France	Cattenom-4	PWR	1991	1300
France	Chinon B-1	PWR	1982	905
France	Chinon B-2	PWR	1983	905
France	Chinon B-3	PWR	1987	905
France	Chinon B-4	PWR	1987	905
France	Chooz B-1	PWR	1967	1500
France	Chooz B-2	PWR	1997	1500
France	Civaux-1	PWR	1997	1495
France	Civaux-2	PWR	1999	1495
France	Cruas-1	PWR	1983	915
France	Cruas-2	PWR	1983	915
France	Cruas-3	PWR	1984	915
France	Cruas-4	PWR	1984	915
France	Dampierre-1	PWR	1980	890
France	Dampierre-2	PWR	1980	890
France	Dampierre-3	PWR	1981	890
France	Dampierre-4	PWR	1981	890
France	Fessenheim-1	PWR	1977	880
France	Fessenheim-2	PWR	1977	880
France	Flamanville-1	PWR	1985	1330
France	Flamanville-2	PWR	1986	1330
France	Golfech-1	PWR	1990	1330
France	Golfech-2	PWR	1993	1330
France	Gravelines-1	PWR	1980	910
France	Gravelines-2	PWR	1981	910
France	Gravelines-3	PWR	1982	910
France	Gravelines-4	PWR	1983	910
France	Gravelines-5	PWR	1984	910
France	Gravelines-6	PWR	1985	910

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
France	Nogent-1	PWR	1987	1310
France	Nogent-2	PWR	1988	1310
France	Paluel-1	PWR	1984	1310
France	Paluel-2	PWR	1985	1310
France	Paluel-3	PWR	1986	1310
France	Paluel-4	PWR	1986	1310
France	Penly-1	PWR	1990	1310
France	Penly-2	PWR	1992	1310
France	St. Alban-1	PWR	1985	1335
France	St. Alban-2	PWR	1986	1335
France	St. Laurent B-1	PWR	1981	915
France	St. Laurent B-2	PWR	1981	915
France	Tricastin-1	PWR	1980	915
France	Tricastin-2	PWR	1980	915
France	Tricastin-3	PWR	1981	915
France	Tricastin-4	PWR	1981	915
Germany	Brunsbuettel	BWR	1976	771
Germany	Gundremmingen-B	BWR	1984	1284
Germany	Gundremmingen-C	BWR	1984	1288
Germany	Isar-1	BWR	1977	878
Germany	Kruemmel	BWR	1983	1260
Germany	Philippsburg-1	BWR	1979	890
Germany	Biblis-A	PWR	1974	1167
Germany	Biblis-B	PWR	1976	1240
Germany	Brokdorf	PWR	1986	1370
Germany	Emsland	PWR	1988	1329
Germany	Grafenrheinfeld	PWR	1981	1275
Germany	Grohnde	PWR	1984	1360
Germany	Isar-2	PWR	1976	1400
Germany	Neckarwestheim-1	PWR	1976	785
Germany	Neckarwestheim-2	PWR	1989	1269
Germany	Obrigheim	PWR	1968	340
Germany	Philippsburg-2	PWR	1984	1392
Germany	Stade	PWR	1972	640
Germany	Unterweser	PWR	1978	1345
Hungary	Paks-1	WWER	1982	437
Hungary	Paks-2	WWER	1984	441
Hungary	Paks-3	WWER	1986	433
Hungary	Paks-4	WWER	1987	444
India	Tarapur-1	BWR	1969	150
India	Tarapur-2	BWR	1969	150
India	Kaiga-1	HWR	2000	202
India	Kaiga-2	HWR	1999	202
India	Kakrapar-1	HWR	1992	202
India	Kakrapar-2	HWR	1995	202
India	Kalpakkam-1	HWR	1983	155
India	Kalpakkam-2	HWR	1985	202
India	Narora-1	HWR	1989	202
India	Narora-2	HWR	1992	202
India	Rajasthan-1	HWR	1972	90
India	Rajasthan-2	HWR	1980	187
India	Rajasthan-3	HWR	2000	202
India	Rajasthan-4	HWR	2000	202

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
Japan	Fukushima-Daiichi-1	BWR	1971	460
Japan	Fukushima-Daiichi-2	BWR	1974	784
Japan	Fukushima-Daiichi-3	BWR	1976	784
Japan	Fukushima-Daiichi-4	BWR	1978	784
Japan	Fukushima-Daiichi-5	BWR	1978	784
Japan	Fukushima-Daiichi-6	BWR	1979	1100
Japan	Fukushima-Daini-1	BWR	1982	1100
Japan	Fukushima-Daini-2	BWR	1984	1100
Japan	Fukushima-Daini-3	BWR	1985	1100
Japan	Fukushima-Daini-4	BWR	1987	1100
Japan	Hamaoka-1	BWR	1976	540
Japan	Hamaoka-2	BWR	1978	840
Japan	Hamaoka-3	BWR	1987	1100
Japan	Hamaoka-4	BWR	1993	1137
Japan	Kashiwazaki Kariwa-1	BWR	1985	1100
Japan	Kashiwazaki Kariwa-2	BWR	1990	1100
Japan	Kashiwazaki Kariwa-3	BWR	1993	1100
Japan	Kashiwazaki Kariwa-4	BWR	1994	1100
Japan	Kashiwazaki Kariwa-5	BWR	1990	1100
Japan	Kashiwazaki Kariwa-6	BWR	1996	1356
Japan	Kashiwazaki Kariwa-7	BWR	1997	1356
Japan	Onagawa-1	BWR	1984	524
Japan	Onagawa-2	BWR	1995	825
Japan	Onagawa-3	BWR	2002	825
Japan	Shika-1	BWR	1993	540
Japan	Shimane-1	BWR	1974	460
Japan	Shimane-2	BWR	1989	820
Japan	Tokai-2	BWR	1978	1100
Japan	Tsuruga-1	BWR	1970	357
Japan	Fugen	HWR	1979	165
Japan	Genkai-1	PWR	1975	559
Japan	Genkai-2	PWR	1981	559
Japan	Genkai-3	PWR	1994	1180
Japan	Genkai-4	PWR	1997	1180
Japan	Ikata-1	PWR	1977	566
Japan	Ikata-2	PWR	1982	566
Japan	Ikata-3	PWR	1994	890
Japan	Mihama-1	PWR	1970	340
Japan	Mihama-2	PWR	1972	500
Japan	Mihama-3	PWR	1976	826
Japan	Ohi-1	PWR	1979	1175
Japan	Ohi-2	PWR	1979	1175
Japan	Ohi-3	PWR	1991	1180
Japan	Ohi-4	PWR	1993	1180
Japan	Sendai-1	PWR	1984	890
Japan	Sendai-2	PWR	1985	890
Japan	Takahama-1	PWR	1974	826
Japan	Takahama-2	PWR	1975	826
Japan	Takahama-3	PWR	1985	870
Japan	Takahama-4	PWR	1985	870
Japan	Tomari-1	PWR	1989	579
Japan	Tomari-2	PWR	1991	579
Japan	Tsuruga-2	PWR	1987	1160
Kazakhstan	Bn-350 [f]	FBR	1973	52

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
Lithuania	Ignalina-1	LWGR	1983	1185
Lithuania	Ignalina-2	LWGR	1987	1185
Mexico	Laguna Verde-1	BWR	1990	655
Mexico	Laguna Verde-2	BWR	1995	655
Netherlands	Borssele	PWR	1973	449
Pakistan	Kanupp	HWR	1971	125
Pakistan	Chasnupp-1	PWR	2000	300
Rep. of Korea	Wolsong-1	HWR	1982	629
Rep. of Korea	Wolsong-2	HWR	1997	650
Rep. of Korea	Wolsong-3	HWR	1998	650
Rep. of Korea	Wolsong-4	HWR	1999	650
Rep. of Korea	Kori-1	PWR	1977	556
Rep. of Korea	Kori-2	PWR	1983	605
Rep. of Korea	Kori-3	PWR	1985	895
Rep. of Korea	Kori-4	PWR	1985	895
Rep. of Korea	Ulchin-1	PWR	1988	920
Rep. of Korea	Ulchin-2	PWR	1989	920
Rep. of Korea	Ulchin-3	PWR	1998	960
Rep. of Korea	Ulchin-4	PWR	1998	960
Rep. of Korea	Yonggwang-1	PWR	1986	900
Rep. of Korea	Yonggwang-2	PWR	1986	900
Rep. of Korea	Yonggwang-3	PWR	1994	950
Rep. of Korea	Yonggwang-4	PWR	1995	950
Rep. of Korea	Yonggwang-5	PWR	2001	950
Rep. of Korea	Yonggwang-6 [b]	PWR	2002	950
Romania	Cernavoda-1	HWR	1996	655
Russian Federation	Beloyarsky-3	FBR	1980	560
Russian Federation	Bilibino Unit A	LWGR	1974	11
Russian Federation	Bilibino Unit B	LWGR	1974	11
Russian Federation	Bilibino Unit C	LWGR	1975	11
Russian Federation	Bilibino Unit D	LWGR	1976	11
Russian Federation	Kursk-1	LWGR	1976	925
Russian Federation	Kursk-2	LWGR	1979	925
Russian Federation	Kursk-3	LWGR	1983	925
Russian Federation	Kursk-4	LWGR	1985	925
Russian Federation	Leningrad-1	LWGR	1973	925
Russian Federation	Leningrad-2	LWGR	1975	925
Russian Federation	Leningrad-3	LWGR	1979	925
Russian Federation	Leningrad-4	LWGR	1981	925
Russian Federation	Smolensk-1	LWGR	1982	925
Russian Federation	Smolensk-2	LWGR	1985	925
Russian Federation	Smolensk-3	LWGR	1990	925
Russian Federation	Balakovo-1	WWER	1985	950
Russian Federation	Balakovo-2	WWER	1987	950
Russian Federation	Balakovo-3	WWER	1988	950
Russian Federation	Balakovo-4	WWER	1993	950
Russian Federation	Kalinin-1	WWER	1984	950
Russian Federation	Kalinin-2	WWER	1986	950
Russian Federation	Kola-1	WWER	1973	411
Russian Federation	Kola-2	WWER	1974	411
Russian Federation	Kola-3	WWER	1981	411
Russian Federation	Kola-4	WWER	1984	411
Russian Federation	Novovoronezh-3	WWER	1971	385
Russian Federation	Novovoronezh-4	WWER	1972	385

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
Russian Federation	Novovoronezh-5	WWER	1980	950
Russian Federation	Volgodonsk-1	WWER	2001	950

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
Slovakia	Bohunice-1	WWER	1978	408
Slovakia	Bohunice-2	WWER	1980	408
Slovakia	Bohunice-3	WWER	1984	408
Slovakia	Bohunice-4	WWER	1985	408
Slovakia	Mochovce-1	WWER	1998	405
Slovakia	Mochovce-2	WWER	1999	405
Slovenia	Krško	PWR	1981	676
South Africa	Koeberg-1	PWR	1984	900
South Africa	Koeberg-2	PWR	1985	900
Spain	Cofrentes	BWR	1984	1080
Spain	Santa Maria De Garona	BWR	1970	466
Spain	Almaraz-1	PWR	1980	974
Spain	Almaraz-2	PWR	1983	983
Spain	Asco-1	PWR	1982	1028
Spain	Asco-2	PWR	1985	1027
Spain	Jose Cabrera-1	PWR	1968	160
Spain	Trillo-1	PWR	1987	1066
Spain	Vandellos-2	PWR	1987	1087
Sweden	Barsebeck-1	BWR	1975	600
Sweden	Barsebeck-2	BWR	1977	600
Sweden	Forsmark-1	BWR	1980	968
Sweden	Forsmark-2	BWR	1981	964
Sweden	Forsmark-3	BWR	1985	1155
Sweden	Oskarshamn-1	BWR	1971	467
Sweden	Oskarshamn-2	BWR	1974	602
Sweden	Oskarshamn-3	BWR	1985	1160
Sweden	Ringhals-1	BWR	1974	830
Sweden	Ringhals-2	PWR	1975	875
Sweden	Ringhals-3	PWR	1980	915
Sweden	Ringhals-4	PWR	1982	915
Switzerland	Leibstadt	BWR	1984	1165
Switzerland	Muehleberg	BWR	1972	355
Switzerland	Beznau-1	PWR	1969	365
Switzerland	Beznau-2	PWR	1971	365
Switzerland	Goesgen	PWR	1993	970
Ukraine	Chernobyl-3 [c]	LWGR	1981	925
Ukraine	Khmelnitski-1	WWER	1987	950
Ukraine	Rivne-1	WWER	1980	381
Ukraine	Rivne-2	WWER	1981	376
Ukraine	Rivne-3	WWER	1986	950
Ukraine	South Ukraine-1	WWER	1982	950
Ukraine	South Ukraine-2	WWER	1985	950
Ukraine	South Ukraine-3	WWER	1989	950
Ukraine	Zaporozhe-1	WWER	1984	950
Ukraine	Zaporozhe-2	WWER	1985	950
Ukraine	Zaporozhe-3	WWER	1986	950
Ukraine	Zaporozhe-4	WWER	1987	950
Ukraine	Zaporozhe-5	WWER	1989	950
Ukraine	Zaporozhe-6	WWER	1995	950

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
United Kingdom	Dungeness-B1 Unit A	AGR	1985	555
United Kingdom	Dungeness-B2 Unit B	AGR	1983	555
United Kingdom	Hartlepool-A1 Unit A	AGR	1983	605
United Kingdom	Hartlepool-A2 Unit B	AGR	1984	605
United Kingdom	Heysham-1 Unit A	AGR	1983	575
United Kingdom	Heysham-1 Unit B	AGR	1984	575
United Kingdom	Heysham-2 Unit A	AGR	1988	625
United Kingdom	Heysham-2 Unit B	AGR	1988	625
United Kingdom	Hinkley Point-B Unit A	AGR	1976	610
United Kingdom	Hinkley Point-B Unit B	AGR	1976	610
United Kingdom	Hunterston-B1	AGR	1976	595
United Kingdom	Hunterston-B2	AGR	1977	595
United Kingdom	Torness Unit A	AGR	1988	625
United Kingdom	Torness Unit B	AGR	1989	625
United Kingdom	Hinkley Point-A1 [d]	GCR	1965	235
United Kingdom	Hinkley Point-A2 [d]	GCR	1965	235
United Kingdom	Bradwell-1 [e]	GCR	1962	123
United Kingdom	Bradwell-2 [e]	GCR	1962	123
United Kingdom	Calder Hall-1	GCR	1956	50
United Kingdom	Calder Hall-2	GCR	1957	50
United Kingdom	Calder Hall-3	GCR	1958	50
United Kingdom	Calder Hall-4	GCR	1959	50
United Kingdom	Chapelcross-1	GCR	1959	50
United Kingdom	Chapelcross-2	GCR	1959	50
United Kingdom	Chapelcross-3	GCR	1959	50
United Kingdom	Chapelcross-4	GCR	1960	50
United Kingdom	Dungeness-A Unit A [a]	GCR	1965	225
United Kingdom	Dungeness-A Unit B [a]	GCR	1965	225
United Kingdom	Oldbury-A Unit A [a]	GCR	1967	217
United Kingdom	Oldbury-A Unit B [a]	GCR	1968	217
United Kingdom	Sizewell-A Unit A [a]	GCR	1966	210
United Kingdom	Sizewell-A Unit B [a]	GCR	1966	210
United Kingdom	Wylfa Unit A [a]	GCR	1971	490
United Kingdom	Wylfa Unit B [a]	GCR	1971	490
United Kingdom	Sizewell-B	PWR	1995	1188
United States	Browns Ferry-1	BWR	1974	1065
United States	Browns Ferry-2	BWR	1975	1104
United States	Browns Ferry-3	BWR	1977	1108
United States	Brunswick-1	BWR	1977	820
United States	Brunswick-2	BWR	1975	811
United States	Clinton-1	BWR	1987	948
United States	Columbia	BWR	1984	1107
United States	Cooper	BWR	1974	764
United States	Dresden-2	BWR	1970	788
United States	Dresden-3	BWR	1971	788
United States	Duane Arnold-1	BWR	1975	538
United States	Enrico Fermi-2	BWR	1988	1088
United States	Fitzpatrick	BWR	1975	805
United States	Grand Gulf-1	BWR	1985	1206
United States	Hatch-1	BWR	1975	837
United States	Hatch-2	BWR	1979	859
United States	Hope Creek-1	BWR	1986	1038
United States	Lasalle-1	BWR	1984	1074
United States	Lasalle-2	BWR	1984	1074

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
United States	Limerick-1	BWR	1986	1132
United States	Limerick-2	BWR	1990	1134
United States	Monticello	BWR	1971	573
United States	Nine Mile Point-1	BWR	1969	565
United States	Nine Mile Point-2	BWR	1988	1119
United States	Oyster Creek	BWR	1969	619
United States	Peach Bottom-2	BWR	1974	1093
United States	Peach Bottom-3	BWR	1974	1093
United States	Perry-1	BWR	1987	1197
United States	Pilgrim-1	BWR	1972	663
United States	Quad Cities-1	BWR	1973	786
United States	Quad Cities-2	BWR	1973	786
United States	River Bend-1	BWR	1986	942
United States	Susquehanna-1	BWR	1983	1093
United States	Susquehanna-2	BWR	1985	1101
United States	Vermont Yankee	BWR	1972	510
United States	Arkansas One-1	PWR	1974	836
United States	Arkansas One-2	PWR	1980	858
United States	Beaver Valley-1	PWR	1976	814
United States	Beaver Valley-2	PWR	1987	824
United States	Braidwood-1	PWR	1988	1134
United States	Braidwood-2	PWR	1988	1130
United States	Byron-1	PWR	1985	1115
United States	Byron-2	PWR	1987	1115
United States	Callaway-1	PWR	1984	1125
United States	Calvert Cliffs-1	PWR	1975	830
United States	Calvert Cliffs-2	PWR	1977	837
United States	Catawba-1	PWR	1985	1129
United States	Catawba-2	PWR	1986	1129
United States	Comanche Peak-1	PWR	1990	1150
United States	Comanche Peak-2	PWR	1993	1150
United States	Crystal River-3	PWR	1977	829
United States	Davis Besse-1	PWR	1978	877
United States	Diablo Canyon-1	PWR	1985	1134
United States	Diablo Canyon-2	PWR	1986	1087
United States	Donald Cook-1	PWR	1975	1000
United States	Donald Cook-2	PWR	1978	1060
United States	Farley-1	PWR	1977	833
United States	Farley-2	PWR	1981	840
United States	Fort Calhoun-1	PWR	1973	478
United States	H.B. Robinson-2	PWR	1971	683
United States	Indian Point-2	PWR	1974	942
United States	Indian Point-3	PWR	1976	968
United States	Kewaunee	PWR	1974	511
United States	Mcguire-1	PWR	1981	1104
United States	Mcguire-2	PWR	1984	1104
United States	Millstone-2	PWR	1975	871
United States	Millstone-3	PWR	1986	1139
United States	North Anna-1	PWR	1978	906
United States	North Anna-2	PWR	1980	905
United States	Oconee-1	PWR	1973	846
United States	Oconee-2	PWR	1974	846
United States	Oconee-3	PWR	1974	846
United States	Palisades	PWR	1971	730

Country	*Name*	*Type*	*Startup*	*Installed MW(e)*
United States	Palo Verde-1	PWR	1986	1243
United States	Palo Verde-2	PWR	1986	1243
United States	Palo Verde-3	PWR	1988	1247
United States	Point Beach-1	PWR	1970	501
United States	Point Beach-2	PWR	1972	504
United States	Prairie Island-1	PWR	1973	520
United States	Prairie Island-2	PWR	1974	520
United States	R.E. Ginna	PWR	1970	480
United States	Salem-1	PWR	1977	1102
United States	Salem-2	PWR	1981	1100
United States	San Onofre-2	PWR	1983	1070
United States	San Onofre-3	PWR	1984	1080
United States	Seabrook-1	PWR	1990	1156
United States	Sequoyah-1	PWR	1981	1122
United States	Sequoyah-2	PWR	1982	1119
United States	Shearon Harris-1	PWR	1987	868
United States	South Texas-1	PWR	1988	1250
United States	South Texas-2	PWR	1989	1250
United States	St. Lucie-1	PWR	1976	839
United States	St. Lucie-2	PWR	1983	839
United States	Surry-1	PWR	1972	805
United States	Surry-2	PWR	1973	807
United States	Three Mile Island-1	PWR	1974	789
United States	Turkey Point-3	PWR	1972	693
United States	Turkey Point-4	PWR	1973	693
United States	Virgil C. Summer-1	PWR	1984	961
United States	Vogtle-1	PWR	1987	1152
United States	Vogtle-2	PWR	1989	1153
United States	Waterford-3	PWR	1985	1075
United States	Watts Bar-1	PWR	1996	1121
United States	Wolf Creek	PWR	1985	1166

[a] No energy generated in period.

[b] Startup in December 2002.

[c] Shutdown in December 2000.

[d] Ceased operation in 2000.

[e] Ceased operation in 2002.

[f] Shutdown in 1999.

Table A-5 Energy generated by nuclear power plants in the period 1998–2002 (GW a)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2	0.468	0.423	0.254	0.691	0.334
United Kingdom	Hartlepool-A 1-2	0.964	1.082	1.030	1.019	
United Kingdom	Heysham-1 A-B	0.943	0.943	1.020	0.974	
United Kingdom	Heysham-2 A-B	1.054	0.824	1.075	1.081	
United Kingdom	Hinkley Point-B A-B	0.951	0.940	0.985	0.548	
United Kingdom	Hunterston-B 1-2	1.068	1.017	0.831	1.006	
United Kingdom	Torness A-B	1.073	1.158	0.949	0.943	
BWR						
China - Taiwan Province	Chinshan 1-2	1.093	1.002	1.169	1.114	1.035
China - Taiwan Province	Kuosheng 1-2	1.531	1.712	1.627	1.467	1.757
Finland	Olkiluoto 1-2	1.534	1.621	1.606	1.616	1.611
Germany	Brunsbuettel	0.476	0.740	0.689	0.686	0.102
Germany	Gundremmingen B-C	2.234	2.135	2.339	2.409	2.435
Germany	Isar-1	0.755	0.894	0.792	0.701	0.898
Germany	Kruemmel	0.556	1.251	1.077	0.969	1.011
Germany	Philippsburg-1	0.827	0.825	0.828	0.832	0.787
India	Tarapur 1-2	0.234	0.223	0.252	0.261	0.268
Japan	Fukushima-Daiichi 1-6	3.459	3.619	3.395	3.825	3.052
Japan	Fukushima-Daini 1-4	3.804	3.690	3.585	3.134	2.223
Japan	Hamaoka 1-4	2.898	2.854	3.146	2.515	1.220
Japan	Kashiwazaki Kariwa 1-7	7.126	7.113	6.768	6.907	5.224
Japan	Onagawa 1-3	1.222	1.125	1.218	1.808	1.775
Japan	Shiga-1	0.540	0.410	0.460	0.450	0.520
Japan	Shimane 1-2	1.220	1.150	0.770	1.170	1.230
Japan	Tokai-2	1.080	0.040	1.020	0.740	0.740
Japan	Tsuruga-1	0.214	0.211	0.000	0.295	0.291
Mexico	Laguna Verde 1-2	1.008	1.091	0.904	0.956	1.068
Spain	Cofrentes	0.930	0.852	0.847	0.942	0.899
Spain	Santa Maria De Garona	0.433	0.380	0.440	0.392	0.439
Sweden	Barsebeck 1-2	0.970	0.707	0.338	0.513	0.445
Sweden	Forsmark 1-3	2.683	2.702	2.174	2.614	2.626
Sweden	Oskarshamn 1-3	1.587	1.720	1.622	1.937	1.530
Sweden	Ringhals-1	0.639	0.569	0.372	0.672	0.685
Switzerland	Leibstadt	0.918	0.949	1.007	1.037	1.047
Switzerland	Muehleberg	0.303	0.308	0.321	0.316	0.323
United States	Browns Ferry 2-3	1.962	2.091	2.150	2.080	2.074
United States	Brunswick 1-2	1.521	1.495	1.575	1.581	1.573
United States	Clinton-1	0.000	0.537	0.786	0.899	0.874
United States	Columbia	0.790	0.696	0.982	0.943	1.025
United States	Cooper	0.556	0.743	0.541	0.594	0.721
United States	Dresden 2-3	1.355	1.411	1.511	1.431	1.551
United States	Duane Arnold-1	0.438	0.417	0.509	0.441	0.523
United States	Enrico Fermi-2	0.816	1.083	0.940	0.978	1.062
United States	Fitzpatrick	0.563	0.750	0.688	0.809	0.753
United States	Grand Gulf-1	1.049	0.962	1.221	1.133	1.148
United States	Hatch 1-2	1.460	1.488	1.520	1.608	1.604
United States	Hope Creek-1	0.993	0.879	0.830	0.921	1.009
United States	Lasalle 1-2	0.381	1.672	2.144	2.229	2.046
United States	Limerick 1-2	1.907	2.089	2.161	2.212	2.203
United States	Monticello	0.470	0.531	0.485	0.443	0.573
United States	Nine Mile Point 1-2	1.387	1.410	1.447	1.511	1.521
United States	Oyster Creek	0.491	0.615	0.446	0.597	0.574

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Peach Bottom 2-3	1.881	2.057	2.064	2.043	2.110
United States	Perry-1	1.163	1.042	1.151	0.888	1.139
United States	Pilgrim-1	0.651	0.511	0.629	0.587	0.659
United States	Quad Cities 1-2	0.795	1.476	1.414	1.482	1.400
United States	River Bend-1	0.894	0.651	0.839	0.892	0.967
United States	Susquehanna 1-2	1.881	1.896	2.001	2.034	1.978
United States	Vermont Yankee	0.383	0.463	0.519	0.476	0.452
FBR						
Kazakhstan	Bn-350	0.010	0.000	0.000	0.000	0.000
Russian Fed.	Beloyarsky-3	0.267	0.425	0.407	0.444	0.431
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2					
United Kingdom	Oldbury-A A-B					
United Kingdom	Sizewell-A A-B					
United Kingdom	Wylfa Unit A-B					
LWGR						
Lithuania	Ignalina 1-2	1.360	0.990	0.840	1.140	1.410
Russian Fed.	Bilibino Unit A-D	0.015	0.019	0.024	0.021	0.017
Russian Fed.	Kursk 1-4	1.982	2.302	2.316	1.858	2.023
Russian Fed.	Leningrad 1-4	1.897	2.403	2.274	2.731	2.613
Russian Fed.	Smolensk 1-3	1.533	2.080	2.143	2.121	1.998
Ukraine	Chernobyl-3	0.500	0.348	0.706	0.000	0.000
HWR						
Argentina	Atucha-1	0.271	0.159	0.192	0.163	0.115
Argentina	Embalse	0.520	0.594	0.464	0.585	0.501
Canada	Bruce B5-8	2.169	2.511	2.169	2.740	2.397
Canada	Darlington 1-4	2.968	2.854	3.082	2.968	3.196
Canada	Gentilly-2	0.434	0.434	0.559	0.537	0.514
Canada	Pickering B5-8	1.484	1.598	1.142	1.484	1.598
Canada	Point Lepreau	0.422	0.468	0.457	0.514	0.434
India	Kaiga 1-2	0.000	0.000	0.146	0.291	0.371
India	Kakrapar 1-2	0.271	0.334	0.358	0.365	0.376
India	Kalpakkam 1-2	0.206	0.235	0.221	0.262	0.105
India	Narora 1-2	0.322	0.292	0.311	0.331	0.373
India	Rajasthan 1-4	0.123	0.224	0.336	0.467	0.504
Japan	Fugen	0.114	0.080	0.081	0.024	0.117
Pakistan	Kanupp	0.040	0.008	0.042	0.046	0.051
Rep. of Korea	Wolsong 1-4	1.440	1.828	2.420	2.355	2.429
Romania	Cernavoda-1	0.562	0.549	0.577	0.576	0.583

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		PWR				
Belgium	Doel 1-4	2.545	2.572	2.543	2.557	2.492
Belgium	Tihange 1-3	2.473	2.760	2.686	2.474	2.650
Brazil	Angra 1-2	0.353	0.415	0.637	1.131	1.486
China	Guangdong 1-2	1.477	1.610	1.678	1.712	1.684
China	Lingao 1-2	0.000	0.000	0.000	0.000	0.613
China	Qinshan-1	0.133	0.084	0.232	0.282	0.204
China	Qinshan-2 1-2	0.000	0.000	0.000	0.000	0.398
China - Taiwan Province	Maanshan 1-2	1.583	1.670	1.586	1.469	1.722
France	Belleville 1-2	1.234	1.653	1.612	2.058	2.163
France	Blayais 1-4	3.032	2.644	2.220	2.797	2.989
France	Bugey 2-5	2.704	2.676	2.549	2.400	2.502
France	Cattenom 1-4	3.960	3.881	4.028	3.383	4.173
France	Chinon-B 1-4	2.865	2.661	2.715	2.797	2.903
France	Chooz-B 1-2	0.186	1.392	1.785	2.247	2.206
France	Civaux 1-2	0.000	0.333	1.596	1.265	1.945
France	Cruas 1-4	2.888	2.789	2.839	2.696	2.862
France	Dampierre 1-4	2.546	2.423	2.503	2.378	2.582
France	Fessenheim 1-2	1.166	1.327	1.086	1.394	1.090
France	Flamanville 1-2	1.727	1.624	2.048	2.124	1.900
France	Golfech 1-2	1.933	1.991	2.014	1.881	2.179
France	Gravelines 1-6	4.331	3.935	4.052	4.039	4.047
France	Nogent 1-2	1.760	2.016	2.141	2.115	1.966
France	Paluel 1-4	3.781	3.989	4.237	3.880	3.806
France	Penly 1-2	2.151	1.899	2.038	2.128	1.782
France	St. Alban 1-2	1.690	2.038	1.913	2.049	1.947
France	St. Laurent-B 1-2	1.420	1.245	1.167	1.468	1.467
France	Tricastin 1-4	2.747	2.363	2.592	2.709	2.879
Germany	Biblis-A	1.214	0.881	0.716	1.152	0.749
Germany	Biblis-B	1.000	1.060	1.912	0.900	1.227
Germany	Brokdorf	1.292	1.332	1.361	1.346	1.381
Germany	Emsland	1.300	1.292	1.300	1.316	1.354
Germany	Grafenrheinfeld	1.104	1.005	1.169	1.273	1.191
Germany	Grohnde	1.343	1.350	1.333	1.320	1.305
Germany	Isar-2	1.301	1.400	1.363	1.415	1.389
Germany	Neckarwestheim-1	0.729	0.720	0.757	0.736	0.762
Germany	Neckarwestheim-2	1.295	1.279	1.282	1.275	1.197
Germany	Obrigheim	0.332	0.338	0.320	0.337	0.342
Germany	Philippsburg-2	1.295	1.338	1.289	1.084	1.330
Germany	Stade	0.614	0.556	0.590	0.519	0.565
Germany	Unterweser	0.794	0.975	1.154	1.270	0.812
Japan	Genkai 1-4	2.660	3.022	3.121	2.572	2.872
Japan	Ikata 1-3	1.692	1.668	1.689	1.599	1.776
Japan	Mihama 1-3	1.507	1.285	1.268	1.385	1.495
Japan	Ohi 1-4	3.681	3.787	3.778	3.867	4.328
Japan	Sendai 1-2	1.550	1.393	1.390	1.621	1.645
Japan	Takahama 1-4	3.042	2.941	2.950	3.006	3.018
Japan	Tomari 1-2	1.067	1.045	0.994	0.981	1.079
Japan	Tsuruga-2	1.017	0.521	1.089	1.032	1.044
Netherlands	Borssele	0.41	0.411	0.422	0.428	0.421
Pakistan	Chasnupp-1	0.000	0.000	0.060	0.181	0.155

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Rep. of Korea	Kori 1-4	2.719	2.647	2.837	2.811	2.897
Rep. of Korea	Ulchin 1-4	2.266	2.500	3.264	3.419	3.002
Rep. of Korea	Yonggwang 1-5	3.304	3.250	3.297	3.582	4.102
Slovenia	Krško	0.547	0.513	0.519	0.575	0.606
South Africa	Koeberg 1-2	1.550	1.537	1.484	1.222	1.372
Spain	Almaraz 1-2	1.589	1.725	1.698	1.798	1.779
Spain	Asco 1-2	1.684	1.754	1.841	1.784	1.847
Spain	Jose Cabrera-1	0.126	0.127	0.126	0.121	0.108
Spain	Trillo-1	0.752	0.780	0.937	0.903	0.893
Spain	Vandellos-2	0.954	0.825	0.911	1.029	0.914
Sweden	Ringhals 2-4	2.226	2.362	2.113	2.225	2.203
Switzerland	Beznau 1-2	0.673	0.577	0.640	0.645	0.675
Switzerland	Goesgen	0.888	0.852	0.883	0.890	0.912
United Kingdom	Sizewell-B	1.156	0.909	0.973	1.050	
United States	Arkansas One 1-2	1.495	1.478	1.333	1.689	1.663
United States	Beaver Valley 1-2	0.529	1.354	1.383	1.505	1.552
United States	Braidwood 1-2	1.972	2.162	2.149	2.192	2.290
United States	Byron 1-2	1.872	2.064	2.203	2.308	2.211
United States	Callaway-1	0.972	0.981	1.141	0.957	0.957
United States	Calvert Cliffs 1-2	1.523	1.521	1.580	1.559	1.384
United States	Catawba 1-2	2.006	2.047	2.044	2.118	2.243
United States	Comanche Peak 1-2	2.038	1.982	2.110	2.092	1.893
United States	Crystal River-3	0.740	0.728	0.822	0.744	0.833
United States	Davis Besse-1	0.700	0.841	0.773	0.878	0.106
United States	Diablo Canyon 1-2	1.955	1.903	1.946	2.073	1.865
United States	Donald Cook 1-2	0.000	0.000	0.562	1.799	1.762
United States	Farley 1-2	1.314	1.436	1.434	1.390	1.562
United States	Fort Calhoun-1	0.388	0.409	0.445	0.402	0.435
United States	H.B. Robinson-2	0.628	0.649	0.712	0.630	0.640
United States	Indian Point 2-3	1.161	1.663	1.084	1.796	1.826
United States	Kewaunee	0.423	0.505	0.434	0.395	0.510
United States	Mcguire 1-2	2.140	1.962	2.106	2.119	2.057
United States	Millstone 2-3	0.387	1.454	1.872	1.765	1.707
United States	North Anna 1-2	1.633	1.747	1.738	1.495	1.561
United States	Oconee 1-3	1.992	2.264	2.328	2.175	2.361
United States	Palisades	0.615	0.585	0.656	0.269	0.727
United States	Palo Verde 1-3	3.454	3.471	3.468	3.289	3.523
United States	Point Beach 1-2	0.652	0.807	0.875	0.919	0.902
United States	Prairie Island 1-2	0.861	0.989	0.995	0.904	0.989
United States	R.E. Ginna	0.492	0.403	0.434	0.489	0.438
United States	Salem 1-2	1.629	1.821	1.979	1.966	1.939
United States	San Onofre 2-3	1.996	1.902	2.073	1.732	2.062
United States	Seabrook-1	0.958	0.992	0.904	0.992	1.061
United States	Sequoyah 1-2	2.136	2.165	1.915	2.165	2.111
United States	Shearon Harris-1	0.766	0.827	0.785	0.617	0.894
United States	South Texas 1-2	2.380	2.220	2.186	2.269	2.179
United States	St. Lucie 1-2	1.572	1.569	1.635	1.532	1.638
United States	Surry 1-2	1.477	1.483	1.495	1.445	1.561
United States	Three Mile Island-1	0.806	0.722	0.816	0.618	0.835
United States	Turkey Point 3-4	1.323	1.353	1.287	1.328	1.378
United States	Virgil C. Summer-1	0.935	0.842	0.726	0.771	0.842
United States	Vogtle 1-2	2.124	2.106	2.230	2.238	1.947
United States	Waterford-3	0.984	0.850	0.968	1.089	1.010
United States	Watts Bar-1	1.105	0.944	1.036	1.099	1.036
United States	Wolf Creek	1.187	1.045	1.036	1.181	1.032

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
WWER						
Armenia	Armenia-2	0.162	0.216	0.210	0.207	0.237
Bulgaria	Kozloduy 1-6	1.948	1.831	2.075	2.232	2.308
Czech Rep.	Dukovany 1-4	1.504	1.525	1.551	1.552	1.518
Czech Rep.	Temelin 1-2	0.000	0.000	0.000	0.000	0.609
Finland	Loviisa 1-2	0.860	0.896	0.857	0.879	0.833
Hungary	Paks 1-4	1.601	1.619	1.595	1.592	1.609
Russian Fed.	Balakovo 1-4	2.057	2.207	2.982	3.050	3.055
Russian Fed.	Kalinin 1-2	1.261	1.387	1.451	1.523	1.626
Russian Fed.	Kola 1-4	0.899	0.914	0.930	1.022	1.018
Russian Fed.	Novovoronezh 3-5	1.030	0.977	1.184	1.134	1.299
Russian Fed.	Volgodonsk-1	0.000	0.000	0.000	0.000	0.819
Slovakia	Bohunice 1-4	1.090	1.104	1.110	1.231	1.269
Slovakia	Mochovce 1-2	0.107	0.271	0.624	0.567	0.618
Ukraine	Khmelnitski-1	0.660	0.667	0.713	0.740	0.806
Ukraine	Rivne 1-3	1.251	1.151	1.192	1.293	1.265
Ukraine	South Ukraine 1-3	1.994	2.005	1.848	2.170	2.023
Ukraine	Zaporozhe 1-6	4.040	3.847	4.201	4.384	4.703

Table A-6 Noble gases released from nuclear power plants in airborne effluents (GBq)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2	23100	156	19300	23100	22200
United Kingdom	Hartlepool-A 1-2	12400	37700	12400	19800	10900
United Kingdom	Heysham-1 A-B	12600	6520	14100	5480	12800
United Kingdom	Heysham-2 A-B	16300	13000	14600	17600	19500
United Kingdom	Hinkley Point-B A-B	36600	36000	19100	12700	10700
United Kingdom	Hunterston-B 1-2	61900	68100	58700	64200	38600
United Kingdom	Torness A-B	10800	10500	7450	5700	4680
BWR						
China - Taiwan Province	Chinshan 1-2	404	127	61	35	45
China - Taiwan Province	Kuosheng 1-2	83	339	209	113	242
Finland	Olkiluoto 1-2	300	611	304	57	28
Germany	Brunsbuettel	3790	3720	1360	1750	739
Germany	Gundremmingen B-C		10	700	696	1370
Germany	Isar-1	782	33	333	2000	980
Germany	Kruemmel	430	110	240	580	1200
Germany	Philippsburg-1	670	370	170	140	66
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6	n.d.	n.d.	n.d.	1	0.17
Japan	Fukushima-Daini 1-4	n.d.	n.d.	n.d.	n.d.	34
Japan	Hamaoka 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Kashiwazaki Kariwa 1-7	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Onagawa 1-3	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Shiga-1	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Shimane 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tokai-2	n.d.	4.2 [a]	1	n.d.	n.d.
Japan	Tsuruga-1 [b]	0.84	n.d.	2.6	0.88	0.91
Mexico	Laguna Verde 1-2	232	2833	653	56	162
Spain	Cofrentes	7911	4586	8100	15971	17094
Spain	Santa Maria De Garona	4469	178	109	92	93
Sweden	Barsebeck 1-2	10950	19300	158000	8000	7640
Sweden	Forsmark 1-3	11440	2324	9795	85820	85758
Sweden	Oskarshamn 1-3	44000	31620	670420	211635	254240
Sweden	Ringhals-1	2340000	463000	192000	140000	69400
Switzerland	Leibstadt	6300	3800	14000	6300	8400
Switzerland	Muehleberg	670	530	530	4000	6800
United States	Browns Ferry 2-3		4207	15251	21619	107566
United States	Brunswick 1-2		57461	25789	22459	12617
United States	Clinton-1		0	0	0	48
United States	Columbia				2168	2083
United States	Cooper		50690	55881	36334	28031
United States	Dresden 2-3		4658	23399	9853	6553
United States	Duane Arnold-1		2302	2870	1351	1680
United States	Enrico Fermi-2		608	1492	2323	
United States	Fitzpatrick		2934	3109	1269	3977
United States	Grand Gulf-1		1117	1221	1713	1935
United States	Hatch 1-2		11633	34084	0	1280
United States	Hope Creek-1		2256	1106	0	160
United States	Lasalle 1-2		59855	74407	92093	448107
United States	Limerick 1-2		52096	55389	49728	55907
United States	Monticello		7948	5565	8932	8395
United States	Nine Mile Point 1-2		763	1882	1005	623
United States	Oyster Creek		851	6734	14578	5069

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Peach Bottom 2-3		16280	15148	15818	14652
United States	Perry-1		1373	255	1779	1779
United States	Pilgrim-1		21882	24531	6183	2312
United States	Quad Cities 1-2		3582	4839	8891	12425
United States	River Bend-1		29194	1865	722	1020
United States	Susquehanna 1-2		223	0	251	358
United States	Vermont Yankee		30	280	82	
FBR						
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3	16400	24800	7220	19500	
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2	1300000	1250000	1200000	860000	1200000
United Kingdom	Oldbury-A A-B	180000	191000	157000	224000	284000
United Kingdom	Sizewell-A A-B	841000	1680000	1750000	1840000	1850000
United Kingdom	Wylfa Unit A-B	60600	36500	7450	12700	31900
LWGR						
Lithuania	Ignalina 1-2	123000	70600	61300	96400	101000
Russian Fed.	Bilibino Unit A-D	338000	349000	460000		
Russian Fed.	Kursk 1-4	473000	503000	384000	290000	
Russian Fed.	Leningrad 1-4	444000	419000	294000	356000	
Russian Fed.	Smolensk 1-3	641000	577000	517000	605000	
Ukraine	Chernobyl-3					
HWR						
Argentina	Atucha-1	130000	29000	74000	49000	21000
Argentina	Embalse	21000	160000	14000	46000	24000
Canada	Bruce B5-8	62000	79000	72000	61000	56000
Canada	Darlington 1-4	350000	340000	150000	18000	15000
Canada	Gentilly-2	3400	3800	2600	1900	690
Canada	Pickering B 5-8	220000	210000	210000	210000	200000
Canada	Point Lepreau	3400	3800	5000	5900	3200
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen	n.d.	n.d.	n.d.	n.d.	12
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4	161000	104000	52900	131000	152000
Romania	Cernavoda-1	17500	21300	6950	27200	0

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
PWR						
Belgium	Doel 1-4	3310	2660	95	26	331
Belgium	Tihange 1-3	8040	4320	3520	4650	8460
Brazil	Angra 1-2	6400	220	110	87	630
China	Guangdong 1-2	3658	4476	3336	2597	2887
China	Lingao 1-2					824
China	Qinshan-1	475	313	439	1306	2394
China	Qinshan-2 1-2					183
China - Taiwan Province	Maanshan 1-2	2020	2190	5290	1730	1930
France	Belleville 1-2	21000	19000			1590
France	Blayais 1-4	22000	22000			1640
France	Bugey 2-5	11000	13000			1860
France	Cattenom 1-4	24000	21000			6620
France	Chinon-B 1-4	25000	29000			1760
France	Chooz-B 1-2	15000	10000			1470
France	Civaux 1-2	11000	11000			841
France	Cruas 1-4	16000	17000			34600
France	Dampierre 1-4	26000	21000			7150
France	Fessenheim 1-2	7400	7900			496
France	Flamanville 1-2	17000	15000			2240
France	Golfech 1-2	23000	19000			473
France	Gravelines 1-6	20000	21000			2310
France	Nogent 1-2	12000	13000			7540
France	Paluel 1-4	25000	25000			2500
France	Penly 1-2	12000	14000			4670
France	St. Alban 1-2	17000	17000			2690
France	St. Laurent-B 1-2	11000	11000			580
France	Tricastin 1-4	25000	26000			10500
Germany	Biblis-A	1540	1000	558	562	376
Germany	Biblis-B	2560	1220	5870	2260	444
Germany	Brokdorf	9460	261	286	752	1540
Germany	Emsland	1900	970	140	140	150
Germany	Grafenrheinfeld	62	348	200	71	76
Germany	Grohnde	680	303	155	160	275
Germany	Isar-2	286	500	230	330	280
Germany	Neckarwestheim-1	745	695	633	503	435
Germany	Neckarwestheim-2	310	270	300	291	352
Germany	Obrigheim	260	290	741	438	1270
Germany	Philippsburg-2	120	950	2500	410	3200
Germany	Stade	1340	1460	1580	1580	1660
Germany	Unterweser	3360	3300	4900	3000	2960
Japan	Genkai 1-4	310	29	11	8.8	12
Japan	Ikata 1-3	11	3.4	2.8	3.8	4.2
Japan	Mihama 1-3	170	230	16	14	11
Japan	Ohi 1-4	610	120	57	15	28
Japan	Sendai 1-2	37	67	31	15	16
Japan	Takahama 1-4	420	400	16	18	12
Japan	Tomari 1-2	1.3	2.9	6	8.1	4.5
Japan	Tsuruga-2 [b]	0.84	n.d.	2.6	0.88	0.91
Netherlands	Borssele	11000	3700	2000	4700	11100
Pakistan	Chasnupp-1					
Rep. of Korea	Kori 1-4	3250	3500	1750	7380	9860
Rep. of Korea	Ulchin 1-4	71	225	3300	1060	40200
Rep. of Korea	Yonggwang 1-5	6500	6750	3430	88	9530

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Slovenia	Krško [c]	2330	1160	2290	2110	891
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2	9709	1192	567	1156	368
Spain	Asco 1-2	15124	22414	2597	2846	2352
Spain	Jose Cabrera-1	14921	12417	17141	14478	10603
Spain	Trillo-1	3512	1061	379	255	257
Spain	Vandellos-2	11	867	15408	169	1438
Sweden	Ringhals 2-4	812	4218	611.5	1306.6	12520.6
Switzerland	Beznau 1-2	2700	4800	8000	4200	3600
Switzerland	Goesgen	10000	5300	4600	4700	5400
United Kingdom	Sizewell-B	15700	7290	12500	4930	5140
United States	Arkansas One 1-2		6547	6307	0	691
United States	Beaver Valley 1-2		2442	4440	198	947
United States	Braidwood 1-2		99	37	27	42
United States	Byron 1-2		39	87	65	83
United States	Callaway-1		1558	5010	7939	214
United States	Calvert Cliffs 1-2		5879	3967	2686	3582
United States	Catawba 1-2		2498	2231	38	110
United States	Comanche Peak 1-2		59	39	49	8456
United States	Crystal River-3		2533	1530	15541	436
United States	Davis Besse-1		5255	2363	559	6440
United States	Diablo Canyon 1-2		1795	266	1458	622
United States	Donald Cook 1-2		1	82	741	3593
United States	Farley 1-2		11596	4747	5216	4714
United States	Fort Calhoun-1		14541	126211	83613	83613
United States	H.B. Robinson-2		15	4	14	34
United States	Indian Point 2-3		666	7376	13366	64134
United States	Kewaunee		0	0	5	1
United States	Mcguire 1-2		161	152	178	131
United States	Millstone 2-3		605	453	1444	4827
United States	North Anna 1-2		5758	3877	9818	724
United States	Oconee 1-3		451	341	448	271
United States	Palisades		2073	251	220	1404
United States	Palo Verde 1-3		5760	35215	21164	7642
United States	Point Beach 1-2		125	104	54	143
United States	Prairie Island 1-2		858	3847	1560	67
United States	R.E. Ginna		4476	19666	1294	1180
United States	Salem 1-2		165586	107877	51416	39024
United States	San Onofre 2-3		7311	3830	3215	2351
United States	Seabrook-1		28	28	28	1358
United States	Sequoyah 1-2		10127	8973	8973	39051
United States	Shearon Harris-1		733	658	390	58
United States	South Texas 1-2		8602	17247	23689	14884
United States	St. Lucie 1-2		3166	529	6723	2752
United States	Surry 1-2		45	132	183	51
United States	Three Mile Island-1		7041	41	135	1
United States	Turkey Point 3-4		112	1176	37	1866
United States	Virgil C. Summer-1		9	3	2	2
United States	Vogtle 1-2		5092	261	465	3254
United States	Waterford-3		14466	6980	1524	13949
United States	Watts Bar-1		470	1630	2615	1229
United States	Wolf Creek		1642	837	172	169

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
WWER						
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6	233500	259600	251770	293821	267158
Czech Rep.	Dukovany 1-4	7400	7139	9859	3667	3608
Czech Rep.	Temelin 1-2					18891
Finland	Loviisa 1-2	5100	5900	5500	4900	4900
Hungary	Paks 1-4	60000	53000	77000	90000	56000
Russian Fed.	Balakovo 1-4	6260	10300	3820	3150	
Russian Fed.	Kalinin 1-2	34200	18900	16400	16200	
Russian Fed.	Kola 1-4	60100	26400	79700	49300	
Russian Fed.	Novovoronezh 3-5	50600	39000	23200	27000	
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					32696
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1	21800	31200	12400	66800	13500
Ukraine	Rivne 1-3	83200	123400	172100	126000	100400
Ukraine	South Ukraine 1-3	67800	84000	103000	172000	18900
Ukraine	Zaporozhe 1-6	76600	67500	63000	68300	69400

Note: n.d. = not detected.

[a] Due to JCO's criticality accident.

[b] Total amount for Tsuruga-1 (BWR) and Tsuruga-2 (PWR).

[c] Xenon-133 equivalent discharged activity.

Table A-7 Tritium released from nuclear power plants in airborne effluents (GBq)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2	3320	1200	2670	809	4900
United Kingdom	Hartlepool-A 1-2	1500	1410	1860	1820	1560
United Kingdom	Heysham-1 A-B	1420	978	952	1390	2150
United Kingdom	Heysham-2 A-B	2180	1210	1060	1700	1300
United Kingdom	Hinkley Point-B A-B	1720	2200	3060	5040	5020
United Kingdom	Hunterston-B 1-2	2150	3520	5280	7340	6800
United Kingdom	Torness A-B	2080	1310	1690	2400	3250
BWR						
China - Taiwan Province	Chinshan 1-2	1560	1080	90	998	1230
China - Taiwan Province	Kuosheng 1-2	522	457	333	347	491
Finland	Olkiluoto 1-2	436	524	470	380	129
Germany	Brunsbuettel	46	75	81	83	44
Germany	Gundremmingen B-C	1000	960	940	990	1200
Germany	Isar-1	170	81	93	91	67
Germany	Kruemmel	32	39	35	41	38
Germany	Philippsburg-1	64	55	52	48	35
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6					
Japan	Fukushima-Daini 1-4					
Japan	Hamaoka 1-4					
Japan	Kashiwazaki Kariwa 1-7					
Japan	Onagawa 1-3					
Japan	Shiga-1					
Japan	Shimane 1-2					
Japan	Tokai-2					
Japan	Tsuruga-1					
Mexico	Laguna Verde 1-2	2238	1344	582	1489	1138
Spain	Cofrentes	2484	977	1493	5574	3925
Spain	Santa Maria De Garona	402	391	474	367	361
Sweden	Barsebeck 1-2					285
Sweden	Forsmark 1-3					580
Sweden	Oskarshamn 1-3					433
Sweden	Ringhals-1					101
Switzerland	Leibstadt	370	470	1300	820	750
Switzerland	Muehleberg					
United States	Browns Ferry 2-3		2239	71	2176	4388
United States	Brunswick 1-2		2884	5756	5398	4348
United States	Clinton-1		561	1541	1382	1707
United States	Columbia			0	1872	4070
United States	Cooper		0		0	371
United States	Dresden 2-3		1261	1273	4255	873
United States	Duane Arnold-1		610	386	415	4037
United States	Enrico Fermi-2		0	0	48	46
United States	Fitzpatrick		785	897	1047	881
United States	Grand Gulf-1		6216	3885	2842	2609
United States	Hatch 1-2		668	1097	0	1128
United States	Hope Creek-1		844	1746	6471	889
United States	Lasalle 1-2		1642	2704	8947	4229
United States	Limerick 1-2		364	588	1361	1761
United States	Monticello		505	352	357	510
United States	Nine Mile Point 1-2		5010	9228	2835	2284
United States	Oyster Creek		4917	1931	1032	1088

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Peach Bottom 2-3		4825	3693	94	118
United States	Perry-1		0	1417	365	365
United States	Pilgrim-1		1923	3260	9639	25530
United States	Quad Cities 1-2		3885	2782	3312	6745
United States	River Bend-1		295	228	515	560
United States	Susquehanna 1-2		1945	3522	4780	5065
United States	Vermont Yankee		618	569	411	0
FBR						
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3					
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2	570	507	550	690	460
United Kingdom	Oldbury-A A-B	2390	2420	1630	2130	2790
United Kingdom	Sizewell-A A-B	515	1410	916	2060	2630
United Kingdom	Wylfa Unit A-B	8250	4840	6000	1610	3810
LWGR						
Lithuania	Ignalina 1-2					
Russian Fed.	Bilibino Unit A-D					
Russian Fed.	Kursk 1-4					
Russian Fed.	Leningrad 1-4					
Russian Fed.	Smolensk 1-3					
Ukraine	Chernobyl-3					
HWR						
Argentina	Atucha-1	390000	820000	1200000	850000	970000
Argentina	Embalse	72000	78000	270000	240000	270000
Canada	Bruce B5-8	260000	310000	490000	420000	430000
Canada	Darlington 1-4	190000	220000	230000	240000	190000
Canada	Gentilly-2	140000	130000	250000	190000	180000
Canada	Pickering B5-8	220000	270000	270000	270000	280000
Canada	Point Lepreau	130000	110000	130000	140000	130000
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen					
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4					
Romania	Cernavoda-1	50800	85300	208000	180000	286000

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
PWR						
Belgium	Doel 1-4	52	5670	17	326	1030
Belgium	Tihange 1-3	6350	7170	7560	5650	5260
Brazil	Angra 1-2	71	10	7400	160	1100
China	Guangdong 1-2	566	519	974	675	1670
China	Lingao 1-2					52
China	Qinshan-1	863	716	334	1280	1650
China	Qinshan-2 1-2					3
China - Taiwan Province	Maanshan 1-2	9220	11100	11100	8100	10200
France	Belleville 1-2				2020	2340
France	Blayais 1-4					529
France	Bugey 2-5					337
France	Cattenom 1-4					3440
France	Chinon-B 1-4					1080
France	Chooz-B 1-2					279
France	Civaux 1-2					314
France	Cruas 1-4					392
France	Dampierre 1-4					790
France	Fessenheim 1-2					707
France	Flamanville 1-2				2770	2490
France	Golfech 1-2					2270
France	Gravelines 1-6					2400
France	Nogent 1-2					2190
France	Paluel 1-4				2810	2740
France	Penly 1-2					2520
France	St. Alban 1-2				4640	2840
France	St. Laurent-B 1-2			440	460	679
France	Tricastin 1-4					1210
Germany	Biblis-A	180	240	510	150	480
Germany	Biblis-B	260	180	270	210	190
Germany	Brokdorf	310	320	380	360	250
Germany	Emsland	1900	2500	1600	1500	1400
Germany	Grafenrheinfeld	300	270	360	320	250
Germany	Grohnde	330	260	520	380	580
Germany	Isar-2	990	480	590	300	370
Germany	Neckarwestheim-1	210	130	110	120	120
Germany	Neckarwestheim-2	220	260	250	140	200
Germany	Obrigheim	120	130	130	98	98
Germany	Philippsburg-2	1200	1100	540	300	290
Germany	Stade	590	530	550	730	650
Germany	Unterweser	450	440	330	310	420
Japan	Genkai 1-4					
Japan	Ikata 1-3					
Japan	Mihama 1-3					
Japan	Ohi 1-4					
Japan	Sendai 1-2					
Japan	Takahama 1-4					
Japan	Tomari 1-2					
Japan	Tsuruga-2					
Netherlands	Borssele	333	224	300	277	261
Pakistan	Chasnupp-1					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Rep. of Korea	Kori 1-4					
Rep. of Korea	Ulchin 1-4					
Rep. of Korea	Yonggwang 1-5					
Slovenia	Krško	920	1163	1200	857	1250
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2	7579	7664	8096	7967	8783
Spain	Asco 1-2	2024	3226	1596	1842	2945
Spain	Jose Cabrera-1	31	31	41	43	84
Spain	Trillo-1	588	597	985	656	637
Spain	Vandellos-2	516	249	354	273	254
Sweden	Ringhals 2-4					879
Switzerland	Beznau 1-2					
Switzerland	Goesgen					
United Kingdom	Sizewell-B	1390	686	572	1820	858
United States	Arkansas One 1-2		1975	2627	0	2252
United States	Beaver Valley 1-2		9731	9583	9250	6179
United States	Braidwood 1-2		3752	1317	2227	170
United States	Byron 1-2		57	114	252	183
United States	Callaway-1		3197	2897	2338	2342
United States	Calvert Cliffs 1-2		245	448	414	271
United States	Catawba 1-2		8103	9361	7511	8954
United States	Comanche Peak 1-2		813	1094	1397	2113
United States	Crystal River-3		430	863	537	125
United States	Davis Besse-1		1042	1859	1033	2560
United States	Diablo Canyon 1-2		10715	8177	8140	11348
United States	Donald Cook 1-2		2790	3086	4166	5258
United States	Farley 1-2		2288	1415	930	435
United States	Fort Calhoun-1		236	71	76	76
United States	H.B. Robinson-2		413	354	422	251
United States	Indian Point 2-3		235	256	217	32715
United States	Kewaunee		364	604	1171	87
United States	Mcguire 1-2		5735	7178	7104	9694
United States	Millstone 2-3		695	630	2020	2905
United States	North Anna 1-2		1528	4048	3041	1792
United States	Oconee 1-3		6697	4773	2708	3959
United States	Palisades		623	704	1121	726
United States	Palo Verde 1-3		96977	106856	106449	61716
United States	Point Beach 1-2		4070	3260	2945	2157
United States	Prairie Island 1-2		892	813	1368	1164
United States	R.E. Ginna		1619	1548	1199	1989
United States	Salem 1-2		40463	35416	14437	11854
United States	San Onofre 2-3		1503	2797	3095	1691
United States	Seabrook-1		3445	4362	4362	5154
United States	Sequoyah 1-2		1268	2316	2316	5243
United States	Shearon Harris-1		4392	1814	2745	4085
United States	South Texas 1-2		1334	1858	4059	2545
United States	St. Lucie 1-2		4928	6639	9308	304
United States	Surry 1-2		2017	1025	1181	1462
United States	Three Mile Island-1		3330	1813	5165	4607
United States	Turkey Point 3-4		13	21	37	1
United States	Virgil C. Summer-1		191	124	10	70
United States	Vogtle 1-2		12267	5939	7362	3889
United States	Waterford-3		2634	1986	3441	3070
United States	Watts Bar-1		317	543	2281	1856
United States	Wolf Creek		1878	2002	1950	2161

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		WWER				
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6					
Czech Rep.	Dukovany 1-4	398	221	238	186	93
Czech Rep.	Temelin 1-2					76
Finland	Loviisa 1-2	192	178	194	179	218
Hungary	Paks 1-4	4890	5540	5040	5950	6300
Russian Fed.	Balakovo 1-4					
Russian Fed.	Kalinin 1-2					
Russian Fed.	Kola 1-4					
Russian Fed.	Novovoronezh 3-5					
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					920
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1					
Ukraine	Rivne 1-3					
Ukraine	South Ukraine 1-3					
Ukraine	Zaporozhe 1-6					

Table A-8 Iodine-131 released from nuclear power plants in airborne effluents (GBq)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2	0.004	0.003	0.003	0.002	0.002
United Kingdom	Hartlepool-A 1-2	0.089	0.028	0.031	0.023	0.039
United Kingdom	Heysham-1 A-B	0.75	0.076	0.11	0.11	0.11
United Kingdom	Heysham-2 A-B	0.19	0.043	0.037	0.041	0.041
United Kingdom	Hinkley Point-B A-B	0.013	0.009	0.011	0.057	0.006
United Kingdom	Hunterston-B 1-2					
United Kingdom	Torness A-B					
BWR						
China - Taiwan Province	Chinshan 1-2	0.0000008	0.0000954	0.00117		
China - Taiwan Province	Kuosheng 1-2	0.00145	0.00496	0.00323	0.0035	0.00396
Finland	Olkiluoto 1-2	0.003	0.014	0.079		0.00977
Germany	Brunsbuettel	0.0129	0.0106	0.00293	0.00126	0.00178
Germany	Gundremmingen B-C		0.0025	0.003	0.0012	0.859
Germany	Isar-1	0.0765	0.039	0.0224	0.017	0.0069
Germany	Kruemmel	0.048	0.18	0.13	0.18	0.26
Germany	Philippsburg-1	0.027	0.014	0.0082	0.011	0.0061
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6	0.0022	0.0031	0.0097	nd	0.00023
Japan	Fukushima-Daini 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Hamaoka 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Kashiwazaki Kariha 1-7	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Onagawa 1-3	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Shiga-1	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Shimane 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tokai-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tsuruga-1 [a]	n.d.	n.d.	0.00038	n.d.	n.d.
Mexico	Laguna Verde 1-2	0.0425	0.021	0.098	0.0211	0.0681
Spain	Cofrentes	0.109	0.053	0.212	0.53	0.917
Spain	Santa Maria De Garona	0.008	0.009	0.007	0.005	0.008
Sweden	Barsebeck 1-2	0.007	0.002	0.008	0.0006	0.0005
Sweden	Forsmark 1-3	0.065	0.044	0.045	0.11	0.38
Sweden	Oskarshamn 1-3	0.92	0.22	2.31	1.29	0.34
Sweden	Ringhals-1	2	0.52	0.235	0.347	0.09
Switzerland	Leibstadt	0.42	0.26	0.96	1.1	0.9
Switzerland	Muehleberg	0.0095	0.015	0.014	0.091	0.079
United States	Browns Ferry 2-3			1.97	0.72	10
United States	Brunswick 1-2		1.89	0.53	0.4	0.38
United States	Clinton-1		0.0007	0.006	0.004	0.007
United States	Columbia				0.031	0.023
United States	Cooper		0.21	0.25	0.066	0.031
United States	Dresden 2-3		0.19	0.17	0.19	0.14
United States	Duane Arnold-1		0.014	0.003	0.004	0.003
United States	Enrico Fermi-2		1.51	0.84	0.82	0.34
United States	Fitzpatrick		0.078	0.007	0.003	0.01
United States	Grand Gulf-1		0.007	0.001	0.003	0.003
United States	Hatch 1-2		0.34	0.2	0	0.038
United States	Hope Creek-1		0.017	0.007	0.11	0.13
United States	Lasalle 1-2		1.26	0.85	1.64	12
United States	Limerick 1-2		0.002	0.002	0.00006	0
United States	Monticello		0.27	0.1	0.091	0.1
United States	Nine Mile Point 1-2		3.65	0.046	0.063	0.073
United States	Oyster Creek		0.34	1.85	1.41	0.51

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Peach Bottom 2-3		0.064	0.019	0.012	0.009
United States	Perry-1		0.084	0.11	0.021	0.021
United States	Pilgrim-1		0.097	0.06	0.071	0.09
United States	Quad Cities 1-2		0.1	0.19	0.3	0.2
United States	River Bend-1		1.29	0.16	0.13	0.055
United States	Susquehanna 1-2			0.0001		
United States	Vermont Yankee		0.065	0.024	0.021	
FBR						
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3					
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2					
United Kingdom	Oldbury-A A-B					
United Kingdom	Sizewell-A A-B					
United Kingdom	Wylfa Unit A-B					
LWGR						
Lithuania	Ignalina 1-2	6.94	2.72	2.64	1.95	2.49
Russian Fed.	Bilibino Unit A-D					
Russian Fed.	Kursk 1-4	7.7	8.4	1.9	2.2	
Russian Fed.	Leningrad 1-4	17	2.1	1.7	1.1	
Russian Fed.	Smolensk 1-3	14	5.3	8.3	4.8	
Ukraine	Chernobyl-3					
HWR						
Argentina	Atucha-1	0.008	0.002	0.065	0.028	0.012
Argentina	Embalse	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	Bruce B5-8	0.04	0.035	0.055	0.028	0.049
Canada	Darlington 1-4	0.021	0.032	0.075	0.13	0.15
Canada	Gentilly-2	n.d.	n.d.	0.00006	n.d.	0.00014
Canada	Pickering B5-8	0.097	0.096	0.098	0.1	0.098
Canada	Point Lepreau	n.d.	n.d.	n.d.	n.d.	n.d.
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen	n.d.	n.d.	n.d.	n.d.	n.d.
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4					
Romania	Cernavoda-1	0.000755			0.000142	

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
PWR						
Belgium	Doel 1-4	0.014	0.003	0.009	0.004	0.009
Belgium	Tihange 1-3	0.005	0.006	0.0006	0.008	0.0008
Brazil	Angra 1-2	0.071	0	0.007	0.001	0.0001
China	Guangdong 1-2	0.0287	0.0148	0.0159	0.0108	0.0155
China	Lingao 1-2					0.0089
China	Qinshan-1	0.0629	0.0016	0.001	0.0026	0.003
China	Qinshan-2 1-2					0.0003
China - Taiwan Province	Maanshan 1-2					
France	Belleville 1-2					0.009
France	Blayais 1-4					0.16
France	Bugey 2-5					0.03
France	Cattenom 1-4					0.17
France	Chinon-B 1-4					0.01
France	Chooz-B 1-2					0.17
France	Civaux 1-2					0.002
France	Cruas 1-4					0.33
France	Dampierre 1-4					0.027
France	Fessenheim 1-2					0.018
France	Flamanville 1-2					0.049
France	Golfech 1-2					0.033
France	Gravelines 1-6					0.015
France	Nogent 1-2					0.33
France	Paluel 1-4					0.18
France	Penly 1-2					0.085
France	St. Alban 1-2					0.052
France	St. Laurent-B 1-2					0.002
France	Tricastin 1-4					0.007
Germany	Biblis-A	0.00005	0.00023	0.00065	0.00336	0.000444
Germany	Biblis-B	0.0061	0.00029	0.0308	0.0178	0.0155
Germany	Brokdorf	0.0061				0.002
Germany	Emsland	0.0009	0.0002	0	0	0
Germany	Grafenrheinfeld	n.d.	n.d.			
Germany	Grohnde	0.0003	0.00006		0.00005	0.0086
Germany	Isar-2	n.d.	n.d.			
Germany	Neckarwestheim-1	0.0002	0.0003	0.0001	0.0004	0.00007
Germany	Neckarwestheim-2	0.0001	n.d.			
Germany	Obrigheim	0.0003	0.0007	0.018	0.00008	0.00002
Germany	Philippsburg-2	0.0019	0.0033	0.0019	0.000044	0.00039
Germany	Stade	0.0002	0.0014	0.0009	0.0009	0.00235
Germany	Unterweser	n.d.	0.0005	0.0042	0.001	
Japan	Genkai 1-4	0.0039	n.d.	n.d.	n.d.	n.d.
Japan	Ikata 1-3	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Mihama 1-3	0.0024	0.00032	n.d.	0.000099	0.00038
Japan	Ohi 1-4	0.00012	0.00016	0.0011	0.00027	n.d.
Japan	Sendai 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Takahama 1-4	0.0099	0.00027	n.d.	0.00018	0.00034
Japan	Tomari 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tsuruga-2 [a]	n.d.	n.d.	0.00038	n.d.	n.d.
Netherlands	Borssele	0.2	0.013	0.005	0.028	0.032
Pakistan	Chasnupp-1					

Country	Name	1998	1999	2000	2001	2002
Rep. of Korea	Kori 1-4					
Rep. of Korea	Ulchin 1-4					
Rep. of Korea	Yonggwang 1-5					
Slovenia	Krško [b]	0.0176	0.00363	0.0523	0.000129	0.000323
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2	0.006	0.014	0.002	0.012	0.0005
Spain	Asco 1-2	0.01	0.006			0.0001
Spain	Jose Cabrera-1	0.035	0.007	0.004	0.0001	0.0004
Spain	Trillo-1	0.775	0.09	0.0002	0.0008	0.0001
Spain	Vandellos-2	0.002	0.122	0.244	0.012	0.044
Sweden	Ringhals 2-4	0.018	0.029	0.002	0.0196	0.296
Switzerland	Beznau 1-2	0.007	0.014	0.058	0.0077	0.0088
Switzerland	Goesgen	0.057	0.00014		0.00012	
United Kingdom	Sizewell-B	0.06	0.34			
United States	Arkansas One 1-2		0.00005	0.000005	0	0.001
United States	Beaver Valley 1-2		0.006	0.052	0.002	0.014
United States	Braidwood 1-2		0.0006	0.0006	0.00009	0.0002
United States	Byron 1-2		0.0006	0.00006	0	0.001
United States	Callaway-1		0.0006	0.0003	0.002	0.0001
United States	Calvert Cliffs 1-2		0.17	0.098	0.045	0.021
United States	Catawba 1-2		0	0.0008	0	0
United States	Comanche Peak 1-2		0	0	0	0.006
United States	Crystal River-3		0.0003	0.0001	0.0005	0
United States	Davis Besse-1		0.027	0.09	0.008	0.094
United States	Diablo Canyon 1-2		0.23	0	0.011	0.087
United States	Donald Cook 1-2		0	0	0	0.039
United States	Farley 1-2		0.002	0.025	0.017	0.0003
United States	Fort Calhoun-1		0.12	0.5	0.4	0.4
United States	H.B. Robinson-2		0	0	0.00003	0.00003
United States	Indian Point 2-3		0.0004	0.007	0.003	0.039
United States	Kewaunee		0	1.5	0	0
United States	Mcguire 1-2		0.000007	0	0	0
United States	Millstone 2-3		0.021	0.024	0.03	0.18
United States	North Anna 1-2		0.056	0.018	0.079	0.009
United States	Oconee 1-3		0.009	0.002	0.024	0.0002
United States	Palisades		0.14	0.045	0.037	0.096
United States	Palo Verde 1-3		0.009	0.91	0.91	0.41
United States	Point Beach 1-2		0.00003	0.001	5.20E-08	0.0005
United States	Prairie Island 1-2		0	0.083	0.023	0.00003
United States	R.E. Ginna		0.007	0.014	0.002	0.003
United States	Salem 1-2		1.61	0.34	0.14	0.73
United States	San Onofre 2-3		0.54	0.059	0.099	0.64
United States	Seabrook-1		0.00004	0.000002	0.0002	0.02
United States	Sequoyah 1-2		0.001	0.006	0.006	0.04
United States	Shearon Harris-1		0	0	0.0001	0
United States	South Texas 1-2		0.72	0.054	0.43	0.0004
United States	St. Lucie 1-2		0.032	0.0005	0.066	0.002
United States	Surry 1-2		0.00004	0.0003	0.0008	0.0001
United States	Three Mile Island-1		0.006	0.007	0.00007	0.00001
United States	Turkey Point 3-4		0.049	0.41	0	0.02
United States	Virgil C. Summer-1		0.00004	0.0003	0	0.00008
United States	Vogtle 1-2		0.025	0.001	0.0006	0.76
United States	Waterford-3		0.022	0.007	0	0.028
United States	Watts Bar-1		0.0002	0	0.00004	0
United States	Wolf Creek		0.006	0.0004	0	0

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
WWER						
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6	5.42	2.95	3.26	3.84	2.94
Czech Rep.	Dukovany 1-4	0.108	0.011	0.154	0.016	0.011
Czech Rep.	Temelin 1-2					0.006
Finland	Loviisa 1-2	0.003	0.045	0.000006		0.001
Hungary	Paks 1-4	0.24	0.47	0.14	0.38	0.086
Russian Fed.	Balakovo 1-4	0.83	0.57	0.64	1	
Russian Fed.	Kalinin 1-2	1.3	0.07	0.33	0.8	
Russian Fed.	Kola 1-4	2	2.1	3.6	4.1	
Russian Fed.	Novovoronezh 3-5	1.3	0.5	0.44	1	
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					2.589
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1	0.832	0.269	0.376	0.0544	0.27
Ukraine	Rivne 1-3	1.247	1.719	1.509	1.565	2.129
Ukraine	South Ukraine 1-3	0.008	1.12	3.2	1.45	1.07
Ukraine	Zaporozhe 1-6	0.52	1.2	1.7	1.5	0.62

Note: n.d. = not detected.

[a] Total amount for Tsuruga-1 (BWR) and Tsuruga-2 (PWR).

[b] Iodine-131 equivalent discharged activity.

Table A-9 Carbon-14 released from nuclear power plants in airborne effluents (GBq)

Country	Name	1998	1999	2000	2001	2002
AGR						
United Kingdom	Dungeness-B 1-2		470	277	523	638
United Kingdom	Hartlepool-A 1-2		1740	1470	2090	1780
United Kingdom	Heysham-1 A-B		688	1380	1230	1320
United Kingdom	Heysham-2 A-B		1090	940	1160	1280
United Kingdom	Hinkley Point-B A-B		1210	1000	1140	1070
United Kingdom	Hunterston-B 1-2		2000	1820	1900	2230
United Kingdom	Torness A-B		575	575	561	511
BWR						
China - Taiwan Province	Chinshan 1-2					
China - Taiwan Province	Kuosheng 1-2					
Finland	Olkiluoto 1-2	730	1050	1040	900	1010
Germany	Brunsbuettel	111	274	256	315	168
Germany	Gundremmingen B-C		1230	306	1490	2170
Germany	Isar-1	272	288	341	240	67
Germany	Kruemmel	210	480	360	250	98
Germany	Philippsburg-1	590	620	500	520	540
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6					
Japan	Fukushima-Daini 1-4					
Japan	Hamaoka 1-4					
Japan	Kashiwazaki Kariwa 1-7					
Japan	Onagawa 1-3					
Japan	Shiga-1					
Japan	Shimane 1-2					
Japan	Tokai-2					
Japan	Tsuruga-1					
Mexico	Laguna Verde 1-2					
Spain	Cofrentes					
Spain	Santa Maria De Garona					
Sweden	Barsebeck 1-2					
Sweden	Forsmark 1-3					2650
Sweden	Oskarshamn 1-3					912
Sweden	Ringhals-1					471
Switzerland	Leibstadt	410	650	510	450	750
Switzerland	Muehleberg					
United States	Browns Ferry 2-3					
United States	Brunswick 1-2					
United States	Clinton-1					
United States	Columbia					
United States	Cooper					
United States	Dresden 2-3					
United States	Duane Arnold-1					
United States	Enrico Fermi-2					
United States	Fitzpatrick					
United States	Grand Gulf-1					
United States	Hatch 1-2					
United States	Hope Creek-1					
United States	Lasalle 1-2					
United States	Limerick 1-2					
United States	Monticello					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Nine Mile Point 1-2					
United States	Oyster Creek					
United States	Peach Bottom 2-3					
United States	Perry-1					
United States	Pilgrim-1					
United States	Quad Cities 1-2					
United States	River Bend-1					
United States	Susquehanna 1-2					
United States	Vermont Yankee					
FBR						
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3					
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2		3560	3100	3000	3500
United Kingdom	Oldbury-A A-B		393	3960	4730	4480
United Kingdom	Sizewell-A A-B		1090	1070	1020	1170
United Kingdom	Wylfa Unit A-B		1480	522	404	1540
LWGR						
Lithuania	Ignalina 1-2					
Russian Fed.	Bilibino Unit A-D					
Russian Fed.	Kursk 1-4					
Russian Fed.	Leningrad 1-4					
Russian Fed.	Smolensk 1-3					
Ukraine	Chernobyl-3					
HWR						
Argentina	Atucha-1	490	290	340	290	210
Argentina	Embalse	510	580	390	490	420
Canada	Bruce B5-8			4100	2700	2100
Canada	Darlington 1-4		3500	2800	2600	2800
Canada	Gentilly-2	270	250	230	400	370
Canada	Pickering B5-8			11000	6300	1800
Canada	Point Lepreau	320	280	230	220	290
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen					
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4					
Romania	Cernavoda-1	290	170	232	164	124

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		PWR				
Belgium	Doel 1-4					
Belgium	Tihange 1-3					
Brazil	Angra 1-2					
China	Guangdong 1-2					
China	Lingao 1-2					
China	Qinshan-1					
China	Qinshan-2 1-2					
China - Taiwan Province	Maanshan 1-2					
France	Belleville 1-2				429	450
France	Blayais 1-4					628
France	Bugey 2-5					517
France	Cattenom 1-4					876
France	Chinon-B 1-4					615
France	Chooz-B 1-2					426
France	Civaux 1-2					455
France	Cruas 1-4					599
France	Dampierre 1-4					545
France	Fessenheim 1-2					227
France	Flamanville 1-2				696	376
France	Golfech 1-2					454
France	Gravelines 1-6					822
France	Nogent 1-2					411
France	Paluel 1-4				871	797
France	Penly 1-2					372
France	St. Alban 1-2				428	403
France	St. Laurent-B 1-2			250	328	308
France	Tricastin 1-4					601
Germany	Biblis-A	123	303	374	74	314
Germany	Biblis-B	457	102	395	164	197
Germany	Brokdorf	253	297	370	196	299
Germany	Emsland	590	700	320	360	400
Germany	Grafenrheinfeld	52	50	58	50	261
Germany	Grohnde	314	328	303	259	364
Germany	Isar-2	501	540	580	120	450
Germany	Neckarwestheim-1	7	240	231	159	230
Germany	Neckarwestheim-2	187	113	198	137	215
Germany	Obrigheim	16	47	85	56	62
Germany	Philippsburg-2	231	140	190	287	236
Germany	Stade	86	167	91	152	95
Germany	Unterweser	49	37	56	60	65
Japan	Genkai 1-4					
Japan	Ikata 1-3					
Japan	Mihama 1-3					
Japan	Ohi 1-4					
Japan	Sendai 1-2					
Japan	Takahama 1-4					
Japan	Tomari 1-2					
Japan	Tsuruga-2					
Netherlands	Borssele	86	71	89	116	123
Pakistan	Chasnupp-1					
Rep. of Korea	Kori 1-4					
Rep. of Korea	Ulchin 1-4					
Rep. of Korea	Yonggwang 1-5					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Slovenia	Krško	94	120	120	108	84
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2					
Spain	Asco 1-2					
Spain	Jose Cabrera-1					
Spain	Trillo-1	85	96	13	57	43
Spain	Vandellos-2					
Sweden	Ringhals 2-4					759
Switzerland	Beznau 1-2					
Switzerland	Goesgen					
United Kingdom	Sizewell-B		23	176	179	194
United States	Arkansas One 1-2					
United States	Beaver Valley 1-2					
United States	Braidwood 1-2					
United States	Byron 1-2					
United States	Callaway-1					
United States	Calvert Cliffs 1-2					
United States	Catawba 1-2					
United States	Comanche Peak 1-2					
United States	Crystal River-3					
United States	Davis Besse-1					
United States	Diablo Canyon 1-2					
United States	Donald Cook 1-2					
United States	Farley 1-2					
United States	Fort Calhoun-1					
United States	H.B. Robinson-2					
United States	Indian Point 2-3					
United States	Kewaunee					
United States	Mcguire 1-2					
United States	Millstone 2-3					
United States	North Anna 1-2					
United States	Oconee 1-3					
United States	Palisades					
United States	Palo Verde 1-3					
United States	Point Beach 1-2					
United States	Prairie Island 1-2					
United States	R.E. Ginna					
United States	Salem 1-2					
United States	San Onofre 2-3					
United States	Seabrook-1					
United States	Sequoyah 1-2					
United States	Shearon Harris-1					
United States	South Texas 1-2					
United States	St. Lucie 1-2					
United States	Surry 1-2					
United States	Three Mile Island-1					
United States	Turkey Point 3-4					
United States	Virgil C. Summer-1					
United States	Vogtle 1-2					
United States	Waterford-3					
United States	Watts Bar-1					
United States	Wolf Creek					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		WWER				
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6					
Czech Rep.	Dukovany 1-4	197	313	341	319	366
Czech Rep.	Temelin 1-2					134
Finland	Loviisa 1-2	340	320	280	310	370
Hungary	Paks 1-4	810	950	920	810	730
Russian Fed.	Balakovo 1-4					
Russian Fed.	Kalinin 1-2					
Russian Fed.	Kola 1-4					
Russian Fed.	Novovoronezh 3-5					
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					267
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1					
Ukraine	Rivne 1-3					
Ukraine	South Ukraine 1-3					
Ukraine	Zaporozhe 1-6					

Table A-10 Particulates released from nuclear power plants in airborne effluents (GBq)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2					
United Kingdom	Hartlepool-A 1-2					
United Kingdom	Heysham-1 A-B					
United Kingdom	Heysham-2 A-B					
United Kingdom	Hinkley Point-B A-B					
United Kingdom	Hunterston-B 1-2					
United Kingdom	Torness A-B					
BWR						
China - Taiwan Province	Chinshan 1-2	0.13	0.069	0.051	0.031	0.034
China - Taiwan Province	Kuosheng 1-2	0.00002	0.00004	0.00002	0.007	n.d.
Finland	Olkiluoto 1-2	0.0321	0.0067	0.0135	0.0328	0.03
Germany	Brunsbuettel	0.13	0.057	0.022	0.008	0.0048
Germany	Gundremmingen B-C	0.0004				0.000043
Germany	Isar-1	0.0059	0.0046	0.0045		
Germany	Kruemmel	0.032	0.012	0.011	0.014	0.0075
Germany	Philippsburg-1	0.0069	0.0096	0.0078	0.012	0.0035
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6					
Japan	Fukushima-Daini 1-4					
Japan	Hamaoka 1-4					
Japan	Kashiwazaki Kariwa 1-7					
Japan	Onagawa 1-3					
Japan	Shiga-1					
Japan	Shimane 1-2					
Japan	Tokai-2					
Japan	Tsuruga-1					
Mexico	Laguna Verde 1-2	0.935	0.936	7.646	0.085	0.1044
Spain	Cofrentes	0.0241	0.0319	0.197	0.208	0.109
Spain	Santa Maria De Garona	0.0167	0.0659	0.00989	0.123	0.00791
Sweden	Barsebeck 1-2	4.5	5.09	47.028	7.439	7.878
Sweden	Forsmark 1-3	0.2726	0.2084	0.51707	0.3828	8.4613
Sweden	Oskarshamn 1-3	13.6543	1.835	1.8798	2.7229	1.53
Sweden	Ringhals-1	4450	401	92.9	91.1	96
Switzerland	Leibstadt	0.037	0.033	0.057	0.082	0.062
Switzerland	Muehleberg	0.016	0.011	0.0089	0.01	0.011
United States	Browns Ferry 2-3		0.11	0.42	0.35	0.23
United States	Brunswick 1-2		0.41	0.14	0.11	0.11
United States	Clinton-1		0.002	0.034	0.028	0.012
United States	Columbia				0.038	0.063
United States	Cooper		0.22	0.2	0.087	0.12
United States	Dresden 2-3		0.45	0.62	4	0.65
United States	Duane Arnold-1		0.05	0.15	0.075	0.02
United States	Enrico Fermi-2		0.12	0.16	0.3	0.25
United States	Fitzpatrick		0.004	0.007	0.003	0.006
United States	Grand Gulf-1		0.001	0.001	0.001	0.002
United States	Hatch 1-2		0.17	0.037	0	0.011
United States	Hope Creek-1		0.28	2.2	0.022	0.008
United States	Lasalle 1-2		0.47	0.31	0.16	1.04
United States	Limerick 1-2		0.0007	0.0007	0.00008	9.00E-06
United States	Monticello		0.07	0.031	0.044	0.037
United States	Nine Mile Point 1-2		0.21	3.57	0.45	0.26
United States	Oyster Creek		0.12	0.53	2.06	0.8

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Peach Bottom 2-3		0.018	0.02	0.015	0.016
United States	Perry-1		0.12	0.045	0.024	0.024
United States	Pilgrim-1		0.06	0.1	0.07	0.053
United States	Quad Cities 1-2		0.12	0.39	0.79	1.1
United States	River Bend-1		0.07	0.044	0.043	0.036
United States	Susquehanna 1-2		0.14	0.12	0.27	0.23
United States	Vermont Yankee		0.0008	0.01	0.024	0.00E+00
FBR						
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3	0.039	0.034	0.016	0.061	
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2					
United Kingdom	Oldbury-A A-B					
United Kingdom	Sizewell-A A-B					
United Kingdom	Wylfa Unit A-B					
LWGR						
Lithuania	Ignalina 1-2	0.85	0.8	1.59	1.34	0.91
Russian Fed.	Bilibino Unit A-D					
Russian Fed.	Kursk 1-4	15	12	12		
Russian Fed.	Leningrad 1-4	16	1.96	1.61	1.3	
Russian Fed.	Smolensk 1-3	5.33	3.29	6.04	4.52	
Ukraine	Chernobyl-3					
HWR						
Argentina	Atucha-1	0.008	0.003	0.006	0.009	0.006
Argentina	Embalse	n.d.	n.d.	0.005	n.d.	n.d.
Canada	Bruce B5-8	0.096	0.11	0.079	0.14	0.11
Canada	Darlington 1-4	0.065	0.082	0.086	0.056	0.087
Canada	Gentilly-2	0.0064	0.0074	0.009	0.0083	0.005
Canada	Pickering B5-8	0.04	0.057	0.024	0.026	0.02
Canada	Point Lepreau	0.001	0.0035	0.0011	n.d.	n.d.
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen					
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4					
Romania	Cernavoda-1	0	0	0	0	0

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
PWR						
Belgium	Doel 1-4					
Belgium	Tihange 1-3					
Brazil	Angra 1-2					
China	Guangdong 1-2	0.017	0.008	0.009	0.006	0.006
China	Lingao 1-2					0.003
China	Qinshan-1	0.0088	0.0098	0.0063	0.0096	0.0075
China	Qinshan-2 1-2					0.0004
China - Taiwan Province	Maanshan 1-2	0.13	0.0077	0.0078	0.0046	0.0077
France	Belleville 1-2	0.098	0.087			
France	Blayais 1-4	0.16	1.4			
France	Bugey 2-5	0.25	0.35			
France	Cattenom 1-4	0.22	0.12			
France	Chinon-B 1-4	0.12	0.57			
France	Chooz-B 1-2	0.18	0.22			
France	Civaux 1-2	0.027	0.033			
France	Cruas 1-4	0.07	0.061			
France	Dampierre 1-4	0.13	0.16			
France	Fessenheim 1-2	0.035	0.051			
France	Flamanville 1-2	0.16	0.41			
France	Golfech 1-2	0.15	0.71			
France	Gravelines 1-6	0.65	0.51			
France	Nogent 1-2	0.39	0.24			
France	Paluel 1-4	0.13	0.13			
France	Penly 1-2	0.022	0.028			
France	St. Alban 1-2	0.16	0.14			
France	St. Laurent-B 1-2	0.042	0.043			
France	Tricastin 1-4	0.28	0.1			
Germany	Biblis-A	0.007	0.0092	0.025	0.0014	0.0015
Germany	Biblis-B	0.0056	0.0015	0.0023	0.00032	0.00022
Germany	Brokdorf	0.000066			0.00018	
Germany	Emsland	0.000071		0.00027	0.0003	0.000023
Germany	Grafenrheinfeld	0.0016	0.0018	0.0019	0.0019	0.0017
Germany	Grohnde	0.0018	0.00051			0.00011
Germany	Isar-2					
Germany	Neckarwestheim-1	0.00045	0.00025	0.0005	0.0021	0.0003
Germany	Neckarwestheim-2	0.00022			0.000087	0.000053
Germany	Obrigheim	0.0023	0.0012	0.0009	0.0023	0.00021
Germany	Philippsburg-2	0.00025	0.00033	0.00034	0.00029	0.00018
Germany	Stade	0.00086	0.00053	0.0022	0.0016	0.00011
Germany	Unterweser	0.0017	0.0016	0.0005	0.00087	0.00073
Japan	Genkai 1-4					
Japan	Ikata 1-3					
Japan	Mihama 1-3					
Japan	Ohi 1-4					
Japan	Sendai 1-2					
Japan	Takahama 1-4					
Japan	Tomari 1-2					
Japan	Tsuruga-2					
Netherlands	Borssele			0.012	0.001	0.001
Pakistan	Chasnupp-1					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Rep. of Korea	Kori 1-4					
Rep. of Korea	Ulchin 1-4					
Rep. of Korea	Yonggwang 1-5					
Slovenia	Krško	0.00057	0.000017	0.00106	0.00283	0.000756
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2	0.00145	0.00757	0.00531	0.00177	0.000962
Spain	Asco 1-2	0.01533	0.02758	0.00514	0.0131	0.01811
Spain	Jose Cabrera-1	0.00226	0.00125	0.00228	0.00161	0.0085
Spain	Trillo-1	0.00263	0.00808	0.00078	0.000279	0.00211
Spain	Vandellos-2	0.000127	0.0519	0.0424	0.00258	0.0272
Sweden	Ringhals 2-4	0.002507	0.190189	0.002286	0.000549	0.004773
Switzerland	Beznau 1-2	0.0023	0.0032	0.0004	0.0015	0.0009
Switzerland	Goesgen	0.00045	0.00027	0.00017	0.00025	0.00015
United Kingdom	Sizewell-B					
United States	Arkansas One 1-2		0.001	0.0003	0	0
United States	Beaver Valley 1-2		0.33	0.015	0.011	0.28
United States	Braidwood 1-2		0.0004	0.001	0.002	0.0002
United States	Byron 1-2		0.0005	0.0002	0.0001	0.0001
United States	Callaway-1		0.025	0.021	0.013	0.013
United States	Calvert Cliffs 1-2		0	0	0	0
United States	Catawba 1-2		0	0.0007	0	0
United States	Comanche Peak 1-2		0	0	0	0.0004
United States	Crystal River-3		0.0003	0.00007	0.00001	0.00004
United States	Davis Besse-1		0.00001	0.0002	0.00003	0.23
United States	Diablo Canyon 1-2		0.02868	0.019	0.009	0.034
United States	Donald Cook 1-2		0.00002	0.0006	0.005	0.004
United States	Farley 1-2		0.0004	0.00005	0.0006	0.001
United States	Fort Calhoun-1		0.0006	0.0004	0.0003	0.0003
United States	H.B. Robinson-2		5.80E-07	0.0005	0.0003	0.0004
United States	Indian Point 2-3		0.16	4.38	2.98	3.23
United States	Kewaunee		0	0	0.0002	0
United States	Mcguire 1-2		0.01	5.90E-06	0.0002	0.0001
United States	Millstone 2-3		0.008	0.0008	0.038	0.003
United States	North Anna 1-2		0.005	6.80E-06	0.001	0.0007
United States	Oconee 1-3		0.001	0.0004	0.0003	8.50E-10
United States	Palisades		0.002	0.0006	0.002	0.007
United States	Palo Verde 1-3		0.049	0.067	0.059	0.048
United States	Point Beach 1-2		0.00005	0.002	0.058	0.0005
United States	Prairie Island 1-2		0.022	0.001	0.0008	0.0003
United States	R.E. Ginna		0.0001	0.0001	0	0.00006
United States	Salem 1-2		0.005	0.025	0.091	0.026
United States	San Onofre 2-3		0.058	0.02	0.066	0.012
United States	Seabrook-1		0.004	0.0003	0.0003	0.0004
United States	Sequoyah 1-2		0.004	0.0004	0.0004	0.0002
United States	Shearon Harris-1		0.0003	0.002	0.004	0.002
United States	South Texas 1-2		0.14	0.018	0.051	0.16
United States	St. Lucie 1-2		0.002	0.016	0.002	0.008
United States	Surry 1-2		0.001	0.001	0.002	0.0008
United States	Three Mile Island-1		0.004	3.80E-06	0.0003	0.00E+00
United States	Turkey Point 3-4		0	0.003	0	0
United States	Virgil C. Summer-1		0.0001	0.003	0.0007	9.80E-06
United States	Vogtle 1-2		0.005	0.0003	0.0008	0.0006
United States	Waterford-3		0.0006	0.002	0.00003	0.001
United States	Watts Bar-1		0.0002	0.001	0	0.001
United States	Wolf Creek		0.0039	0.00009	0	0.0005

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		WWER				
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6	1.16	1.305	1.24	1.56	1.71
Czech Rep.	Dukovany 1-4	0.079	0.084	0.064	0.074	0.055
Czech Rep.	Temelin 1-2					0.002
Finland	Loviisa 1-2	0.073	0.0269	0.061	0.041	0.067
Hungary	Paks 1-4	0.287	0.33	0.261	0.528	0.227
Russian Fed.	Balakovo 1-4	0.34	0.33	0.33	0.33	
Russian Fed.	Kalinin 1-2	0.097	0.069	0.11		
Russian Fed.	Kola 1-4	0.044	0.16	0.84	0.81	
Russian Fed.	Novovoronezh 3-5	1.04	1.14	1.73	1.7	
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					0.137
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1	0.0649	0.132	0.0915	0.0419	0.0258
Ukraine	Rivne 1-3	0.240804	0.481928	0.247718	0.247718	0.364704
Ukraine	South Ukraine 1-3	0.147	0.151	0.228	0.37	0.21
Ukraine	Zaporozhe 1-6	0.09339	0.04817	0.136254	0.08328	0.10417

Note: n.d. = not detected.

Table A-11 Tritium released from nuclear power plants in liquid effluents (GBq)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2	172000	122000	119000	356000	290000
United Kingdom	Hartlepool-A 1-2	329000	409000	411000	386000	411000
United Kingdom	Heysham-1 A-B	396000	395000	441000	399000	402000
United Kingdom	Heysham-2 A-B	307000	255000	337000	330000	334000
United Kingdom	Hinkley Point-B A-B	387000	355000	352000	419000	381000
United Kingdom	Hunterston-B 1-2	442000	416000	326000	478000	448000
United Kingdom	Torness A-B	355000	335000	234000	274000	250000
BWR						
China - Taiwan Province	Chinshan 1-2	206	128	94	89	120
China - Taiwan Province	Kuosheng 1-2	374	339	110	101	162
Finland	Olkiluoto 1-2	1180	1050	1040	900	1010
Germany	Brunsbuettel	284	260	352	314	126
Germany	Gundremmingen B-C		6490	5450	4400	5870
Germany	Isar-1	900	350	434	840	350
Germany	Kruemmel	420	350	500	440	610
Germany	Philippsburg-1	520	590	480	650	460
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6	2100	1400	2000	1400	780
Japan	Fukushima-Daini 1-4	690	620	760	1300	910
Japan	Hamaoka 1-4	1300	940	610	620	750
Japan	Kashiwazaki Kariwa 1-7	450	930	960	410	120
Japan	Onagawa 1-3	25	62	90	62	79
Japan	Shiga-1	3.3	160	160	180	65
Japan	Shimane 1-2	310	370	600	520	360
Japan	Tokai-2	1000	910	640	630	860
Japan	Tsuruga-1 [a]	20000	11000	14000	10000	14000
Mexico	Laguna Verde 1-2	1117.4	1415.99	559.07	1003.44	181.41
Spain	Cofrentes	54	227	1706	1250	3059
Spain	Santa Maria De Garona	628	309	67	626	521
Sweden	Barsebeck 1-2	490	690	400	319	302
Sweden	Forsmark 1-3	1530	1420	1400	1850	1280
Sweden	Oskarshamn 1-3	1100	1290	1180	1230	741
Sweden	Ringhals-1	550	986	514	673	736
Switzerland	Leibstadt	590	700	1700	1100	1600
Switzerland	Muehleberg	430	170	140	200	240
United States	Browns Ferry 2-3		397	3	1	0
United States	Brunswick 1-2		3603	4791	4510	238
United States	Clinton-1		0	0	0	0
United States	Columbia				0	0
United States	Cooper		273	37	0	0
United States	Dresden 2-3		2927	6131	7027	3758
United States	Duane Arnold-1		0	0	0	0
United States	Enrico Fermi-2		0	0	0	0
United States	Fitzpatrick		0	178	0	23
United States	Grand Gulf-1		3996	1706	2235	1991
United States	Hatch 1-2		1090	1521	0	944
United States	Hope Creek-1		1091	222	280	144

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Lasalle 1-2		0	4	0	0
United States	Limerick 1-2		1363	1336	1549	719
United States	Monticello		0	0	0	0
United States	Nine Mile Point 1-2		535	846	1713	1702
United States	Oyster Creek			0	0	0
United States	Peach Bottom 2-3		4573	2887	1308	966
United States	Perry-1		176	323	1110	1110
United States	Pilgrim-1		245	394	752	11
United States	Quad Cities 1-2		983	1310	719	1636
United States	River Bend-1		478	625	1721	3404
United States	Susquehanna 1-2		1518	1752	904	2446
United States	Vermont Yankee		0	0	0	0
FBR						
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3					
GCR						
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2	421	2120	1090	2420	3450
United Kingdom	Oldbury-A A-B	173	214	354	344	419
United Kingdom	Sizewell-A A-B	2910	665	1580	2010	341
United Kingdom	Wylfa Unit A-B	9640	4590	4020	6430	4930
LWGR						
Lithuania	Ignalina 1-2		910	870	570	970
Russian Fed.	Bilibino Unit A-D					
Russian Fed.	Kursk 1-4					
Russian Fed.	Leningrad 1-4					
Russian Fed.	Smolensk 1-3					
Ukraine	Chernobyl-3					
HWR						
Argentina	Atucha-1	690000	800000	840000	1500000	870000
Argentina	Embalse	220000	140000	20000	80000	69000
Canada	Bruce B5-8	380000	220000	270000	150000	350000
Canada	Darlington 1-4	75000	89000	110000	94000	69000
Canada	Gentilly-2	250000	360000	340000	450000	500000
Canada	Pickering B5-8	71000	130000	110000	200000	210000
Canada	Point Lepreau	140000	53000	96000	150000	140000
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen	3200	3800	3600	4000	1500
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4					
Romania	Cernavoda-1	61800	19300	43500	52100	84700

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
PWR						
Belgium	Doel 1-4	47000	48000	30900	38000	27500
Belgium	Tihange 1-3	32900	66600	33100	41000	59600
Brazil	Angra 1-2	8500	13000	19000	9500	25000
China	Guangdong 1-2	27500	23900	34200	47600	42400
China	Lingao 1-2					11800
China	Qinshan-1	3050	2370	1020	1000	2600
China	Qinshan-2 1-2					162
China - Taiwan Province	Maanshan 1-2	19100	9800	18900	22600	39900
France	Belleville 1-2	24970	32000	39000	49000	49200
France	Blayais 1-4	47000	46000	36000	47000	54300
France	Bugey 2-5	31000	34000	35000	28000	40000
France	Cattenom 1-4	73000	87000	86000	110000	94300
France	Chinon-B 1-4	46000	41000	38000	39000	44000
France	Chooz-B 1-2	10000	20000	37000	39000	41300
France	Civaux 1-2	990	3600	26000	16000	17800
France	Cruas 1-4	46000	44000	46000	40000	50
France	Dampierre 1-4	37000	40000	32000	35000	43300
France	Fessenheim 1-2	22000	21000	18000	23000	16000
France	Flamanville 1-2	30000	25000	47000	58000	59200
France	Golfech 1-2	24000	23000	27000	49000	70200
France	Gravelines 1-6	58000	68000	47000	53000	42100
France	Nogent 1-2	42000	50000	62000	53000	52300
France	Paluel 1-4	74000	84000	110000	100000	94300
France	Penly 1-2	32000	33000	35000	45000	33200
France	St. Alban 1-2	30000	44000	30000	56000	53300
France	St. Laurent-B 1-2	19000	24000	23000	26000	25200
France	Tricastin 1-4	38000	29000	40000	43000	43300
Germany	Biblis-A	13100	15700	15500	7740	16600
Germany	Biblis-B	16600	15600	14700	10600	15200
Germany	Brokdorf	18600	17600	20800	19700	18000
Germany	Emsland	14800	17100	12600	18400	14900
Germany	Grafenrheinfeld	15000	14400	15500	16500	20600
Germany	Grohnde	16400	18800	17000	12900	17900
Germany	Isar-2	19000	24000	18000	20000	19000
Germany	Neckarwestheim-1	10000	6700	8700	9500	12000
Germany	Neckarwestheim-2	16000	17000	11000	9500	17100
Germany	Obrigheim	5200	6000	5500	5400	5920
Germany	Philippsburg-2	17000	18000	18000	13000	16000
Germany	Stade	2570	2970	2420	5100	3330
Germany	Unterweser	6890	7720	16500	16200	12200
Japan	Genkai 1-4	95000	77000	75000	60000	91000
Japan	Ikata 1-3	55000	48000	55000	47000	52000
Japan	Mihama 1-3	16000	20000	21000	17000	18000
Japan	Ohi 1-4	57000	69000	66000	130000	64000
Japan	Sendai 1-2	33000	35000	43000	42000	32000
Japan	Takahama 1-4	62000	71000	41000	53000	63000
Japan	Tomari 1-2	26000	24000	33000	31000	29000
Japan	Tsuruga-2 [a]	20000	11000	14000	10000	14000
Netherlands	Borssele	7500	6100	7700	6500	7700
Pakistan	Chasnupp-1					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Rep. of Korea	Kori 1-4					
Rep. of Korea	Ulchin 1-4					
Rep. of Korea	Yonggwang 1-5					
Slovenia	Krško	8690	10300	10700	10800	13300
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2	67422	48611	67432	19181	29038
Spain	Asco 1-2	52267	87918	78096	49447	95498
Spain	Jose Cabrera-1	2430	5933	4017	4485	2394
Spain	Trillo-1	17820	10536	15672	19977	16615
Spain	Vandellos-2	33481	16353	35698	10838	28661
Sweden	Ringhals 2-4	25300	39600	25910	24260	23630
Switzerland	Beznau 1-2	11000	8800	8300	11000	9900
Switzerland	Goesgen	13000	14000	14000	12000	14000
United Kingdom	Sizewell-B	48300	55700	53100	64100	65100
United States	Arkansas One 1-2		58492	36672	0	43485
United States	Beaver Valley 1-2		14541	22903	11655	13135
United States	Braidwood 1-2		84360	98420	101380	86580
United States	Byron 1-2		74000	85618	89170	70226
United States	Callaway-1		54790	40445	36489	42439
United States	Calvert Cliffs 1-2		34632	35420	52614	41736
United States	Catawba 1-2		45880	26566	27121	38110
United States	Comanche Peak 1-2		57239	45236	34447	51245
United States	Crystal River-3		20406	22441	12365	16239
United States	Davis Besse-1		25197	13575	20942	14205
United States	Diablo Canyon 1-2		43290	66600	40700	50690
United States	Donald Cook 1-2		7037	12044	12044	25086
United States	Farley 1-2		50228	46191	53757	60051
United States	Fort Calhoun-1		14430	18311	10841	10841
United States	H.B. Robinson-2		40293	16234	12443	19407
United States	Indian Point 2-3		33581	35557	23750	68820
United States	Kewaunee		7601	9850	10003	5123
United States	Mcguire 1-2		20572	31191	19869	21867
United States	Millstone 2-3		23199	67673	47101	56869
United States	North Anna 1-2		43623	31850	30081	25715
United States	Oconee 1-3		25197	38110	37000	33041
United States	Palisades		4942	5299	6031	6047
United States	Palo Verde 1-3		0	0	0	0
United States	Point Beach 1-2		17575	29748	21756	20720
United States	Prairie Island 1-2		20176	21534	25833	19088
United States	R.E. Ginna		7226	14412	7467	8932
United States	Salem 1-2		33618	38388	21408	34510
United States	San Onofre 2-3		15016	88954	35546	55292
United States	Seabrook-1		38473	53021	53021	49950
United States	Sequoyah 1-2		36926	84427	51164	48581
United States	Shearon Harris-1		9827	13602	22618	2612
United States	South Texas 1-2		60801	46357	77451	95041
United States	St. Lucie 1-2		22082	23547	43549	25123
United States	Surry 1-2		24920	30118	37370	19040
United States	Three Mile Island-1		20350	8917	18167	5574
United States	Turkey Point 3-4		31517	32530	42728	33951
United States	Virgil C. Summer-1		32745	21423	18648	12654
United States	Vogtle 1-2		61897	32109	55248	57942
United States	Waterford-3		11833	24568	12562	32035
United States	Watts Bar-1		13629	54512	34532	22237
United States	Wolf Creek		43373	57864	31346	30218

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		WWER				
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6	14668	19711	15633	15094	20380
Czech Rep.	Dukovany 1-4	15518	18135	15743	15818	19016
Czech Rep.	Temelin 1-2					11894
Finland	Loviisa 1-2	9300	13500	11830	13550	13710
Hungary	Paks 1-4	19900	20100	18400	18700	21900
Russian Fed.	Balakovo 1-4					
Russian Fed.	Kalinin 1-2					
Russian Fed.	Kola 1-4					
Russian Fed.	Novovoronezh 3-5					
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					15815
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1	2860	5670	5370	3430	2190
Ukraine	Rivne 1-3					
Ukraine	South Ukraine 1-3	6470	1530	4360	4060	2180
Ukraine	Zaporozhe 1-6		6900	10000		510

[a] Total amount for Tsuruga-1 (BWR) and Tsuruga-2 (PWR).

Table A-12 Other radionuclides released from nuclear power plants in liquid effluents (GBq)

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
AGR						
United Kingdom	Dungeness-B 1-2					
United Kingdom	Hartlepool-A 1-2					
United Kingdom	Heysham-1 A-B					
United Kingdom	Heysham-2 A-B					
United Kingdom	Hinkley Point-B A-B					
United Kingdom	Hunterston-B 1-2					
United Kingdom	Torness A-B					
BWR						
China - Taiwan Province	Chinshan 1-2	0.871	1.130	1.360	2.130	2.150
China - Taiwan Province	Kuosheng 1-2	6.560	2.090	1.180	1.330	0.525
Finland	Olkiluoto 1-2	2.500	1.810	1.090	0.870	0.750
Germany	Brunsbuettel	0.250	0.390	0.210	0.280	0.340
Germany	Gundremmingen B-C	1.100	1.000	0.850	0.410	0.730
Germany	Isar-1	0.260	0.077	0.076	0.270	0.061
Germany	Kruemmel	0.009	0.002	0.002	0.026	0.010
Germany	Philippsburg-1	0.460	0.290	0.160	0.130	0.200
India	Tarapur 1-2					
Japan	Fukushima-Daiichi 1-6	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Fukushima-Daini 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Hamaoka 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Kashiwazaki Kariwa 1-7	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Onagawa 1-3	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Shiga-1	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Shimane 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tokai-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tsuruga-1	n.d.	n.d.	n.d.	n.d.	n.d.
Mexico	Laguna Verde 1-2		0.883	0.759	0.049	0.052
Spain	Cofrentes	0.061	0.267	0.169	0.025	0.370
Spain	Santa Maria De Garona	1.060	2.602	0.133	0.696	0.586
Sweden	Barsebeck 1-2	35.700	26.400	24.700	48.700	40.400
Sweden	Forsmark 1-3	25.541	25.226	18.134	9.089	7.200
Sweden	Oskarshamn 1-3	82.070	26.880	20.570	14.050	14.420
Sweden	Ringhals-1	52.400	29.400	11.400	20.100	6.700
Switzerland	Leibstadt	0.490	0.110	0.250	0.250	0.200
Switzerland	Muehleberg	46.000	19.000	7.600	11.000	6.900
United States	Browns Ferry 2-3		3.200	0.270	0.000	0.000
United States	Brunswick 1-2		3.200	0.088	0.770	0.075
United States	Clinton-1		0.000	0.000	0.000	0.000
United States	Columbia					0.000
United States	Cooper		17.000	0.900	0.000	0.000
United States	Dresden 2-3		14.000	202.000	0.000	1.000
United States	Duane Arnold-1		0.000	0.000	0.000	0.000
United States	Enrico Fermi-2		0.000	0.000	0.000	0.000
United States	Fitzpatrick		0.000	0.051	0.000	0.100
United States	Grand Gulf-1		0.540	1.100	1.300	9.400
United States	Hatch 1-2		6.800	8.600	0.000	1.800
United States	Hope Creek-1		6.000	0.860	1.200	0.098
United States	Lasalle 1-2		0.000	0.190	0.000	0.000
United States	Limerick 1-2		1.200	1.000	0.330	0.120
United States	Monticello		0.000	0.000	0.000	0.000

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
United States	Nine Mile Point 1-2		3.700	4.000	181.000	28.000
United States	Oyster Creek			0.000	0.000	0.000
United States	Peach Bottom 2-3		0.600	0.100	2.000	8.100
United States	Perry-1		0.044	0.043	0.053	0.053
United States	Pilgrim-1		3.400	7.900	0.380	0.037
United States	Quad Cities 1-2		0.950	0.260	0.530	2.800
United States	River Bend-1		9.600	8.400	11.000	5.500
United States	Susquehanna 1-2		1.100	1.400	0.900	1.100
United States	Vermont Yankee		0.000	0.000	0.000	0.000
		FBR				
Kazakhstan	Bn-350					
Russian Fed.	Beloyarsky-3					
		GCR				
United Kingdom	Bradwell 1-2					
United Kingdom	Calder Hall 1-4					
United Kingdom	Chapel Cross 1-4					
United Kingdom	Hinkley Point-A 1-2					
United Kingdom	Dungeness-A 1-2					
United Kingdom	Oldbury-A A-B					
United Kingdom	Sizewell-A A-B					
United Kingdom	Wylfa Unit A-B					
		LWGR				
Lithuania	Ignalina 1-2	3.560	2.010	1.250	3.690	1.190
Russian Fed.	Bilibino Unit A-D					
Russian Fed.	Kursk 1-4					
Russian Fed.	Leningrad 1-4					
Russian Fed.	Smolensk 1-3					
Ukraine	Chernobyl-3					
		HWR				
Argentina	Atucha-1	130.000	350.000	330.000	530.000	390.000
Argentina	Embalse	2.000	4.500	1.600	1.200	1.600
Canada	Bruce B5-8	3.400	1.400	1.700	2.400	3.000
Canada	Darlington 1-4	3.800	14.000	13.000	5.600	8.500
Canada	Gentilly-2	5.600	1.600	0.940	1.200	1.300
Canada	Pickering B5-8	6.300	12.000	13.000	11.000	14.000
Canada	Point Lepreau	6.900	3.300	1.200	1.300	3.000
India	Kaiga 1-2					
India	Kakrapar 1-2					
India	Kalpakkam 1-2					
India	Narora 1-2					
India	Rajasthan 1-4					
Japan	Fugen	n.d.	n.d.	n.d.	n.d.	n.d.
Pakistan	Kanupp					
Rep. of Korea	Wolsong 1-4	n.d.	n.d.	0.290	0.370	0.460
Romania	Cernavoda-1	2.050	3.700	1.100	0.226	0.340

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
PWR						
Belgium	Doel 1-4					
Belgium	Tihange 1-3					
Brazil	Angra 1-2	1.800	1.200	1.400	1.100	2.600
China	Guangdong 1-2	1.861	4.135	2.034	1.877	2.065
China	Lingao 1-2					0.095
China	Qinshan-1	0.259	0.465	0.464	0.293	0.623
China	Qinshan-2 1-2					1.803
China - Taiwan Province	Maanshan 1-2	0.454	0.326	0.204	0.101	0.077
France	Belleville 1-2					
France	Blayais 1-4					
France	Bugey 2-5					
France	Cattenom 1-4					
France	Chinon-B 1-4					
France	Chooz-B 1-2					
France	Civaux 1-2					
France	Cruas 1-4					
France	Dampierre 1-4					
France	Fessenheim 1-2					
France	Flamanville 1-2					
France	Golfech 1-2					
France	Gravelines 1-6					
France	Nogent 1-2					
France	Paluel 1-4					
France	Penly 1-2					
France	St. Alban 1-2					
France	St. Laurent-B 1-2					
France	Tricastin 1-4					
Germany	Biblis-A	0.029	0.110	0.160	0.096	0.300
Germany	Biblis-B	2.000	0.300	0.200	0.260	0.220
Germany	Brokdorf	0.013	0.007	0.004	0.014	0.001
Germany	Emsland	0.000		0.000	0.000	
Germany	Grafenrheinfeld	0.062	0.032	0.045	0.029	0.023
Germany	Grohnde	0.023	0.005	0.037	0.014	0.024
Germany	Isar-2	0.000	0.001	0.037	0.000	0.000
Germany	Neckarwestheim-1	0.005	0.002	0.002	0.001	0.000
Germany	Neckarwestheim-2	0.049	0.036	0.005	0.001	0.170
Germany	Obrigheim	0.680	0.430	0.730	0.110	0.060
Germany	Philippsburg-2	0.830	0.440	0.350	0.490	0.390
Germany	Stade	0.050	0.043	0.038	0.047	0.014
Germany	Unterweser	0.060	0.071	0.770	0.100	0.390
Japan	Genkai 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Ikata 1-3	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Mihama 1-3	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Ohi 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Sendai 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Takahama 1-4	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tomari 1-2	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	Tsuruga-2	n.d.				
Netherlands	Borssele	0.301	0.322	0.330	0.582	0.278
Pakistan	Chasnupp-1					

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
Rep. of Korea	Kori 1-4	0.021	0.005	0.015	0.020	0.036
Rep. of Korea	Ulchin 1-4	n.d.	n.d.	0.030	0.027	0.130
Rep. of Korea	Yonggwang 1-5	n.d.	n.d.	0.020	0.014	0.850
Slovenia	Krško	0.771	0.474	0.576	1.130	0.939
South Africa	Koeberg 1-2					
Spain	Almaraz 1-2	10.998	12.285	11.967	8.975	5.966
Spain	Asco 1-2	12.759	11.621	8.005	18.358	7.823
Spain	Jose Cabrera-1	0.084	0.448	0.322	0.101	0.057
Spain	Trillo-1	0.560	0.784	0.658	1.011	0.725
Spain	Vandellos-2	9.488	20.133	26.638	18.186	19.899
Sweden	Ringhals 2-4	40.580	41.910	24.680	48.000	19.030
Switzerland	Beznau 1-2	41.000	15.000	43.000	25.000	25.000
Switzerland	Goesgen	0.038	0.038	0.007	0.004	0.018
United Kingdom	Sizewell-B					
United States	Arkansas One 1-2		32.000	30.000	0.000	13.000
United States	Beaver Valley 1-2		11.000	13.000	4.200	5.400
United States	Braidwood 1-2		24.000	83.000	4.300	4.100
United States	Byron 1-2		51.000	8.700	11.000	17.000
United States	Callaway-1		4.700	15.000	96.000	9.900
United States	Calvert Cliffs 1-2		29.000	19.000	27.000	15.000
United States	Catawba 1-2		3.300	3.100	3.600	3.000
United States	Comanche Peak 1-2		9.400	4.800	14.000	19.000
United States	Crystal River-3		10.000	16.000	33.000	1.900
United States	Davis Besse-1		1.800	12.000	0.320	127.000
United States	Diablo Canyon 1-2		7.500	5.600	6.700	5.400
United States	Donald Cook 1-2		7.500	4.500	5.000	6.700
United States	Farley 1-2		7.800	16.000	11.000	4.900
United States	Fort Calhoun-1		20.000	33.000	19.000	19.000
United States	H.B. Robinson-2		2.900	0.480	3.200	2.000
United States	Indian Point 2-3		14.000	39.000	22.000	27.000
United States	Kewaunee		1.900	2.800	2.300	1.900
United States	Mcguire 1-2		4.100	5.700	4.600	1.900
United States	Millstone 2-3		8.500	23.000	24.000	58.000
United States	North Anna 1-2		15.000	15.000	19.000	7.800
United States	Oconee 1-3		7.000	4.900	7.500	4.000
United States	Palisades		0.074	0.038	0.011	0.010
United States	Palo Verde 1-3		0.000	0.000	0.000	0.000
United States	Point Beach 1-2		3.400	3.500	0.000	2.900
United States	Prairie Island 1-2		13.000	5.600	3.700	4.000
United States	R.E. Ginna		0.850	0.180	0.039	0.580
United States	Salem 1-2		21.000	9.400	2.500	32.000
United States	San Onofre 2-3		25.000	68.000	23.000	12.000
United States	Seabrook-1		1.700	2.100	2.100	2.000
United States	Sequoyah 1-2		24.000	103.000	17.000	21.000
United States	Shearon Harris-1		2.000	1.700	2.400	1.500
United States	South Texas 1-2		187.000	63.000	119.000	38.000
United States	St. Lucie 1-2		148.000	6.000	93.000	49.000
United States	Surry 1-2		4.900	4.300	1.700	3.100
United States	Three Mile Island-1		0.046	0.037	4.700	0.025
United States	Turkey Point 3-4		4.100	4.500	3.200	2.100
United States	Virgil C. Summer-1		1.900	2.800	1.700	2.000
United States	Vogtle 1-2		13.000	7.300	8.200	4.900
United States	Waterford-3		154.000	99.000	8.300	48.000
United States	Watts Bar-1		2.400	3.500	2.100	5.900
United States	Wolf Creek		50.000	47.000	0.980	4.600

Country	*Name*	*1998*	*1999*	*2000*	*2001*	*2002*
		WWER				
Armenia	Armenia-2					
Bulgaria	Kozloduy 1-6	2.300	1.850	2.030	2.310	1.950
Czech Rep.	Dukovany 1-4	0.056	0.046	0.039	0.029	0.048
Czech Rep.	Temelin 1-2					0.142
Finland	Loviisa 1-2	1.240	0.120	0.100	1.310	3.900
Hungary	Paks 1-4	1.793	2.040	2.564	3.225	2.300
Russian Fed.	Balakovo 1-4					
Russian Fed.	Kalinin 1-2					
Russian Fed.	Kola 1-4					
Russian Fed.	Novovoronezh 3-5					
Russian Fed.	Volgodonsk-1					
Slovakia	Bohunice 1-4					45.490
Slovakia	Mochovce 1-2					
Ukraine	Khmelnitski-1	0.014	0.005	0.155	0.065	0.083
Ukraine	Rivne 1-3	4.881	1.529	1.047	0.168	0.559
Ukraine	South Ukraine 1-3	0.366	0.305	0.197	0.899	0.083
Ukraine	Zaporozhe 1-6	0.390	0.411	0.517	0.350	0.369

Note: n.d. = not detected.

Table A-13 Releases from nuclear fuel cycle reprocessing plants in airborne effluents (GBq)

[I30, V2 and UNSCEAR survey]

Country	*Site*	*1998*	*1999*	*2000*	*2001*	*2002*
^{3}H						
France	La Hague	7.16E+04	7.97E+04	6.66E+04	6.18E+04	6.32E+04
Germany	Karlsruhe	4.20E+03	3.10E+03	3.80E+03	1.50E+03	9.30E+02
Japan	Tokai	1.2E+03	1.2E+03	1.5E+03	2.9E+03	2.6E+03
United Kingdom	Dounreay	7.44E+02	8.67E+02	1.50E+03	4.02E+02	2.92E+02
United Kingdom	Sellafield	2.51E+05	2.36E+05	2.13E+05	2.41E+05	2.53E+05
^{14}C						
France	La Hague					1.69E+04
Germany	Karlsruhe		6.90E+01	6.60E+01	1.90E+01	2.80E+01
Japan	Tokai	n.d.	n.d.	2.2E+01	1.0E+02	1.1E+02
United Kingdom	Sellafield	2.57E+03	2.65E+03	2.61E+03	9.53E+02	8.29E+02
^{86}Kr						
France	La Hague	3.19E+08	2.95E+08	2.34E+08	2.27E+08	2.45E+08
Japan	Tokai	6.4E+01	3.2E+01	1.6E+06	4.0E+06	2.9E+06
United Kingdom	Dounreay			3.50E-02		2.26E-01
United Kingdom	Sellafield	9.90E+07	9.07E+07	7.36E+07	1.04E+08	1.01E+08
^{90}Sr						
Germany	Karlsruhe	8.90E-04	2.10E-04			
United Kingdom	Dounreay	9.90E-01	5.70E-01	4.80E-01	4.05E-01	4.03E-01
United Kingdom	Sellafield	6.00E-02	6.33E-02	5.40E-02	5.30E-02	4.68E-02
^{129}I						
Germany	Karlsruhe	2.90E-03	2.50E-03	2.70E-03	2.90E-03	2.60E-03
Japan	Tokai	2.8E-03	n.d.	8.4E-03	1.3E-02	3.1E-02
United Kingdom	Dounreay	2.80E-02	5.60E-02	5.40E-02	6.72E-02	7.21E-02
United Kingdom	Sellafield	2.65E+01	2.53E+01	2.52E+01	1.99E+01	2.60E+01
^{137}Cs						
United Kingdom	Dounreay	8.00E-02	3.80E-02	5.30E-02	5.99E-02	5.05E-02
United Kingdom	Sellafield	4.41E-01	5.83E-01	5.69E-01	3.34E-01	4.26E-01
^{241}Pu						
United Kingdom	Dounreay	5.60E-01	1.90E-01	2.00E-01	3.28E-02	1.16E-02
United Kingdom	Sellafield	2.66E-01	8.31E-01	2.68E-01	1.78E-01	9.73E-02

Note: n.d. = not detected.

Table A-14 Releases from nuclear fuel cycle reprocessing plants in liquid effluents (GBq)
[I30, V2 and UNSCEAR survey]

Country	*Site*	*1998*	*1999*	*2000*	*2001*	*2002*
^{3}H						
France	La Hague	1.05E+07	1.29E+07	1.05E+07	9.65E+06	1.19E+07
Germany	Karlsruhe	4.30E+03	1.20E+04	1.50E+03	6.90E+02	1.20E+03
Japan	Tokai	4.90E+02	1.40E+03	2.10E+04	1.30E+05	8.00E+04
United Kingdom	Dounreay	4.54E+02	1.37E+02	8.80E+01	9.72E+01	8.94E+01
United Kingdom	Sellafield	2.31E+06	2.52E+06	2.26E+06	2.56E+06	3.32E+06
^{14}C						
France	La Hague	9.76E+03	9.93E+03	8.52E+03	7.22E+03	7.85E+03
United Kingdom	Sellafield	3.74E+03	5.76E+03	4.61E+03	9.47E+03	1.30E+04
^{60}Co						
France	La Hague	5.14E+02	3.21E+02	3.01E+02	3.55E+02	3.80E+02
United Kingdom	Dounreay	1.00E+01	3.61E+00	7.12E-01	7.38E-01	4.45E-01
United Kingdom	Sellafield	2.41E+03	8.90E+02	1.19E+03	1.23E+03	9.00E+04
^{90}Sr						
France	La Hague	1.26E+03	8.49E+02	5.21E+02	3.55E+02	4.50E+02
Japan	Tokai	1.30E-03	n.d.	n.d.	n.d.	n.d.
United Kingdom	Dounreay	1.71E+02	1.63E+02	1.56E+02	1.61E+02	1.55E+02
United Kingdom	Sellafield	1.77E+04	3.12E+04	1.99E+04	2.61E+04	1.98E+04
^{99}Tc						
France	La Hague	2.15E+02	4.27E+02	3.88E+02	2.47E+02	1.40E+02
United Kingdom	Sellafield	5.27E+04	6.88E+04	4.44E+04	7.94E+04	8.54E+04
^{106}Ru						
France	La Hague	2.29E+04	1.38E+04	2.05E+04	1.69E+04	1.13E+04
Japan	Tokai	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
United Kingdom	Dounreay	7.40E+01	2.29E+00	1.75E+00	1.45E+00	8.46E-01
United Kingdom	Sellafield	5.58E+03	2.72E+03	2.68E+03	3.89E+03	6.02E+03
^{129}I						
France	La Hague	1.78E+03	1.83E+03	1.37E+03	1.18E+03	1.33E+03
Japan	Tokai	1.20E-02	5.70E-03	6.40E-03	1.50E-02	6.00E-03
United Kingdom	Sellafield	5.53E+02	4.85E+02	4.69E+02	6.29E+02	7.30E+02
^{137}Cs						
France	La Hague	2.51E+03	1.29E+03	8.72E+02	1.49E+03	9.59E+02
Japan	Tokai	1.10E-02	3.50E-02	0.00E+00	0.00E+00	0.00E+00
United Kingdom	Dounreay	1.82E+02	1.57E+02	1.40E+02	1.49E+01	1.44E+01
United Kingdom	Sellafield	7.54E+03	9.12E+03	6.92E+03	9.57E+03	7.69E+03
^{241}Pu						
France	La Hague	2.34E+02	2.21E+02	2.78E+02	2.10E+02	2.29E+02
United Kingdom	Dounreay	9.60E+01	8.67E+00	3.03E+00	7.37E-01	1.97E-01
United Kingdom	Sellafield	3.54E+03	2.87E+03	3.20E+03	4.58E+03	1.05E+04

Note: n.d. = not detected.

Table A-15 Dose monitoring and recording procedures for occupational exposure

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Argentina[b]	Uranium mining				
	Uranium milling				
	Fuel fabrication	0.1			No
	Reactor operation	0.01		No	No
	Research related to the nuclear fuel cycle	0.1			No
	Nuclear medicine	0.1			No
	Radiotherapy	0.1			No
	Accelerator operation	0.1			No
	Industrial irradiation	0.1			No
	Industrial radiography and well logging	0.1			No
	Radioisotope production and distribution	0.1			No
Australia	Mineral extraction				
Belarus	Diagnostic radiology	0.1			Yes
	Dental radiology	0.1			Yes
	Nuclear medicine	0.1			Yes
	Radiotherapy	0.1			Yes
	Industrial radiography	0.1			Yes
	Radioisotope production and distribution	0.1			Yes
	Educational establishments	0.1			Yes
Brazil	Reactor operation (PWR)	0.2	0.2		Yes
	Diagnostic radiology	0.2	0.2		Yes
	Dental radiology	0.2	0.2		Yes
	Nuclear medicine	0.2	0.2		Yes
	Radiotherapy	0.2	0.2		Yes
	Industrial radiography	0.2	0.2		Yes
	Well logging	0.2	0.2		Yes
	Radioisotope production and distribution	0.2	0.2		Yes
	All other industrial uses	0.2	0.2		Yes
	Educational establishments	0.2	0.2		Yes
	Veterinary medicine	0.2	0.2		Yes
Bulgaria	Reactor operation	0.2	0.2		
	Diagnostic radiology	0.4	0.2		
	Dental radiology	0.4	0.2		
	Nuclear medicine	0.4	0.2		
	Radiotherapy	0.4	0.2		
	Industrial radiography	0.4	0.2		
	All other industrial uses	0.4	0.2		
	Educational establishments	0.4	0.2		
	Veterinary medicine	0.4	0.2		

Country/area	*Occupation*	*MDL [a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Canada	Uranium mining	0.2[c]	0[c]	Yes	Yes
	Uranium milling	0.2[c]	0[c]	Yes	Yes
	Fuel fabrication	0.02	0	Yes	Yes
	Reactor operation	0.2[c]	0[c]	Yes	Yes
	Research related to the nuclear fuel cycle			Yes	Yes
	Diagnostic radiology	0.2 or 0.1[d]	0[e]		Yes
	Dental radiology	0.2 or 0.1[d]	0[e]		Yes
	Nuclear medicine	0.2 or 0.1[d]	0[e]		Yes
	Radiotherapy	0.2 or 0.1[d]	0[e]		Yes
	Industrial radiography	0.2 or 0.1[d]	0[e]		Yes
	Radioisotope production and distribution	0.2 or 0.1[d]	0[e]		Yes
	Well logging	0.2 or 0.1[d]	0[e]		Yes
	Accelerator operation	0.2 or 0.1[d]	0[e]		Yes
	Civilian aviation				Yes
	All military activity			Yes	Yes
	Educational establishments			Yes	Yes
	Veterinary medicine				Yes
Chile	Research related to the nuclear fuel cycle	0.1			Yes
	Diagnostic radiology	0.05			Yes
	Dental radiology	0.05			Yes
	Nuclear medicine	0.05			Yes
	Radiotherapy				
	All other industrial uses				
China	Uranium enrichment and conversion	0.02	0.01		
	Fuel fabrication	0.02	0.01		
	Reactor operation (PWR)	0.02	0.01	Yes	Yes
	Reactor operation (research reactor)	0.02	0.01		
	Research related to the nuclear fuel cycle	0.02	0.01		
	Diagnostic radiology	0.02	0.01		Yes
	Nuclear medicine	0.02	0.01		
	Radiotherapy	0.02	0.01		Yes
	Industrial irradiation	0.02	0.01		Yes
	Industrial radiography	0.02	0.01		Yes
	Radioisotope production and distribution				
	Accelerator operation	0.02	0.01		Yes
China - Taiwan Province	Reactor operation (BWR)	0.08	0		Yes
	Reactor operation (PWR)	0.06	0		Yes
	Research related to the nuclear fuel cycle	0.07	0		Yes
	Medical uses	0.12	0		Yes
	Industrial uses	0.2	0		Yes
	Civilian aviation	0.12	0		Yes
	Oil and natural gas industries	0.12	0		Yes
	Miscellaneous	0.12	0		Yes
Croatia	Medical uses	0.05	0.00		Yes
	Industrial irradiation	0.05	0.00		
	Industrial radiography	0.05	0.00		Yes
	Radioisotope production and distribution	0.05	0.00		Yes
	Well logging	0.05	0.00		Yes
	Veterinary medicine	0.05	0.00		Yes
	Other specified group	0.05	0.00		Yes
Cyprus	Medical uses	-	-	-	-
	Industrial radiography	-	-	-	-
	Veterinary medicine	-	-	-	-

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Czech Rep.	Uranium mining	0.05	0.05	Yes	Yes
	Uranium milling	0.05	0.05	Yes	Yes
	Research related to the nuclear fuel cycle	0.05	0		
	Diagnostic radiology	0.05	0		
	Nuclear medicine	0.05	0		
	Radiotherapy	0.05	0		
	Industrial irradiation	0.05	0		
	Industrial radiography	0.05	0		
	Well logging	0.05	0		
	Civilian aviation	0.05	0		
	All military activities	0.05	0		
	Other specified occupational group	0.05	0		
Denmark	Research related to the nuclear fuel cycle	0.01	0.01		
	Diagnostic radiology	0.05	0.1		Yes
	Nuclear medicine	0.05	0.1		Yes
	Radiotherapy	0.05	0.1		Yes
	Industrial irradiation	0.05	0.1		Yes
	Industrial radiography	0.05	0.1		Yes
	All other industrial uses	0.05	0.1		Yes
	Civilian aviation	0[f]	-		No
	Veterinary medicine	0.05	0.1		Yes
	Other specified occupational group	0.05	0.1		Yes
El Salvador	Diagnostic radiology	0.05	1		Yes
	Dental radiology	0.05	1		Yes
	Nuclear medicine	0.05	1		Yes
	Radiotherapy	0.05	1		Yes
	Industrial radiography	0.05	1		Yes
	All other industrial uses	0.05	1		Yes
	Educational establishments	0.05	1		Yes
Estonia	Industrial radiography	0.01	0.08		Yes
	All other industrial uses	0.01	0.08		Yes
	Educational establishments	0.01	0.08		Yes
	Veterinary medicine	0.01	0.08		Yes
Finland	Diagnostic radiology	[g]	0		Yes
	Dental radiology	[g]	0		Yes
	Nuclear medicine	[g]	0		Yes
	Radiotherapy	[g]	0		Yes
	Industrial radiography	[g]	0		Yes
	Radioisotope production and distribution	[g]	0		Yes
	Accelerator operation	[g]	0		Yes
	All other industrial uses	[g]	0		Yes
	Civilian aviation[h]	0.1	0		No
	Other mineral mining	[i]	[i]	[j]	
	Radon in workplaces other than mines	[i]	[i]	Yes[k]	
	Educational establishments	[g]	0		Yes
	Veterinary medicine	[g]	0		Yes
	Other specified occupational group	[g]	0		Yes

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
France	Uranium enrichment and conversion	-	-	-	-
	Reactor operation	-	-	-	-
	Reactor operation (research reactor)	-	-	-	-
	Diagnostic radiology	-	-	-	-
	Dental radiology	-	-	-	-
	Nuclear medicine	-	-	-	-
	Radiotherapy	-	-	-	-
	All other medical uses	-	-	-	-
	All other industrial uses	-	-	-	-
	Veterinary medicine	-	-	-	-
	Educational establishments	-	-	-	-
	Other specified occupational group	-	-	-	-
Germany	Uranium mining	0.1	0	Yes[l]	Yes[l]
	Uranium milling	0.1	0	Yes[l]	Yes[l]
	Uranium enrichment and conversion	0.001			
	Fuel fabrication	0.001			
	Diagnostic radiology	0.1	0.1		No[m]
	Dental radiology	0.1	0.1		No[m]
	All other medical uses	0.1	0.1		No[m]
	All other industrial uses	0.1	0.1		No[m]
	Other mineral mining	0.3	0	Yes[l]	
	Radon in workplaces other than mines	0.3	0	Yes[l]	
	Veterinary medicine	0.1	0.1		No[m]
	Educational establishments	0.1	0.1	No[m]	No[m]
Greece	Reactor operation (research reactor)	[n]	[n]		Yes
	Diagnostic radiology	[n]	[n]		Yes
	Dental radiology	[n]	[n]		Yes
	Nuclear medicine	[n]	[n]	Yes[m]	Yes
	Radiotherapy	[n]	[n]		Yes
	Industrial irradiation	[n]	[n]		Yes
	Industrial radiography	[n]	[n]		Yes
	Radioisotope production and distribution	[n]	[n]	Yes[m]	Yes
	Accelerator operation	[n]	[n]		Yes
	All other industrial uses	[n]	[n]		Yes
	Educational establishments	[n]	[n]	Yes[m]	Yes
	Veterinary medicine	[n]	[n]		Yes
	Other specified occupational group	[n]	[n]		Yes
Hungary	Diagnostic radiology	[o]	[o]		Yes[p]
	Dental radiology	[o]	[o]		Yes[p]
	Nuclear medicine	[o]	[o]		Yes[p]
	Radiotheraphy	[o]	[o]		Yes[p]
	Industrial radiography	[o]	[o]		Yes[p]
	Radioisotope production and distribution	[o]	[o]		Yes[p]
	All other industrial uses	[o]	[o]		Yes[p]
	Educational establishments	[o]	[o]		Yes[p]
	Veterinary medicine	[o]	[o]		Yes[p]
Iceland	Diagnostic radiology	0.05	0.1		No
	Nuclear medicine	0.05	0.1	No	No
	Radiotherapy	0.05	0.1		No
	Industrial radiography	0.05	0.1		No

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Indonesia	Diagnostic radiology	0.1	0.1		Yes
	Dental radiology	0.1	0.1		Yes
	Industrial irradiation	0.1	0.1		Yes
	Industrial radiography	0.1	0.1		Yes
	Well logging	0.1	0.1		Yes
	All other industrial uses	0.1	0.1		Yes
Japan	Uranium enrichment and conversion	0.1	0	No[q]	No[q]
	Fuel fabrication	0.1	0	No[q]	No[q]
	Reactor operation (BWR)	0.1	0	No[q]	No[q]
	Reactor operation (GCR)	0.1	0	No[q]	No[q]
	Reactor operation (HWR)	0.1	0	No[q]	No[q]
	Reactor operation (PWR)	0.1	0	No[q]	No[q]
	Fuel reprocessing	0.1	0	No[q]	No[q]
	Research related to the nuclear fuel cycle	0.1	0	No[q]	No[q]
Kuwait	Medical uses	0.2	0.2	No	Yes
	Industrial radiography	0.2	0.2		Yes
	Well logging	0.2	0.2		Yes
	All other industrial uses	0.2	0.2		Yes
	Other specified occupational group	0.2	0.2		Yes
Lithuania	Medical uses	0.08	0.01		Yes
	Industrial radiography	0.08	0.01		Yes
	All other industrial uses	0.08	0.01		Yes
	Civilian aviation[r]				
	Educational establishments	0.08	0.01		Yes
	Other specified occupational group	0.08	0.01		Yes
Luxembourg	Diagnostic radiology	0.05	0.1		Yes
	Dental radiology	0.05	0.1		Yes
	Radiotherapy	0.05	0.1		Yes
	All other medical uses	0.05	0.1		Yes
	Industrial radiography	0.05	0.1		Yes
	All other industrial uses	0.05	0.1		Yes
	Educational establishments	0.05	0.1		Yes
	Veterinary medicine	0.05	0.1		Yes
Malta	Medical uses	0.1	0		Yes[s]
	Industrial radiography	0.1	0		Yes[s]
	Other specified occupational group	0.1	0		Yes[s]
Mexico	Nuclear medicine	0	0		Yes
	Radiotherapy	0	0		Yes
	All other medical uses	0	0		Yes
	Industrial irradiation	0	0		Yes
	Industrial radiography	0	0		Yes
	Well logging	0	0		Yes
	Accelerator operation	0	0		Yes
	All other industrial uses	0	0		Yes
	Educational establishments	0	0		Yes

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Netherlands	Uranium enrichment and conversion	0.05	0.01		Yes
	Reactor operation	0.05	0.01		Yes
	Research related to the nuclear fuel cycle	0.05	0.01		Yes
	Medical uses	0.05	0.01		Yes
	Industrial irradiation	0.05	0.01		Yes
	Industrial radiography	0.05	0.01		Yes
	Radioisotope production and distribution	0.05	0.01		Yes
	Accelerator operation	0.05	0.01		Yes
	All other industrial uses	0.05	0.01		Yes
	Civilian aviation	0.05	0.01		Yes
	Processing material industries	0.05	0.01		Yes
	All military activities	0.05	0.01		Yes
	Educational establishments	0.05	0.01		Yes
	Veterinary medicine	0.05	0.01		Yes
	Other specified occupational group	0.05	0.01		Yes
Norway	Diagnostic radiology	0.1	0		No
	Dental radiology	0.1	0		No
	Nuclear medicine	0.1	0		No
	Radiotherapy	0.1	0		No
	All other medical uses	0.1	0		No
	Industrial radiography	0.1	0		No
	Well logging	0.1	0		No
	All other industrial uses	0.1	0		No
	Educational establishments	0.1	0		No
	Veterinary medicine	0.1	0		No
	Other specified occupational group	0.1	0		No
Peru	Diagnostic radiology	0.1	0.1	No	No
	Nuclear medicine	0.1	0.1		No
	Radiotherapy	0.1	0.1		No
Philippines	Diagnostic radiology	[t]	0		
	Dental radiology	[t]	0		
	Nuclear medicine	[t]	0		
	Radiotherapy	[t]	0		
	Industrial radiography	[t]	0		
Poland	Research related to the nuclear fuel cycle	0.4	1	No	No
	All other medical uses	0.1	0.5	Yes	Yes
	Other specified occupational group	0.5	5		No

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Romania	Uranium mining underground				
	Fuel fabrication				
	Reactor operation				
	Research related to the nuclear fuel cycle				
	Diagnostic radiology				
	Dental radiology				
	Nuclear medicine				
	Radiotherapy				
	All other medical uses				
	Industrial radiography				
	Luminizing				
	Radioisotope production and distribution				
	Well logging				
	Accelerator operation				
	All other industrial uses				
	All other military activities	0.2			Yes
	Educational establishments				
	Veterinary medicine				
Slovakia	Reactor operation	0.1	0.1		Yes
	Research related to the nuclear fuel cycle	0.1	0.1	Yes	Yes
	Diagnostic radiology	0.1	0.1		Yes
	Nuclear medicine	0.1	0.1	Yes	Yes
	Radiotherapy	0.1	0.1		Yes
	Industrial radiography	0.1	0.1		Yes
	Well logging	0.1	0.1		Yes
	Educational establishments	0.1	0.1	Yes	Yes
	Veterinary medicine	0.1	0.1		Yes
	Radon in workplaces other than mines	0.1	0.1	Yes	Yes
Slovenia[u]	Uranium mining underground	0.01[c,v]	MDL	Yes	Yes
	Reactor operation (PWR)	0.01	0		No
	Diagnostic radiology	0.04	0		Yes
	Dental radiology	0.04	0		Yes
	Nuclear medicine	0.04 or 0.01	0	No	Yes
	Radiotherapy	0.01	0		Yes
	All other medical uses	0.04 or 0.01	0	No	Yes
	Industrial radiography	0.04	0		Yes
	All other industrial uses	0.04	0		Yes
	Extractive industries, minerals other than coal	[v]	0	Yes	
	Radon in workplaces other than mines	0.01[c,v]	0	Yes	
	Veterinary medicine	0.04	0		Yes
	Other specified occupational group	0.04 or 0.01	0		Yes

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
Spain	Uranium milling	0.005	0.1[w]	Yes	Yes
	Fuel fabrication	0.005	0.1[w]	Yes	Yes
	Reactor operation (PWR)	0.005	0	Yes	Yes
	Reactor operation (BWR)	0.005	0	Yes	Yes
	Diagnostic radiology	0.005	0.1		Yes
	Dental radiology	0.005	0.1		Yes
	Nuclear medicine	0.005	0.1	Yes	Yes
	Radiotherapy	0.005	0.1		Yes
	All other medical uses	0.005	0.1	Yes	Yes
	Industrial irradiation	0.005	0.1		Yes
	Industrial radiography	0.005	0.1		Yes
	Well logging	0.005	0.1		Yes
	All other industrial uses	0.005	0.1		Yes
	Educational establishments	0.005	0.1	Yes	Yes
	Other specified occupational group	0.005	0.1		Yes
Switzerland	Reactor operation (PWR)	0.075	0		Yes
	Reactor operation (BWR)	0.075	0		Yes
	Research related to the nuclear fuel cycle				
	Dental radiology	0.075	0		Yes
	All other medical uses	0.075	0	Yes	Yes
	Luminizing	0.075	0		Yes
	All other industrial uses	0.075	0	Yes	Yes
	Educational establishments	0.075	0	Yes	Yes
	Veterinary medicine	0.075	0		Yes
	Other specified occupational group	0.075	0		Yes
Ukraine	Reactor operation (PWR)	0.05	0.04		Yes[x]
	Reactor operation (PWR 100)	0.05	0		Yes
	Reactor operation (RWP 100)	0.05	0		Yes
United Kingdom	Uranium enrichment and conversion	-	-	-	-
	Fuel fabrication	-	-	-	-
	Fuel reprocessing, oxide fuel	-	-	-	-
	Research related to the nuclear fuel cycle	-	-	-	-
	Diagnostic radiology	-	-	-	-
	Dental radiology	-	-	-	-
	Nuclear medicine	-	-	-	-
	Radiotherapy	-	-	-	-
	Industrial irradiation	-	-	-	-
	Industrial radiography	-	-	-	-
	Radioisotope production and distribution	-	-	-	-
	All other industrial uses	-	-	-	-
	Civilian aviation	-	-	-	-
	Extractive industries, coal mining	-	-	-	-
	Other mineral mining	-	-	-	-
	Radon in workplaces other than mines	-	-	-	-
	All military activities	-	-	-	-
	Educational establishments	-	-	-	-
	Veterinary medicine	-	-	-	-
	Other specified occupational group	-	-	-	-

Country/area	*Occupation*	*MDL[a] or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Monitoring labs accredited*	
				Internal	*External*
United States	Uranium enrichment and conversion	-	-	-	-
	Fuel fabrication	-	-	-	-
	Reactor operation (BWR)	-	-	-	-
	Reactor operation (PWR)	-	-	-	-
	Waste management	-	-	-	-
	Industrial radiography	-	-	-	-
	Radioisotope production and distribution	-	-	-	-
	All military activities	-	-	-	-

[a] Minimum detectable level.

[b] The Nuclear Regulatory Authority organizes periodic intercomparison measurement exercises for the monitoring laboratories.

[c] For external whole-body gamma irradiation.

[d] Depending on dosimetry processor.

[e] If under 2 mSv.

[f] Based on calculations. There is a legal requirement to report doses above 6 mSv.

[g] 0.3 mSv in three months (1995−1997); 0.1 mSv in a month or 0.3 mSv in three months (1998−2002)

[h] For 2001-2002. The doses are estimated using a special computation program [O4]. The calculation is based on the flight routes and flying times of aircrews and on changes in cosmic radiation dose rate at altitudes of 8–12 km. The calculation program has been checked by the regulatory authority.

[i] Not applicable, because doses are recorded only if the action level of 400 Bq/m^3 is exceeded.

[j] Based on regular measurements conducted by the regulatory authority.

[k] For the year 2001 records were based on regular measurements conducted by the regulatory authority.

[l] Authorized by the regulatory authority.

[m] Regulatory authority.

[n] 0.2 mSv (1995−1999); 0.1 mSv (2000−2002).

[o] 0.4 mGy (1995−1996); 0.15 mGy (1997−1999); 0.1 mSv (2000−).

[p] Since 2001.

[q] There is no official accreditation system, but voluntary intercomparison exercises are carried out.

[r] The data provided come from the assessment of average doses received by aircrews of Lithuanian airlines. The assessment was made using direct measurements of doses and calculations. No personal monitoring is carried out and no personal dose records are kept for aircrews.

[s] In the United Kingdom. Not yet in Malta.

[t] 0.15 (film badge); 0.04 (TLD).

[u] Authorized by the Ministry of Health.

[v] ~1 Bq/m^3 for radon.

[w] In a month.

[x] Since 2003.

Table A-16 Exposures to workers from natural sources of radiation

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	1.40		5.60	4.00									
	1995–1999													
	2000–2002													
Canada	1995–1999	0.00	0.00	0.01	1.44	1.51	0.00	0.00	0.06	0.28	0.00	0.00	0.64	
	2000–2002	0.01	0.01	0.01	0.56	1.36	0.00	0.00	0.00	6.59	0.00	0.00	0.00	
Czech Rep.	1995–1999	0.96	0.38	1.45	1.52	1.53	0.00	0.00	0.00	0.81	0.00	0.00	0.00	
	2000–2002	1.15	1.15	1.47	1.28	1.28	0.00	0.00	0.00	0.68	0.00	0.00	0.00	
Denmark	2002	3.99	3.99	6.79	1.70	1.70	0.00	0.00	0.00	0.73	0.00	0.00	0.01	0.90
Finland	1990–1994	1.93		3.78	1.96									
	1995–1999	1.81		3.81	2.11									
	2000–2002	2.52	2.22	4.16	1.65	1.85	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.00
Germany[b]	2004	30.20		55.20	1.80									
Lithuania	2002	0.16	0.00	0.24	1.50									
Netherlands	2001-2002	12.50	12.38	17.00	1.30	1.37	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.77
United Kingdom	1991	24.00		50.00	2.08									
	1995–1999													
	2002	40.00		80.00	2.00									
Total	1990–1994	27.30		59.40	2.15									
	1995–1999	2.77		5.27	1.90	1.82								
	2000–2002	90.54		164.87	1.82	1.44								

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Coal mining														
Myanmar	1994	<0.01	<0.01	0.00	0.68	0.68	0.00	0.00	0.00	0.50				
	1995–1999													
	2000–2002													
United Kingdom	1991	48.70		28.60	0.59									
	1995–1999													
	2002	5.00		3.00	0.60									
Total	1990–1994	48.70		28.60	0.59		0.00	0.00	0.00	0.50				
	1995–1999													
	2002	5.00		3.00	0.60									

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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
Other mineral mining														
Australia	1990–1994	0.34	0.26	0.19	0.56	0.73	0.00	0.00			0.00	0.02	0.05	0.70
	1995–1999													
	2001	0.18		0.11	0.62									
Finland	1990–1994	0.42		0.54	1.30									
	1995–1999	0.03	0.03	0.18	5.67	5.66	0.05	0.24	0.51	0.77	0.15	0.54	0.87	0.98
	2000–2002	0.02	0.02	0.08	3.53	3.52	0.00	0.00	0.48	0.65	0.00	0.00	0.84	0.98
Germany	1990–1994	1.02	1.00	2.35	2.31	2.19	0.00	0.01	0.09	0.71	0.00	0.04	0.03	0.93
	1995–1999	0.31	0.24	0.54	1.74	2.24	0.00	0.02	0.06	0.52	0.01	0.13	0.30	0.89
	2000–2002	0.21	0.14	0.36	1.69	2.62	0.00	0.03	0.08	0.50	0.00	0.17	0.39	0.93
Slovenia[c]	1990–1994	0.18	0.18	6.38	34.70	34.70	0.79	0.84	0.91	0.99				
	1995–1999													
	2000–2002	0.06	0.06	0.09	1.57	1.57	0.00	0.00	0.05	0.51	0.00	0.00	0.24	0.86
South Africa	1990–1994	250.00		640.00	2.60									
	1995–1999													
	2000–2002													
United Kingdom	1991	1.35		6.10	4.53									
	1995–1999													
	2001	0.80		0.93	1.16									
Total	1990–1994	3.30		15.60	4.71		0.10	0.11	0.17	0.63	0.00	0.04	0.27	0.91
	1995–1999	0.34	0.27	0.72	2.11	2.63								
	2000–2002	1.28	0.22	1.58	1.23	7.16								

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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
Oil and natural gas industries														
China - Taiwan Province	1995–1999	0.06	0.00	0.00	0.01	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
	2000–2002	0.05	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.01	0.01	0.00	0.66	0.66	0.00	0.00	0.00	0.25				
	1995–1999													
	2000–2002													
Ukraine	1999	0.43		1.08	2.50									
	2000–2002	0.52			0.7–4.0									
United Kingdom	1990–1994	0.58	0.21	0.12	0.21	0.59	0.00	0.00	0.01	0.03				
	1995–1999													
	2000–2002													
Total	1990–1994	0.59		0.12	0.21		0.00	0.00	0.01	0.03				
	1995–1999	0.49	0.00	2.17	1.26	0.25								
	2000–2002	0.57	0.00			0.00								
Handling of minerals and ores														
Netherlands	1995–1999	0.40	0.40	0.27	0.68	0.68	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00
	2000–2002	0.28	0.28	0.18	0.64	0.64	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
South Africa	1990–1994	2.37	2.37	2.58	1.09	1.09	0.00	0.00	0.02	0.10	0.00	0.02	0.14	0.29
	1995–1999													
	2000–2002													
Total	1990–1994													
	1995–1999	0.40	0.40	0.27	0.68	0.68								
	2000–2002	0.28	0.28	0.18	0.64	0.64								

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Radon in workplaces other than mines														
Finland	1995–1999													
	2001–2002	0.03	0.03	0.02	0.68	0.67	0.00	0.00	0.00	0.27	0.00	0.00	0.00	0.60
Germany	1995–1999	0.27	0.18	0.55	2.06	3.09	0.00	0.02	0.13	0.47	0.04	0.15	0.50	0.93
	2000–2002	0.22	0.14	0.35	1.61	2.54	0.01	0.02	0.11	0.36	0.08	0.17	0.52	0.90
Slovakia	2000–2002	0.06	0.06	0.17	2.91	2.90	0.01	0.04	0.17	0.70				
Slovenia	2000–2002	0.09	0.09	0.35	3.98	3.98	0.00	0.04	0.33	0.81	0.00	0.11	0.64	0.98
United Kingdom	1995–1999						0.00							
	2002	50.00		270.00	5.30		0.02	0.10	0.36					
Total	1995–1999	0.27	0.18	0.55	2.08	3.09	0.00	0.02	0.13	0.47	0.04	0.15	0.50	0.93
	2000–2002	50.40	0.32	270.90	5.38		0.01	0.04	0.19	0.54	0.03	0.09	0.39	0.83

[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] Monitoring started on 1 August 2003. Data in the table correspond to 2004.

[c] Reported data relate to workers in lead and zinc mines.

Table A-17 Exposures to workers from uranium mining[a,b]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Annual amount of ore extracted (kt U)* [c]	*Equivalent amount of energy (GW a)*	*Monitored workers* (10^3)[d]	*Measurably exposed workers* (10^3)	*Annual collective effective dose* [d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium extracted (man Sv /kt)*	*Average per unit energy generated (man Sv /(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]	1975–1979	0.11	0.49	0.37		4.89	45.30	9.90	13.20		0.54				0.95			
	1980–1984	0.15	0.66	0.95		2.29	15.70	3.40	2.41									
	1985–1989	0.47	2.77	0.51		1.25	2.70	0.59	2.45		0.00				0.00			
	1991–1994	0.07	0.42	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
	1995–1999	0.03	0.85	0.09	0.09	0.03	1.07	1.26	0.28	0.28	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.40
	2000-2002	0.00																
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	0	0.01	0.51	0	0.01	0.04	0.86
	1995–1999																	
	2001	7.72		0.68		0.48			0.71									
Canada[f, g, h]	1975–1979	6.82	31.00	6.22	5.47	41.20	6.04	1.33	6.62	7.53	0.20				0.57			
	1980–1984	8.22	37.50	8.88	7.42	50.60	6.16	1.35	5.70	6.82	0.23				0.62			
	1985–1989	11.81	53.50	6.28	5.24	31.60	2.68	0.59	4.80	6.04	0.21				0.67			
	1990–1994	9.38	40.90	2.43	1.94	8.69	0.93	0.21	3.58	4.46	0.04	0.11	0.26	0.58	0.18	0.44	0.75	0.96
	1995–1999	10.57	48.10	2.33	1.40	3.79	0.36	0.08	1.63	2.68	0.01	0.04	0.10	0.31	0.13	0.33	0.62	0.90
	2000–2002	11.92	54.24	1.71	0.96	1.41	0.12	0.03	0.83	1.48	0.00	0.00	0.03	0.25	0.00	0.03	0.24	0.80
China	1985–1989	(0.8)		6.6		114			17.3									
	1990–1994	(0.76)		[2.1]		[48]												
	1995–1999																	
	2000–2002																	

Country	*Period*	*Annual amount of ore extracted (kt U)* [c]	*Equivalent amount of energy (GW a)*	*Monitored workers (10^3)* [d]	*Measurably exposed workers (10^3)*	*Annual collective effective dose* [d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium extracted (man Sv /kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
Czech Rep. [i,j]	1975–1979	1.78	8.11	9.06		60.4	33.9	7.45	6.67									
	1980–1984	2.02	9.19	8.48		50.2	24.8	5.47	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
	1995–1999	0.60	2.74	0.77		9.37	16.1	3.42	12.17									
	2000–2002	0.49	2.22	0.50	0.497	3.84	7.9	1.73	7.72	7.72	0.14	0.27	0.56	0.96	0.37	0.57	0.83	1.00
France	1983–1984	1.85	8.42	1.28	1.25	17.00	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	8.47	4.13		8.48	8.48	0.18	0.31	0.6	0.86				
	1995–1999																	
	2000–2002																	
Gabon	1985–1989	(0.9)		0.24		5.06			21.00									
	1991–1994	0.60	2.72	0.19		2.58	4.30	0.95	13.40		0.36	0.55	0.72	0.88				
	1995–1999																	
	2000–2002																	
Germany[k]	1975–1979	6.26	28.50	14.70	14.70	160.00	25.50	5.61	10.90	10.90	0.46				0.72			
	1980–1984	4.73	21.50	15.10	15.10	147.00	31.00	6.82	9.69	9.69	0.42				0.65			
	1985–1989	4.07	18.50	16.10	1.61	133.00	32.70	7.18	8.24	8.24	0.31				0.57			
	1990–1994	0.77	3.48	4.71	4.68	20.20	26.40	5.82	4.30	4.33	0.05	0.16	0.42	0.82	0.13	0.35	0.71	0.96
	1995–1999	0.04	0.16	1.77	1.63	3.07	87.71	19.28	1.73	1.92	0.00	0.01	0.07	0.46	0.01	0.07	0.31	0.82
	2000–2002	0.09	0.40	1.41	1.41	1.10	12.36	2.72	0.79	0.79	0.00	0.00	0.02	0.2	0.01	0.02	0.17	0.65
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]												
	1995–1999																	
	2000–2002																	

Country	*Period*	*Annual amount of ore extracted (kt U)*[c]	*Equivalent amount of energy (GW a)*	*Monitored workers (10^3)*[d]	*Measurably exposed workers (10^3)*	*Annual collective effective dose*[d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium extracted (man Sv /kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
Romania	1995–1999	0.11	0.49	2.32	2.24	17.31	159.97	35.16	7.47	7.72	0.15	0.29	0.54	0.79	0.44	0.67	0.90	0.98
	2000–2002	0.09	0.40	0.36	0.35	1.89	21.75	4.78	5.25	5.31	0.12	0.27	0.50	0.85	0.32	0.59	0.85	0.99
Russian Fed.	1985–1989								16.3									
	1990–1994	(2.84)		2.89	2.89	6.39			2.21	2.21	0.01				0.09			
	1995–1999																	
	2000–2002																	
Slovenia[m]	1990–1994	0.01	0.05	0.11	0.11	0.27	23.3	5.13	2.46	2.62	0	0	0.27	0.53	0	0	0.61	0.87
	1995–1999																	
	2000–2002			0.08	0.08	0.09			1.15	1.15	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.78
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	0	0	0.02	0	0	0	0.19
	1995–1999																	
	2000–2002																	
South Africa[n]	1975–1979	3.27	14.9	79		346	107	23.3	4.39									
	1980–1984	5.07	23	93.6		399	78.8	17.3	4.27									
	1985–1989	3.53	16	82.2		278	78.8	17.3	3.38									
	1990–1994	(1.83)		[26]		[64]												
	1995–1999																	
	2000–2002																	
United States	1975–1979	5.51	25.1	6.85		30.9	5.6	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]												
	1995–1999																	
	2000–2002																	

Country	*Period*	*Annual amount of ore extracted (kt U)* [c]	*Equivalent amount of energy (GW a)*	*Monitored workers (10^3)* [d]	*Measurably exposed workers (10^3)*	*Annual collective effective dose* [d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium extracted (man Sv /kt)*	*Average per unit energy generated (man Sv /(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	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	85.4	13.5	12.6	68.1	3.58	0.8	5.07	5.39	0.1	0.21	0.42	0.76	0.32	0.54	0.8	0.97
		[24.0]	87.00	[42.3]		[189]												
	1995–1999	11.35	52.35	7.28	5.37	33.57	2.96	0.64	4.61	6.26	0.04	0.08	0.18	0.40	0.14	0.27	0.46	0.78
	2000–2002	20.30	57.25	4.72	3.29	8.81	0.43	0.15	1.87	2.67	0.05	0.11	0.22	0.54	0.14	0.24	0.42	0.84
World[o,p,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		0.3				0.61			
	1985–1989	59	270	260		1100	20	4.3	4.4		0.25				0.52			
	1990–1994	39	180	69	62	310	8	1.7	4.5	5.00	0.1	0.21	0.42	0.76	0.32	0.54	0.8	0.97
	1995–1999	34	155	22	16	85	2	0.5	3.9	5.34	0.04	0.08	0.18	0.40	0.14	0.27	0.46	0.78
	2000–2002	34	155	12	10	22	1	0.1	1.9	2.30	0.05	0.11	0.22	0.54	0.14	0.24	0.42	0.84

[a] Data are annual values averaged over the periods indicated.

[b] Previously the data for underground and open-pit mines were presented separately. For this table the data for previous periods have 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 reference [O5] is given marked in round brackets and red type. Where other significant data were missing, the Committee made estimates, marked in square brackets and blue type. These estimates are based on the average trends for countries reporting for both 1985–1989 and 1990–1994.

[d] In the absence of reported data for 1990–1994, the Committee estimated the number of monitored workers and the collective dose on the basis of the overall trend for those countries reporting for both 1985–1989 and 1990–1994. See also footnote *c* .

[e] Data contain a contribution from uranium milling.

[f] Part of Canada's production goes to the United States, 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 irradiation; an external dose of 2.6 mSv (the average external dose to monitored workers in 1982–1983) has been added here to reported doses from before 1981. The reported distribution ratios from before 1981 did not take account of external exposure and are therefore underestimates.

[i] Data for 1975–1989 are for Czechoslovakia.

[j] Exposures from inhalation of dust are not included; measurements indicated that it would contribute less than 3 mSv to the annual committed effective dose.

Country	*Period*	*Annual amount of ore extracted (kt U)*[c]	*Equivalent amount of energy (GW a)*	*Monitored workers* (10^3)[d]	*Measurably exposed workers* (10^3)	*Annual collective effective dose*[d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium extracted (man Sv /kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1

[k] The 1975–1989 data are 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. For 1995-2002, the values correspond only to measures for decommissioning mining facilities.

[l] Because of the low grade of the ore, the contribution from dust is very small and has been ignored.

[m] Uranium mining was carried out 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 the total and normalized collective doses, are those that can be attributed to uranium mining. Estimates of dose have been made for the whole workforce on the basis of measurements and knowledge of the 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 summations may differ from one period to another. The distribution ratios are averages of those reported, and the data for these ratios are often less complete than data for the other quantities.

[p] The first line of 1990–1994 values 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 1990–1994 values includes the estimates made by the Committee for China, India, South Africa and the United States.

[q] For 1990–1994, the world 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 A-18 Exposures to workers from uranium milling[a,b]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy (GW a)* [c]	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose* [d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium refined (man Sv /kt)*	*Average per unit energy generated (man Sv /(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	4.2	19.1	0.61	0.61	2.04	0.49	0.11	3.36	3.36	0				0			
	1991–1994			0.45	0.35	0.19			0.43	0.55	0	0	0	0.14	0.02	0.02	0.04	0.59
	1995–1999																	
	2000–2002																	
Canada[e]	1975–1979	4.31	19.6	0.67	0.46	0.66	0.15	0.03	0.99	1.44								
	1980–1984	5.5	25	0.85	0.36	0.37	0.07	0.02	0.43	1.04								
	1985–1989	9.29	42.2	0.83	0.66	1.30	0.14	0.03	1.56	1.95	0.01				0.01			
	1990–1994	9.04	41.14	0.35	0.32	0.64	0.07	0.02	1.84	2.03	0.00	0.00	0.04	0.67	0.00	0.01	0.12	0.77
	1995–1999	10.69	48.63	0.44	0.38	0.85	0.08	0.02	1.92	2.24	0.00	0.01	0.08	0.59	0.00	0.08	0.32	0.91
	2000–2002	11.60	52.79	0.44	0.38	0.77	0.07	0.01	1.76	2.02	0.00	0.00	0.05	0.61	0.00	0.00	0.17	0.91
China	1985–1989			3.05		9.67			3.17									
	1995–1999																	
	2000–2002																	
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									
Czech Rep.	1995–1999	0.60	2.74	0.121	0.08	0.44	0.73	0.16	3.61									
	2000–2002	0.48	2.17	0.157	0.16	0.43	0.90	0.20	2.77	2.77	0.00	0.00	0.05	0.83	0.00	0.00	0.11	0.95
France[g]	1988–1989	2.77	12.6	0.34	0.33	2.04	0.74	0.16	5.43	6.28								
	1995–1999																	
	2000–2002																	

Country	*Period*	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy (GW a)* [c]	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose* [d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium refined (man Sv /kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
Germany[h]	1975–1979	5.47	24.90	3.45	3.45	43.80	8.00	1.76	12.70	12.70								
	1980–1984	4.60	20.90	3.24	3.24	34.10	7.40	1.63	10.50	10.50								
	1985–1989	4.07	18.50	2.99	2.99	24.80	6.10	1.34	8.30	8.30								
	1995–1999			0.33	0.33	0.41			1.24	1.24	0.00	0.00	0.02	0.47	0.00	0.03	0.10	0.79
	2000–2002			0.21	0.21	0.08			0.35	0.35	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.17
India[i]	1981–1984	0.13	0.58	0.49		3.58	27.90	6.15	7.35									
	1985–1989	0.15	0.68	0.58		3.40	22.60	4.97	5.86									
	1995–1999																	
	2000–2002																	
South Africa	1979	3.60	16.40	0.39	0.09	0.07	0.02	0.00	0.17	0.78								
	1980–1984	4.46	20.30	0.65	0.28	1.93	0.43	0.10	2.97	6.95								
	1985–1989	3.00	13.70	0.64	0.26	1.08	0.36	0.08	1.68	4.20								
	1995–1999																	
	2000–2002																	
Spain	2000–2002	0.06	0.27	0.12	0.01	0.00			0.02	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
United States	1975–1979	8.90	40.50	0.30	0.10	0.03	0.00	0.00	0.11	0.34								
	1980–1984	16.80	76.40	4.80	3.00	4.48	0.27	0.06	0.93	1.49								
	1985–1989	4.30	19.60	1.00	0.60	0.95	0.22	0.05	0.95	1.59								
	1995–1999																	
	2000–2002																	
Total	1975–1979	18.70	85.00	4.40		44.50	2.38	0.52	10.10									
	1980–1984	28.80	131.00	10.40		53.20	1.85	0.41	5.10									
	1985–1989	22.40	102.00	6.98		43.70	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	0.02	0.37	0.01	0.01	0.08	0.68
	1995–1999	11.29		0.90	0.79	1.70			1.90	2.15	0.00	0.01	0.05	0.53	0.00	0.06	0.21	0.85
	2000–2002	12.14		0.92	0.76	1.28			1.39	1.69	0.00	0.00	0.03	0.37	0.00	0.00	0.07	0.51

Country	*Period*	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy (GW a)* [c]	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose* [d]			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
						Total (man Sv)	*Average per unit uranium refined (man Sv /kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
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	270	18		116	2.01	0.44	6.3									
	1990–1994	39	180	6		20	0.50	0.11	3.3									
	1995–1999	34	155	3	2	4	0.13	0.03	1.6	1.86	0.00	0.01	0.05	0.53	0.00	0.06	0.21	0.85
	2000–2002	34	155	3	2	3	0.08	0.02	1.1	1.32	0.00	0.00	0.03	0.37	0.00	0.00	0.07	0.51

[a] Data are annual values averaged over the periods indicated.

[b] Insufficient data are available to make a reliable world estimate.

[c] Estimated on the simplifying assumption that all the milled uranium is used in LWRs. The assumed uranium requirement is 220 t/(GW a).

[d] Doses from the inhalation of radon daughters estimated using a conversion factor of 5.0 mSv/WLM.

[e] For 1975–1983, the quoted values are for extraction only; data for milling for this period are reported together with data for mining.

[f] The contribution from internal exposure is small and was not explicitly estimated.

[g] The contribution from radon also includes the contribution from inhalation of ore dust.

[h] Doses estimated on the basis of grab samples.

[i] Because of the low grade of the ore, the contribution from dust was very small and has been ignored.

[j] The world estimate is based on assuming the amount of ore refined be equal to the amount mined, and on the downward trends for numbers of monitored workers and the collective dose seen in Australia and Canada for the periods 1985–1989 and 1990–1994.

Table A-19 Exposures to workers from uranium enrichment and conversion[a]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	Period	Annual amount of separative work (MSWU)[b]	Electrical energy equivalent of uranium (GW a)[c]	Monitored workers (10^3)	Measurably exposed workers (10^3)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)[d]				Distribution ratio (collective dose)			
						Total (man Sv)	Average per unit uranium enriched (man Sv /MSWU)	Average per unit energy generated (man Sv /(GW a))	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
China	1995–1999			1.36	1.07	0.37			0.27	0.34	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.56
	2000–2002			1.23	0.63	0.28			0.23	0.45	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.67
France	1979			2.36	0.07		0.04		0.02	0.54								
	1980–1984			2.33	0.05		0.04		0.02	0.69								
	1985–1989			1.77	0.01	0.00			0.00	0.37	0.00							
	1990–1994			4.04	0.17	0.08			0.02	0.44	0.00	0.00	0.00	0.04				
	1995–1999			3.98		0.50			0.13									
	2000–2002			5.97		0.82			0.14									
Germany	1995–1999			0.21	0.16	0.01			0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	2000–2002			0.29	0.13	0.00			0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Japan	1987–1989	0.2		0.14		0.00												
	1990–1994			3.60		0.06			0.00									
	1995–1999			0.89		0.02			0.03									
	2000–2002			0.96		0.02			0.02									
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
	1995–1999			0.10	0.10	0.03			0.34	0.34	0.00	0.00	0.00	0.06	0.00	0.00	0.06	0.35
	2000–2002			0.11	0.11	0.04			0.34	0.35	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.27
South Africa	1985–1989	0.10		0.09		0.04	0.34	0.04	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
	1995–1999																	
	2000–2002																	

Country	Period	Annual amount of separative work (MSWU)[b]	Electrical energy equivalent of uranium (GW a)[c]	Monitored workers (10^3)	Measurably exposed workers (10^3)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)[d]				Distribution ratio (collective dose)			
						Total (man Sv)	Average per unit uranium enriched (man Sv /MSWU)	Average per unit energy generated (man Sv /(GW a))	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United Kingdom	1975–1979			0.35		0.04			0.12									
	1980–1984	0.06	0.47	0.22		0.05	0.67	0.09	0.22									
	1985–1989	0.29	2.23	0.16		0.02	0.17	0.02	0.15									
	1990–1994	0.63	5.11	0.77		0.15	0.04	0.01	0.20									
	1995–1999			0.33		0.05			0.17									
	2000–2002			0.32		0.09			0.28									
United States	1975–1979[e]			10.30	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								
	1995–1999			10.32	1.02	0.36	-	-	0.04	0.35	0.00	0.00	0.00	0.01				
	2000–2002			9.35	1.37	0.45	-	-	0.05	0.34	0.00	0.00	0.00	0.01				
Total[f]	1975–1979			11		5			0.5		0.00				0.00			
	1980–1984			4		1			0.2		0.00	0.00	0.00	0.08	0.00	0.02	0.12	0.73
	1985–1989			5		0.4			0.1		0.00							
	1990–1994			13		1			0.1		0.00							
	1995–1999			17	2	1			0.1	0.6	0.00	0.00	0.00	0.04	0.00	0.00	0.02	0.46
	2000–2002			18	2	2			0.1	0.8	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.47

[a] Data are annual values averaged over the periods indicated.

[b] MSWU = million separative work units.

[c] Estimated on the simplifying assumption that all the enriched uranium is used in LWRs. The assumed fuel cycle requirement is 0.13 MSWU/(GW a).

[d] Values are for the monitored workforce.

[e] Data from USDOE reports [U21].

[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 summations may differ from one period to another.

Table A-20 Exposures to workers from fuel fabrication[a,b]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Average annual production of fuel (kt U)* [c]	*Equivalent amount of energy (GW a)* [c, d]	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)* [e]				*Distribution rati (collective dose*		
						Total (man Sv)	*Average per unit mass of fuel (man Sv/kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*
Argentina[f]	1980–1984	0.03	0.14	0.10		0.03	0.84	0.18	0.24								
	1985–1989	0.05	0.21	0.11		0.02	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
	1995–1999	0.15	0.70	0.05	0.05	0.10	0.64	0.14	2.10	2.11	0.00	0.00	0.08	0.73	0.00	0.00	0.24
	2000–2002	0.13	0.61	0.04	0.04	0.02	0.17	0.03	0.53	0.58	0.00	0.00	0.00	0.18	0.00	0.00	0.00
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	[8.7]	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
	1995–1999			0.26	0.20	0.57			2.23	2.89	0.03	0.04	0.16	0.51	0.01	0.13	0.53
	2000–2002			0.63	0.47	0.90			1.42	1.94	0.01	0.07	0.07	0.39	0.02	0.09	0.34
China	1990–1994	0.02	0.31	1.17	1.13	1.33	87.60	4.33	1.13	1.18	0.00	0.00	0.04	0.30	0.00	0.00	0.23
	1995–1999	0.08		1.13	1.11	2.33	31.92		2.07	2.09	0.00	0.02	0.10	0.47	0.01	0.13	0.41
	2000–2002	0.09		1.05	1.04	3.30	35.92		3.14	3.17	0.01	0.04	0.18	0.78	0.05	0.16	0.48
France	1990–1994	[1.26]	[34]	0.58	0.30	1.50			2.59	5.03	0.04	0.08	0.17	0.52			
	1995–1999																
	2000–2002																
Germany	1995–1999	0.40		0.34	0.29	0.17	0.43		0.50	0.59	0.00	0.00	0.00	0.19	0.00	0.00	
	2000–2002	0.44		0.34	0.28	0.10	0.23		0.29	0.34	0.00	0.00	0.00	0.10	0.00	0.00	0.00
Japan	1979	0.83	14.50	1.44		0.69	0.83	0.05	0.48								
	1980–1984	1.07	18.10	2.13		1.38	1.29	0.08	0.64								
	1987–1989	1.29	20.70	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
	1995–1999			2.71		0.41			0.15								
	2000–2002			1.71		0.33			0.19								

Country	Period	Average annual production of fuel (kt U)[c]	Equivalent amount of energy (GW a)[c, d]	Monitored workers (10^3)	Measurably exposed workers (10^3)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)[e]				Distribution rati (collective dose		
						Total (man Sv)	Average per unit mass of fuel (man Sv/kt)	Average per unit energy generated (man Sv /(GW a))	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5
Romania	1995–1999			1.43	1.32	6.99			4.90	5.25	0.06	0.14	0.39	0.62	0.26	0.46	0.82
	2000–2002			0.63	0.63	1.75			2.78	2.80	0.00	0.01	0.11	0.83	0.02	0.04	0.27
Russian Fed.	1992–1994	[1.95]			0.43	1.53		3.60	0.00								
	1995–1999																
	2000–2002																
South Africa	1990–1994	[0.1]		0.30	0.25	0.24			0.81	0.97	0.00	0.00	0.00	0.28	0.03	0.04	0.06
	1995–1999																
	2000–2002																
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
	1995–1999																
	2000–2002	0.21	5.73	0.43	0.07	0.00	0.01	0.00	0.01	0.05	0.00	0.00	0.00	0.02	0.00	0.00	0.00
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
	1995–1999																
	2000–2002																
United Kingdom	1975–1979	1.39	14.50	2.56		5.79	4.17	0.40	2.26		0.00						
	1980–1984	1.20	12.90	2.91		5.16	4.30	0.40	1.77		0.00						
	1985–1989	1.27	14.70	2.96		8.99	7.08	0.61	3.04		0.02						
	1990–1994	[1.2]	[13.9]	3.08		5.64			1.83								
	1995–1999			2.38		1.75			0.74								
	2000–2002			2.26		1.77			0.78								
United States	1975–1979	0.95	25.80	11.10	5.85	19.00	19.80	0.73	1.71	3.24	0.01				0.39		
	1980–1984	1.19	32.30	9.45	5.49	8.68	7.26	0.27	0.92	1.58	0.00				0.12		
	1985–1989[i]	1.92	51.80	9.95	3.88	4.51	2.35	0.09	0.45	1.16	0.00				0.02		
	1990–1994[j]	[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
	1995–1999[k]			8.17	3.91	10.23			1.25	2.62	0.00	0.04	0.08	0.20			
	2000–2002[k]			6.86	4.00	10.49			1.52	2.62	0.00	0.04	0.08	0.26			

Country	*Period*	*Average annual production of fuel (kt U)* [c]	*Equivalent amount of energy (GW a)* [c, d]	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)* [e]				*Distribution rati (collective dos*		
						Total (man Sv)	*Average per unit mass of fuel (man Sv/kt)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*
Total	1975–1979	3.13	46.60	14.80		26.70	8.53	0.57	1.80								
	1980–1984	4.64	69.90	15.60		16.20	3.49	0.23	1.04								
	1985–1989	6.35	104.00	17.90		17.00	2.67	0.16	0.94								
	1990–1994	8.79	143.00	16.20	8.30	16.80	1.91	0.12	1.03	2.02	0.00	0.01	0.03	0.16	0.11	0.31	0.55
	1995–1999	0.63		16.45	6.87	22.55			1.37	3.28	0.01	0.04	0.14	0.45	0.06	0.14	0.50
	2000–2002	0.87		13.95	6.52	18.66			1.34	2.86	0.00	0.02	0.06	0.37	0.01	0.05	0.18
World	1975–1979	4	60	20		36	10.0	0.6	1.8		0.01				0.38		
	1980–1984	6	100	21		21	3.4	0.2	1.0		0.00				0.11		
	1985–1989	10	180	28		22	2.3	0.1	0.8		0.00				0.02		
	1990–1994	11	210	21	11	22	1.9	0.1	1.0	2.0	0.00	0.01	0.03	0.16	0.11	0.31	0.55
	1995–1999		261	22	9	30		0.1	1.4	2.8	0.00	0.02	0.09	0.45	0.01	0.06	0.39
	2000–2002		272	20	10	31		0.1	1.6	2.9	0.01	0.02	0.08	0.37	0.01	0.06	0.21

[a] Data are annual values averaged over the periods indicated.

[b] Data in previous reports covered the different types of fuel separately. For the present report, the previous data for 1975–1989 have been aggregated for all fuel types.

[c] Where a country did not report a value for average annual production of fuel, it has been assumed that the value equals the fuel requirements of that country. The data for this have been taken from reports [O10, O11]. These estimates are shown in square brackets.

[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] 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 for average annual production are in kt UO_2.

[i] Calculation of *SR* distribution ratios based on data from 1993 and 1994.

[j] The total reported for measurably exposed workers has been increased pro rata to the data for monitored workers to take account of those countries that reported a collective dose but not the numbe measurably exposed workers.

[k] Data from NRC reports [U29, U30, U31, U32, U33, U34, U36, U37].

o e)
SR_1
0.82
0.96
0.36
0.96
0.93
0.88
0.79
0.85
0.97
0.74

o e)
SR_1
0.97
0.96
0.56
0.25
0.31
0.58
0.96

o e)
SR_1
0.89
0.93
0.70
0.89
0.91
0.73

OECD

r of

Table A-21 Exposures to workers at nuclear power reactors[a]

Data from ISOE and the UNSCEAR Global Survey of Occupational Radiation Exposures

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
PWR																	
Armenia																	
1995–1999[c]	1.00	0.17	2.82	2.82	16.13												
2000–2002[c]	1.00	0.24	0.86	0.86	3.64												
Belgium																	
1975–1979	4.00	1.14	5.28	1.32	4.63	2.39		2.21									
1980–1984	5.20	2.01	10.10	1.94	5.00	4.50		2.24									
1985–1989	7.60	4.26	17.90	2.36	4.22	8.38		2.14									
1990–1994	7.00	4.82	9.61	1.37	1.99												
1995–1999[c]	7.00	5.19	5.22	0.75	1.01												
2000–2002[c]	7.00	5.37	2.94	0.42	0.55												
Brazil																	
1990–1994	1.00		0.93	0.93		1.03	0.39	0.90	2.39	0.00	0.01	0.06	0.21	0.04	0.19	0.52	0.92
1995–1999[c]	1.00	0.35	1.16	1.16	3.30	2.13	0.49	0.54	2.36	0.00	0.01	0.06	0.23	0.02	0.17	0.51	0.93
2000–2002[c]	1.75	1.28	1.52	0.87	1.18	3.54	1.12	0.43	1.36	0.00	0.00	0.01	0.15	0.00	0.00	0.20	0.83
Bulgaria																	
1990–1994	5.80	1.57	12.20	2.10	7.77	2.29		5.33									
1995–1999[c]	6.00	1.98	8.75	1.46	4.42	1.22	0.47	0.99	2.62	0.00	0.01	0.04	0.25	0.00	0.02	0.10	0.22
2000–2002[c]	5.50	2.15	4.60	0.84	2.14	1.40	0.57	0.80	1.95	0.00	0.00	0.02	0.22	0.02	0.03	0.22	0.72
China																	
1992–1994	1.67	0.56	0.43	0.26	0.75	0.82	0.46	0.52	0.92	0.00	0.01	0.02	0.10	0.09	0.15	0.33	0.65
1995–1999[c]	3.00	1.57	2.06	0.69	1.31	2.84	2.16	0.72	2.38	0.00	0.00	0.03	0.19	0.02	0.08	0.25	0.75
2000–2002[c,d]	3.50	2.26	2.33	0.66	1.03	3.14	2.20	0.48	1.14	0.00	0.00	0.02	0.15	0.02	0.03	0.11	0.59

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)*[b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
China - Taiwan Province																	
1984	1.00	0.34	0.26	0.26	0.77	3.68		0.07									
1985–1989	2.00	1.06	1.41	0.71	1.34	2.52		0.56									
1990–1994	2.00	1.48	2.12	1.06	1.43	1.94	1.42	1.09	1.49	0.01	0.03	0.06	0.19	0.29	0.43	0.62	0.90
1995–1999[c]	2.00		1.99	1.01		1.65	1.02	1.20	1.95	0.01	0.03	0.07	0.20	0.30	0.44	0.65	0.91
2000–2002[c,d]	2.00		1.63	0.82		1.67	0.76	0.97	2.13	0.01	0.02	0.05	0.20	0.20	0.34	0.56	0.91
Czech Rep.[e]																	
1975–1977	1.00	0.11	0.09	0.09	0.79	0.87	0.08	0.10	1.17	0.00				0.12			
1980–1989	2.20	0.62	1.84	0.83	2.97	1.56	0.80	1.18	2.30	0.01				0.17			
1985–1989	7.00	2.11	3.97	0.57	1.88	4.14	2.43	0.96	1.64	0.01				0.12			
1990–1994	4.00	1.25	1.47	0.37	1.17	2.36	1.20	0.63	1.11	0.00	0.00	0.02	0.12	0.03	0.07	0.20	0.59
1995–1999[c]	4.00	1.46	1.43	0.36	0.97	2.34	0.92	0.63	1.61	0.00	0.00	0.02	0.13	0.04	0.09	0.27	0.66
2000–2002[c]	4.00	1.54	0.94	0.23	0.61	6.01	2.00	1.09	1.64								
Finland																	
1977–1979	1.00	0.34	0.79	0.79	2.31	0.93	0.47	0.84	1.69								
1980–1984	1.80	0.67	1.80	1.00	2.71	1.26	0.73	1.43	2.48	0.01				0.07			
1985–1989	2.00	0.84	1.73	0.87	2.05	1.09	0.65	1.59	2.66	0.01				0.07			
1990–1994	2.00	0.77	2.45	1.23	3.20	1.24	0.77	1.97	3.19	0.01	0.05	0.14	0.38	0.12	0.32	0.64	0.95
1995–1999[c]	2.00	0.86	1.67	0.83	1.94	1.21	0.66	1.35	2.47	0.01	0.02	0.09	0.29	0.06	0.21	0.53	0.92
2000–2002[c]	2.00	0.76	1.74	0.87	2.28												
France																	
1977–1979	3.50	1.93	4.34	1.24	2.24	3.40	0.89	1.28	4.87								
1980–1984	17.20	11.10	29.40	1.71	2.65	14.40	6.40	2.05	4.60	0.03							
1985–1989	41.00	28.30	78.90	1.92	2.79	29.70	16.80	2.65	4.68	0.05							
1990–1994	52.00	38.30	113.00	2.17	2.95												
1995–1999[c]	54.00	43.78	75.59	1.40	1.73	46.76		0.94									
2000–2002[c]	56.00	47.11	55.47	0.99	1.18	60.07		0.78									

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
Germany[f]																	
1975–1979	8.80	3.31	22.20	4.92	14.90	7.32		5.97		0.04				0.45			
1980–1984	11.60	6.34	43.00	6.94	13.30	11.70		6.79		0.06				0.44			
1985–1989	16.40	10.90	41.80	4.71	10.30	19.00	1.58	4.58	5.85	0.05				0.42			
1990–1994	14.00	12.50	27.10	1.94	2.17												
1995–1999[c]	14.00	13.40	20.54	1.47	1.53												
2000–2002[c]	13.50	13.54	14.43	1.07	1.07												
Hungary																	
1983–1984	0.50	0.36	0.32	0.21	0.89	1.26	0.29	0.25	1.09								
1985–1989	3.40	1.19	1.70	0.50	1.43	2.81	0.99	0.61	1.72	0.00				0.05			
1990–1994	4.00	1.58	2.92	0.73	1.84	3.46	1.06	0.84	2.74	0.01	0.02	0.05	0.18	0.11	0.26	0.57	0.93
1995–1999[c]	4.00	1.60	2.07	0.52	1.29	4.00	0.97	0.54	2.14	0.00	0.01	0.03	0.13	0.02	0.11	0.44	0.89
2000–2002[c]	4.00	1.58	3.21	0.76	1.92	4.24	1.06	0.72	2.85	0.00	0.01	0.05	0.16	0.03	0.16	0.53	0.93
Japan																	
1975–1979	7.00	2.02	14.10	2.02	6.99	7.21	6.11	1.96	2.32	0.02				0.18			
1980–1984	11.80	5.44	30.70	2.60	5.65	13.20	9.22	2.32	3.33	0.02				0.16			
1985–1989	16.20	9.22	33.50	2.07	3.63	18.60	12.10	1.80	2.76	0.01				0.12			
1990–1994	20.20	10.88	26.40	1.30	2.42	22.60	12.70	1.17	2.08	0.00	0.02	0.07					
1995–1999[c,i]	22.80	15.22	23.62	1.04	1.55	27.04	6.11	0.98	20.81	0.00	0.01	0.05					
2000–2002[c,d,i]	23.00	16.66	25.13	1.09	1.51	25.21	11.34	1.01	18.69	0.00	0.01	0.05					
Netherlands																	
1975–1979	1.00	0.37	4.10	4.10	11.00	0.60		6.89		0.14				0.44			
1980–1984	1.00	0.39	3.58	3.58	9.24	0.96		3.75		0.06				0.30			
1985–1989	1.00	0.39	2.83	2.83	7.21	1.14		2.48		0.02				0.15			
1990–1994	1.00	0.40	2.59	2.59	6.47	1.77	1.25	1.47	2.07	0.00	0.02	0.09	0.34	0.00	0.15	0.51	0.92
1995–1999[c]	1.00	0.39	1.18	1.18	3.05	1.61	1.04	0.96	1.49	0.00	0.01	0.06	0.26	0.01	0.08	0.42	0.89
2000–2002[c]	1.00	0.42	0.42	0.42	0.93	1.06	0.59	0.57	1.02	0.00	0.00	0.01	0.18	0.00	0.02	0.16	0.77

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Pakistan																	
1995–1999[c]																	
2000–2002[c]	0.50	0.10	0.08	0.15	0.78												
Rep. of Korea																	
1995–1999	10.20	7.94	9.79	0.96	1.23	7.62	3.30	1.67	3.77	0.02	0.04	0.11	0.27	0.16	0.39	0.70	0.95
2000–2002	12.75	8.57	7.79	0.61	0.91												
Russian Fed.[d,l]																	
1978–1979	7.50	1.70	19.40	2.59	11.20	3.20		6.14									
1980–1984	12.80	3.80	32.80	2.56	8.66	6.60		4.99									
1985–1989	22.00	8.70	57.10	2.60	6.55	12.30		4.63									
1990–1994			29.20			10.50											
1995–1999																	
2000–2002[c]	13.75	7.76	17.46	1.27	2.25												
Slovakia																	
1990–1994	4.00	1.31	2.74	0.68	2.09	1.39	1.39	1.97	1.97	0.00	0.02	0.12	0.45	0.02	0.13	0.49	0.90
1995–1999[c]	4.00	1.24	2.73	0.68	2.20												
2000–2002[c]	5.50	1.81	2.27	0.41	1.25												
Slovenia																	
1990–1994	1.00	0.48	1.40	1.40	2.92	0.69	0.69	2.04	2.04	0.01	0.07	0.13	0.41	0.10	0.27	0.59	0.92
1995–1999[c]	1.00	0.54	1.40	1.40	2.57	0.88	0.86	1.65	1.69	0.00	0.02	0.10	0.38	0.01	0.11	0.47	0.89
2000–2002[c]	1.00	0.59	1.28	1.28	2.16	0.92	0.81	1.39	1.58	0.01	0.02	0.07	0.34	0.07	0.17	0.42	0.89
South Africa																	
1984	2.00	0.45	0.12	0.06	0.27	1.72	0.08	0.07	1.45	0.00				0.29			
1985–1989	2.00	0.96	1.61	0.81	1.68	1.72	0.59	0.94	2.75	0.01				0.18			
1990–1994	2.00	1.06	2.07	1.03	1.95	1.79	0.77	1.15	2.70	0.01	0.03	0.07	0.23	0.13	0.31	0.60	0.93
1995–1999[c]	2.00	1.49	1.83	0.91	1.23												
2000–2002[c]	2.00	1.41	1.72	0.86	1.21												

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)*[b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Spain[g]																	
1975–1979	1.00	0.13	2.60	2.60	20.70	0.22		11.70									
1980–1984	2.60	0.67	6.76	2.60	10.10	1.51		4.21									
1985–1989	5.60	3.25	17.70	3.17	5.45	5.30	3.81	3.35	4.65								
1990–1994	7.00	5.01	12.90	1.85	2.58	6.85	4.53	1.88	2.46	0.01	0.03	0.09	0.31	0.13	0.30	0.57	0.92
1995–1999[c]	7.00	5.16	8.66	1.24	1.68												
2000–2002[c]	7.00	5.78	3.41	0.49	0.59	4.77	2.23	0.72	1.55	0.00	0.01	0.03	0.18	0.11	0.20	0.40	0.85
Sweden																	
1975–1979	1.00	0.47	1.52	1.52	3.28		0.62		2.46	0.03				0.24			
1980–1984	2.20	0.87	3.58	1.63	4.10		0.97		3.68	0.03				0.27			
1985–1989	3.00	1.93	4.80	1.60	2.49		1.82		2.65	0.03				0.19			
1990–1994	3.00	2.13	2.70	0.90	1.27									0.19			
1995–1999[c]	3.00	2.28	1.98	0.66	0.87		2.15		0.97					0.16			
2000–2002[c]	3.00	2.21	1.38	0.46	0.62												
Switzerland																	
1975–1979	2.20	0.71	4.16	1.89	5.83	0.63		6.64									
1980–1984	3.00	1.44	7.46	2.49	5.20	1.49		5.01									
1985–1989	3.00	1.44	6.60	2.20	4.58	1.67		3.95									
1990–1994	3.00	1.50	4.11	1.37	2.74	2.15		1.91		0.01	0.04	0.13	0.37	0.10	0.26	0.60	0.92
1995–1999[c]	3.00	1.60	1.94	0.65	1.21	1.72	1.19	1.12	1.61	0.00	0.01	0.06	0.30	0.00	0.07	0.39	0.88
2000–2002[c]	3.00	1.42	1.52	0.51	0.93	1.52	0.98	0.93	1.45	0.00	0.01	0.04	0.26	0.00	0.07	0.35	0.87
Ukraine																	
1995–1999[c]	13.00	7.79	24.50	1.88	3.15	12.37		2.31									
2000–2002[c]	13.00	8.91	18.71	1.44	2.10	13.12		1.48									
United Kingdom																	
1995–1999[c]	1.00	0.93	0.35	0.35	0.38												
2000–2002[c]	1.00	1.02	0.32	0.32	0.32												

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United States[e]																	
1975–1979	34.20	16.20	147.00	4.31	9.13	38.80	22.80	3.80	6.47	0.09				0.57			
1980–1984	46.80	22.10	276.00	5.89	12.50	83.10	51.00	3.32	5.41	0.08				0.53			
1985–1989	63.00	37.40	225.00	3.58	6.02	109.20	61.40	2.06	3.67	0.04				0.36			
1990–1994	72.60	51.50	154.00	2.12	2.99	114.10	58.00	1.35	0.31	0.00	0.03	0.09	0.27	0.01	0.13	0.42	0.91
1995–1999[c,j]	70.80	55.05	89.47	1.26	1.66	95.63	46.35	1.36	2.59	0.00	0.03	0.08	0.28				
2000–2002[c,d,j]	69.00	58.41	62.87	0.91	1.07	92.31	42.00	0.70	1.50	0.00	0.00	0.03	0.20				
Total PWR[k]																	
1975–1979	64.40	26.10	212.00	3.29	8.13	60.90		3.48		0.09				0.56			
1980–1984	121.00	56.30	451.00	3.73	8.01	144.00		3.14		0.06				0.48			
1985–1989	192.00	112.00	487.00	2.53	4.36	219.00		2.22		0.03				0.32			
1990–1994	209.30	137.00	380.00	1.82	2.78	260.00	140.00	1.45	2.61	0.00	0.02	0.08	0.27	0.07	0.21	0.51	0.90
1995–1999[c]	236.80	169.99	290.75	1.23	1.71	209.02	67.67	1.39	4.30	0.00	0.01	0.06	0.24	0.07	0.16	0.43	0.81
2000–2002[c]	255.75	190.90	234.03	0.92	1.23	218.97	65.66	1.07	3.56	0.00	0.01	0.04	0.20	0.05	0.11	0.33	0.82
World PWR																	
1975–1979	78	27	220	2.8	8.1	63		3.5		0.09				0.56			
1980–1984	140	56	450	3.3	8.0	140		3.1		0.06				0.48			
1985–1989	220	120	500	2.3	4.3	230		2.2		0.03				0.32			
1990–1994	242	149	415	1.7	2.8	310	166	1.3	2.5	0.00	0.02	0.28	0.27	0.07	0.21	0.51	0.90
1995–1999[c]	254	170	506	2.0	3.0	265	101	1.9	3.3	0.00	0.02	0.07	0.25	0.08	0.18	0.47	0.87
2000–2002[c]	266	191	415	1.6	2.2	283	99	1.7	2.7	0.00	0.01	0.04	0.21	0.06	0.12	0.32	0.81
BWR																	
China - Taiwan Province																	
1981–1984	3.80	1.83	14.40	3.84	7.85	6.32		2.28									
1985–1989	4.00	2.32	18.20	4.55	7.84	6.69		2.72									
1990–1994	4.00	2.39	13.56	3.39	5.69	6.17	4.92	2.20	2.76	0.03	0.06	0.13	0.32	0.37	0.53	0.73	0.95
1995–1999[c]	4.00		9.01	2.26		4.24	2.80	2.12	3.21	0.03	0.06	0.12	0.32	0.36	0.52	0.72	0.95
2000–2002[c]	4.00		8.26	2.06		4.02	2.92	2.05	2.83	0.03	0.06	0.12	0.35	0.25	0.42	0.66	0.92

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)*[b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland																	
1978–1979	1.00	0.21	0.12	0.12	0.55	1.44	0.29	0.08	0.40								
1980–1984	2.00	1.02	0.87	0.44	0.86	1.61	0.88	0.54	0.99	0.00				0.00			
1985–1989	2.00	1.33	1.80	0.90	1.36	1.92	1.14	0.94	1.59	0.00				0.03			
1990–1994	2.00	1.33	1.87	0.94	1.41	2.12	1.18	0.88	1.59	0.00	0.01	0.04	0.23	0.02	0.14	0.37	0.85
1995–1999[c]	2.00	1.45	1.48	0.74	1.02	2.06	1.13	0.71	1.30	0.00	0.00	0.02	0.20	0.00	0.08	0.26	0.82
2000–2002[c,d]	2.00	1.63	1.35	0.67	0.83												
Germany[f]																	
1975–1979	3.00	0.72	6.64	27.80	5.33	3.74	19.90										
1980–1984	4.40	2.12	7.59	15.70	3.28	10.20	33.40										
1985–1989	7.00	5.68	2.78	3.42	1.56	12.40	19.40										
1990–1994	7.00	4.82	2.23	3.24			15.60										
1995–1999[c]	6.00	5.31	7.81	1.30	1.47												
2000–2002[c]	6.00	5.64	5.43	0.91	0.96												
India																	
1980–1984	2.00	0.20	38.00	19.00	189.00	3.35	3.30	11.40	11.50	0.24							
1985–1989	2.00	0.21	23.20	11.60	113.00	2.69	2.56	8.63	9.06	0.16							
1995–1999																	
2000–2002																	
Japan																	
1975–1979	7.80	2.30	72.90	9.35	31.60	18.20	17.70	4.01	4.12	0.07				0.34			
1980–1984	13.00	6.24	91.40	7.03	14.60	27.40	18.90	3.34	4.83	0.06				0.34			
1985–1989	18.40	10.60	63.60	3.46	6.02	34.80	20.70	1.83	3.07	0.02				0.20			
1990–1994	23.40	13.50	44.30	1.89	3.30	39.60	20.60	1.12	2.15	0.01	0.01	0.04					
1995–1999[c]	27.60	20.04	50.47	1.83	2.52	39.86	2.64	1.14		0.01	0.02	0.07					
2000–2002[c,d,i]	28.75	16.80	58.37	2.03	3.02	38.71	3.52	1.41		0.01	0.04	0.09					

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)*^{b}		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	*NR$_{15}$*	*NR$_{10}$*	*NR$_5$*	*NR$_1$*	*SR$_{15}$*	*SR$_{10}$*	*SR$_5$*	*SR$_1$*
Mexico																	
1990–1994	1.00	0.49	4.64	4.64	9.40												
1995–1999^c	2.00	1.04	8.69	4.35	8.38												
2000–2002^c	2.00	1.06	4.96	2.48	4.68												
Netherlands																	
1975–1979	1.00	0.05	2.31	2.31	49.20	0.28		8.38		0.20				0.24			
1980–1984	1.00	0.05	2.24	2.24	48.10	0.47		4.81		0.11				0.27			
1985–1989	1.00	0.05	1.62	1.62	32.90	0.56		2.87		0.04				0.19			
1995–1999^c	0.40	0.02	0.40	1.00	20.78												
2000–2002	-																
Spain^g																	
1975–1979	1.00	0.32	5.36	5.36	16.80	0.62		8.60									
1980–1984	1.20	0.27	7.85	6.54	29.20	0.97		8.08									
1985–1989	2.00	1.09	10.10	5.05	9.26	2.66	2.06	3.80	4.90								
1990–1994	2.00	1.20	7.74	3.87	6.43	2.87	2.24	2.70	3.01	0.01	0.04	0.15	0.47	0.05	0.22	0.57	0.95
1995–1999^c	2.00	1.33	3.71	1.86	2.80												
2000–2002^c	2.00	1.14	2.58	1.29	0.26	2.52	1.30	1.02	1.98	0.00	0.01	0.06	0.25	0.02	0.14	0.44	0.89
Sweden																	
1975–1979	4.60	1.64	5.98	1.30	3.65		2.09		2.86	0.03				0.24			
1980–1984	6.60	3.46	8.22	1.25	2.38		3.13		2.63	0.03				0.27			
1985–1989	9.00	5.64	10.70	1.19	1.89		3.71		2.88	0.03				0.19			
1990–1994	9.00	5.70	15.80	1.76	2.77												
1995–1999^c	9.00	6.00	17.03	1.89	2.73		6.28		2.65					0.07	0.19	0.45	0.77
2000–2002^c	8.00	5.27	8.27	1.03	1.31												
Switzerland																	
1990–1994	2.00	1.18	3.97	1.99	3.36	2.58		1.54		0.01	0.02	0.09	0.33	0.06	0.21	0.53	0.91
1995–1999^c	2.00	1.27	2.78	1.43	2.27	2.35	1.98	1.18	1.41	0.00	0.01	0.05	0.33	0.00	0.07	0.33	0.88
2000–2002^c	2.00	1.42	1.70	0.98	1.38	1.94	1.59	0.87	1.07	0.00	0.00	0.03	0.25	0.00	0.03	0.26	0.83

Country/area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Annual collective effective dose			Number of workers		Average annual effective dose (mSv)[b]		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
			Average (man Sv)	Average per reactor (man Sv)	Average per unit energy generated (man Sv /(GW a))	Monitored workers (10^3)	Measurably exposed workers (10^3)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United States[h]																	
1975–1979	22.80	9.37	156.00	6.83	16.60	33.30	19.90	4.68	7.84	0.06				0.65			
1980–1984	26.20	10.40	268.00	10.20	25.70	53.30	35.10	5.03	7.63	0.08				0.63			
1985–1989	32.20	14.70	181.00	5.63	12.30	77.20	40.50	2.35	4.48	0.03				0.43			
1990–1994	37.00	21.50	131.00	3.54	6.08	76.60	40.10	1.71	3.27	0.00	0.04	0.12	0.30	0.14	0.28	0.62	0.94
1995–1999[c,j]	36.40	24.88	77.27	2.12	2.98	63.28	34.30	1.25	2.30	0.00	0.02	0.07	0.29				
2000–2002[c,d,j]	35.00	28.94	56.73	1.62	1.96	55.41	30.43	1.02	1.86	0.00	0.01	0.05	0.25				
Total BWR																	
1975–1979	40.60	14.30	262.00	6.46	18.10	55.90		4.69		0.07				0.61			
1980–1984	59.00	25.20	454.00	7.69	18.00	102.00		4.47		0.08				0.55			
1985–1989	77.60	41.60	330.00	4.25	7.93	139.00		2.38		0.03				0.36			
1990–1994	87.40	52.10	238.00	2.73	4.58	160.00	87.00	1.56		0.01	0.04	0.12	0.31	0.13	0.33	0.63	0.94
1995–1999[c]	91.40	61.34	178.65	1.95	2.91	111.80	49.13	1.60	3.64	0.01	0.02	0.07	0.29	0.11	0.21	0.44	0.85
2000–2002[c]	89.75	61.90	147.65	1.65	2.39	102.59	39.75	1.44	3.71	0.01	0.02	0.07	0.28	0.09	0.20	0.45	0.88
World BWR																	
1975–1979	51	15	279	5.5	18.3	59		4.7		0.07				0.61			
1980–1984	65	25	454	7.0	18.0	102		4.5		0.08				0.55			
1985–1989	84	42	331	4.0	7.9	139		2.4		0.03				0.36			
1990–1994	90	50	240	2.7	4.8	160	87	1.6	2.9	0.00	0.04	0.12	0.31	0.13	0.33	0.63	0.94
1995–1999[c]	91	62	237	2.6	3.8	144	63	1.6	2.6	0.01	0.02	0.07	0.29	0.11	0.21	0.44	0.85
2000–2002[c]	90	67	160	1.8	2.4	113	44	1.4	2.1	0.01	0.02	0.07	0.28	0.09	0.20	0.45	0.88
HWR																	
Argentina																	
1975–1979	1.00	0.26	4.52	4.52	17.20	0.43		10.50		0.26				0.73			
1980–1984	1.40	0.32	8.04	5.74	25.20	0.77		10.50		0.27				0.79			
1985–1989	2.00	0.61	12.60	6.29	20.80	1.06		11.90		0.29				0.80			
1990–1994	2.00	0.87	12.00	6.01	13.80	1.47	1.26	8.17	9.54	0.20	0.27	0.41	0.66	0.65	0.77	0.90	0.99
1995–1999[c]	2.00	0.85	8.68	4.34	10.21	1.45	1.19	5.94	7.25	0.15	0.25	0.38	0.60	0.54	0.73	0.89	0.99
2000–2002[c]	2.00	0.73	14.33	7.17	19.63	1.70	1.56	8.50	9.24	0.25	0.37	0.50	0.69	0.64	0.82	0.93	0.99

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
Canada																	
1975–1979	8.40	2.45	24.00	2.85	9.77	5.65	2.62	4.24	9.15	0.11				0.70			
1980–1984	13.00	4.53	20.10	1.57	4.43	9.27	3.54	2.16	5.67	0.05				0.49			
1985–1989	18.00	8.03	16.70	0.94	2.07	11.00	4.61	1.51	3.61	0.02				0.23			
1990–1994	22.00	8.63	15.90	0.72	1.66	15.00	5.05	1.06	3.15	0.01	0.02	0.07	0.22	0.11	0.22	0.59	0.93
1995–1999^{c}	19.80	9.75	14.45	0.73	1.42	13.20	4.59	1.07	2.98	0.00	0.02	0.07	0.23	0.08	0.22	0.57	0.94
2000–2002^{c,d}	16.00	5.15	16.02	1.00	1.47	19.03	5.37	0.77	2.75	0.00	0.01	0.05	0.17	0.05	0.20	0.53	0.92
Czechoslovakia																	
1975–1979	1.00		4.61	4.61		0.85	0.65	5.42	7.03	0.11				0.58			
1980–1984	1.00		0.77	0.77		0.51	0.36	1.51	2.13	0.02				0.22			
1985–1989	1.00		0.88	0.88		0.54	0.31	1.62	2.83	0.02				0.24			
Japan																	
1990–1994	1.00	0.11	3.28	3.28	29.06	1.79	1.11	1.84	2.96	0.01	0.04	0.12	0.36	0.09	0.29	0.61	0.94
1995–1999^{c}	1.00	0.11	2.30		24.36	1.77	0.22	2.30	14.21	0.00	0.00	0.10					
2000–2002^{c,d,i}	1.00	0.07	1.85		40.25	1.64	0.10	1.85	17.25	0.00	0.01	0.06					
Pakistan																	
1990–1994	1.00	0.48	1.87	1.87	3.92	0.65	0.54	2.89	3.23	0.02	0.07	0.20	0.51	0.14	0.32	0.65	0.95
1995–1999^{c}	0.60	0.02	1.24	2.07	59.24												
2000–2002^{c}	0.75	0.04	2.55	3.39	71.65												
Rep. of Korea																	
1983–1984	1.00	0.41	0.65	0.65	1.58	0.72		0.90									
1985–1989	1.00	0.59	1.13	1.13	1.91	0.81		1.40									
1995–1999^{c}	2.20	1.18	2.56	1.17	2.18												
2000–2002^{c}	4.00	2.56	2.65	0.71	1.11												
Romania																	
1995–1999^{c}	0.60	0.36	0.19	0.32	0.53	1.64	0.25	0.10	0.58	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.74
2000–2002^{c}	1.00	0.61	0.60	0.60	0.99	0.84	0.40	1.01	1.36	0.00	0.00	0.01	0.21	0.00	0.00	0.12	0.83

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)*[b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total HWR																	
1975–1979	9.40	2.71	28.50	3.03	10.50	6.08		4.68		0.12				0.71			
1980–1984	16.60	5.13	40.90	2.47	7.97	12.80		3.20		0.08				0.58			
1985–1989	25.00	9.61	59.00	2.36	6.14	17.30		3.41		0.07				0.48			
1990–1994	24.00	9.25	27.90	1.16	3.02	16.50	6.31	1.69	4.43	0.02	0.04	0.10	0.26	0.34	0.46	0.72	0.96
1995–1999[c]	26.20	12.26	29.42	1.12	2.40	18.05	6.25	1.63	4.71	0.04	0.07	0.14	0.29	0.21	0.32	0.49	0.89
2000–2002[c]	24.75	9.16	38.00	1.54	4.15	23.20	7.43	1.64	5.12	0.06	0.10	0.16	0.36	0.23	0.34	0.53	0.91
World HWR																	
1975–1979	12	3	32	2.6	11.0	7		4.8		0.12				0.71			
1980–1984	19	6	46	2.4	8.0	14		3.2		0.07				0.58			
1985–1989	26	10	60	2.3	6.2	18	1	3.4		0.07				0.48			
1990–1994	31	12	35	1.1	3.0	20	8	1.7	4.4	0.02	0.04	0.10	0.26	0.34	0.46	0.72	0.96
1995–1999[c]	34	12	29	1.2	2.4	18	6	1.6	4.7	0.04	0.07	0.14	0.29	0.21	0.32	0.49	0.89
2000–2002[c]	39	13	38	1.0	2.9	23	7	1.6	5.1	0.06	0.10	0.16	0.36	0.23	0.34	0.53	0.91
GCR																	
France																	
1990–1994	2.00	0.32	0.58	0.29	1.78												
1995–1999																	
2000–2002																	
Japan																	
1979	1.00	0.10	1.00	1.00	10.00	1.59	0.81	0.63	1.23	0.00							
1980–1984	1.00	0.10	1.00	1.00	10.00	2.13	0.95	0.47	1.05	0.00				0.02			
1985–1989	1.00	0.10	1.00	1.00	10.00	2.01	0.84	0.50	1.19	0.00				0.01			
1990–1994	1.00	0.08	0.42	0.42	4.99	1.74	0.54	0.24	0.78	0.00	0.00	0.01					
1995–1999[c]	0.60	0.07	0.20	0.34	2.86	1.62		0.17		0.00	0.00	0.00					
2000–2002[c,d,i]	-	0.00	0.25			1.28		0.19		0.00	0.00	0.01					

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Spain																	
1975–1979	1.00	0.37	0.30	0.30	0.80	0.07		3.98									
1980–1984	1.00	0.36	0.37	0.37	1.02	0.18		2.08									
1985–1989	1.00	0.33	0.28	0.28	0.85	0.25	0.13	1.12	2.18								
1990–1994																	
1995–1999																	
2000–2002																	
United Kingdom																	
1975–1979	30.00	3.40	24.50	0.82	7.20	8.56		2.86		0.02							
1980–1984	32.00	4.40	26.40	0.82	6.00	18.00		1.46		0.00							
1985–1989	37.00	6.09	19.50	0.52	3.20	25.40		0.77		0.00							
1990–1991	36.00	7.72	15.00	0.42	1.94	26.40		0.57		0.00							
1995–1999[c]	34.00	9.88	6.90	0.23	0.78	19.55	19.55	0.35	0.35								
2000–2002[c]	22.50	1.65	4.00	0.13	0.33	16.72	16.72	0.24	0.24								
Total GCR																	
1975–1979	31.20	3.79	25.00	0.80	6.59	8.95		2.80		0.02							
1980–1984	34.00	4.86	27.80	0.82	5.72	20.30		1.37		0.01							
1985–1989	39.20	6.52	20.80	0.53	3.19	27.60		0.75		0.00				0.01			
1990–1994	39.00	8.14	15.90	0.41	1.96												
1995–1999[c]	34.60	9.95	7.10	0.21	0.71	21.17	19.55	0.34	0.36								
2000–2002[c]	22.50	1.65	4.25	0.19	2.57	18.00	16.72	0.24	0.25								
World GCR																	
1975–1979	40	5	36	0.9	6.6	13		2.8									
1980–1984	41	6	34	0.8	5.8	25		1.4									
1985–1989	44	7	24	0.5	3.2	31		0.8									
1990–1994	38	8	16	0.4	2.0	30		0.5									
1995–1999[c]	35	10	7	0.2	0.7	21	20	0.3	0.4								
2000–2002[c]	23	2	4	0.2	2.6	18	17	0.2	0.3								

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
LWGR																	
Lithuania[g]																	
1990–1994	2.00		16.06	8.03													
1995–1999[c]	2.00	1.40	15.08	7.54	10.76												
2000–2002[c]	2.00	1.41	8.58	4.29	6.09												
Russian Fed.[d]																	
1990–1994	10.40		100.60	9.67													
1995–1999																	
2000–2002																	
Ukraine																	
1995–1999	0.20	0.08	2.29	11.47	30.29												
2000–2002	0.25	0.19	0.06	0.24	0.32												
Total LWGR																	
1990–1994	12.40		116.66				116.70										
1995–1999[c]	2.20	1.48	17.37	7.90	11.74												
2000–2002[c]	2.25	1.60	8.64	3.84	5.40												

Country/area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Annual collective effective dose*			*Number of workers*		*Average annual effective dose (mSv)* [b]		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
			Average (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv /(GW a))*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
World LWGR																	
1978–1979	12	4	36	3.0	8.2	5		6.6									
1980–1984	16	8	62	3.8	8.3	10		6.4									
1985–1987	20	10	173	8.7	16.7	13		13.2									
1990–1994	20	9	190	9.4	20.3												
1995–1999																	
2000–2002																	

[a] Data are annual values averaged over the periods indicated.

[b] The different procedures for the recording and inclusion of doses in the database may result in large variability of doses between utilities and between countries.

[c] Data for the periods 1995–1999 and 2000–2003 from the OECD-IAEA ISOE database [L5]; except number of workers and effective dose, which were from the UNSCEAR Survey.

[d] Data from Rosenergoatom Concern Annual Report [R22].

[e] Data for 1975–1989 are for Czechoslovakia.

[f] Data for 1975–1989 cover the Federal Republic of Germany and the German Democratic Republic. Within the period 1990–1994, the data for 1990 relate to the Federal Republic of Germany.

[g] Calculation of distribution ratios based on data from 1993 and 1994.

[h] Calculation of *SR* distribution ratios based on data from 1993 and 1994.

[i] Number of measurably exposed workers and their effective dose above 5 mSv for the periods 1995–1999 and 2000–2002.

[j] NR_{15} refers to NR_{20}.

[k] Excludes data from the Russian Federation.

[l] Before 1985 data are for the USSR.

Table A-22 Exposures to workers from fuel reprocessing[a]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	Period	Average annual amount of fuel processed (kt U)	Electrical energy equivalent (GW a)	Monitored workers (10^3)	Measurably exposed workers (10^3)	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/ kt U)	Average per unit energy generated (man Sv/ (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	0.36	1.46	4.35	2.97	12.80			2.94	4.31	0.06				0.29			
	1980–1984	0.38	3.87	6.70	3.89	14.10			2.10	3.62	0.01				0.11			
	1985–1989	0.43	8.85	9.28	3.86	12.50			1.35	3.25	0.01				0.12			
	1990–1994			13.00	3.31	4.72			0.36	1.43	0.00	0.00	0.01	0.26				
	1995–1999		1.40															
	2000–2002		1.39															
India	1981–1984			1.48	1.27	6.76			4.57	5.33	0.09				0.46			
	1985–1989			1.66	1.32	5.53			3.34	4.19	0.05				0.31			
	1990–1994[c]			1.66	1.32	5.53												
	1995–1999																	
	2000–2002																	
Japan	1975–1979	0.01		0.84		0.38	38.00		0.44		0.00							
	1980–1984	0.03		1.37		1.23	41.00		0.89		0.00							
	1985–1989	0.05		1.87		1.83	35.20		0.98		0.01							
	1990–1994	0.07	1.40	2.58	0.71	0.82	11.10	0.60	0.32	1.15	0.00	0.00	0.01	0.08	0.03	0.03	0.13	0.64
	1995–1999	0.03	0.50	3.79		0.31	12.40	0.62	0.08									
	2000–2002	0.02	0.49	4.08		0.50	20.83	1.02	0.11									
Russian Fed.	1990–1994			12.00	11.50	33.90			2.82	2.96					0.19			
	1995–1999																	
	2000–2002																	

Country	*Period*	*Average annual amount of fuel processed (kt U)*	*Electrical energy equivalent (GW a)*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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/ kt U)*	*Average per unit energy generated (man Sv/ (GW a))*	*Monitored workers*	*Measurably exposed workers*	*NR_{15}*	*NR_{10}*	*NR_5*	*NR_1*	*SR_{15}*	*SR_{10}*	*SR_5*	*SR_1*
United Kingdom	1977–1979	0.72	2.17	5.61		46.60	65.00	21.50	8.31		0.19							
	1980–1984	0.97	2.94	6.62		40.10	41.00	13.60	6.05		0.14							
	1985–1989	0.89	2.69	7.22		29.40	33.00	11.00	4.07		0.10							
	1990–1994			10.20		20.70			2.03		0.00	0.03	0.12		0.08			
	1995–1999			9.63		11.51			1.20									
	2000–2002		1.24	12.63		10.02			0.79									
United States	1975–1979		1.41	2.65	2.05	10.80			4.06	5.27								
	1980–1984		1.09	2.95	2.06	7.43			2.51	3.61								
	1985–1989		1.18	3.21	1.78	4.89			1.52	2.74								
	1990–1994[d]			5.61	1.99	1.64			0.30	0.82								
	1995–1999																	
	2000–2002																	
World[e]	1975–1979			8		53			7.1									
	1980–1984			9		46			4.9									
	1985–1989			17		36			3.0		0.05							
	1990–1994			45	24	67			1.5	2.8					0.13			
	1995–1999			59		61			1.1									
	2000–2002			76		68			0.9									

[a] Data are annual values averaged over the periods indicated.

[b] Values based on the monitored workforce; if not available, values based on the measurably exposed workers.

[c] No data were 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 USDOE facilities is mainly associated with defence activities rather than commercial fuel reprocessing [U21].

[e] Great care should be taken when comparing different periods. In particular, the world estimates for the periods from 1975 to 1989 were based on the French and United Kingdom operations, because the other major contribution, from the United States, was considered to be more concerned with defence activities. The data for 1990–1994 cover all contributions, and in particular a contribution from the Russian Federation, which accounts for some 50% of the annual collective effective dose.

Table A-23 Exposures to workers from research related to the nuclear fuel cycle[a]
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.20	0.01	0.20	1.00	20.00								
	1980–1984	0.20	0.01	0.17	0.85	17.00								
	1985–1989	0.13	0.02	0.07	0.54	3.90								
	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
	1995–1999	0.07	0.05	0.05	0.70	0.95	0.00	0.00	0.01	0.17	0.00	0.00	0.14	0.61
	2000–2002	0.07	0.06	0.05	0.67	0.77	0.00	0.00	0.00	0.20	0.00	0.00	0.04	0.61
Canada[b]	1975–1979	4.49	3.94	13.50	2.95	3.36	0.01				0.44			
	1980–1984	4.56	4.30	11.10	2.43	2.57	0.04				0.41			
	1985–1989	4.20	3.97	6.10	1.45	1.54	0.03				0.40			
	1990–1994	4.12	3.25	6.00	1.46	1.85	0.02	0.04	0.07	0.25	0.23	0.39	0.54	0.78
	1995–1999	3.33	2.56	3.90	1.17	1.52	0.01	0.03	0.06	0.19	0.07	0.29	0.50	0.74
	2000–2002	2.58	2.15	2.87	1.11	1.33	0.00	0.02	0.06	0.19	0.03	0.20	0.46	0.72
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			
	1995–1999	0.30	0.14	0.04	0.12	0.27	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.11
	2000–2002	0.30	0.23	0.08	0.25	0.31	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.26
China	1990–1994	1.27	0.90	1.00	0.79	1.10	0.01	0.01	0.03	0.14	0.26	0.35	0.50	0.77
	1995–1999	0.72	0.46	0.36	0.50	0.79	0.00	0.01	0.01	0.12	0.11	0.16	0.27	0.66
	2000–2002	0.58	0.49	0.34	0.58	0.66	0.00	0.00	0.01	0.15	0.01	0.04	0.18	0.60

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Czech Rep.[d]	1975–1979	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									
	1995–1999	0.72	0.46	0.36	0.50	0.79	0.00	0.01	0.01	0.12	0.11	0.16	0.27	0.66
	2000–2002	0.58	0.49	0.34	0.58	0.66	0.00	0.00	0.01	0.15	0.01	0.04	0.18	0.60
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
	1995–1999	0.75	0.16	0.20	0.27	1.23	0.00	0.00	0.01	0.08	0.00	0.01	0.29	0.80
	2000–2002	0.53	0.08	0.07	0.13	0.96	0.00	0.00	0.00	0.04	0.00	0.00	0.21	0.71
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
	1995–1999													
	2000–2002													
France	1975–1979	20.90	3.19	9.32	0.44	2.92	0.01							
	1980–1984	21.00	2.86	8.47	0.40	2.97	0.00							
	1985–1989	19.60	2.48	6.14	0.31	2.47	0.00							
	1990–1994	16.30	1.87	3.68	0.23	1.97	0.00	0.00	0.01	0.11				
	1995–1999	9.69		2.56	0.26		0.00	0.00	0.00	0.01				
	2000–2002	13.85		1.57	0.11		0.00	0.00	0.00	0.02				

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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									
	1995–1999													
	2000–2002													
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								
	1995–1999	0.15	0.01	0.01	0.06	1.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.67
	2000–2002	0.13	0.01	0.01	0.08	0.86	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.62
India	1980–1984	2.78	1.97	6.36	2.29	3.23	0.03				0.36			
	1985–1989	3.62	2.38	4.65	1.28	1.96	0.01				0.18			
	1995–1999													
	2000–2002													
Indonesia[h]	1975–1979	0.02		0.09	3.87		0.13				0.37			
	1980–1984	0.03	0.04	0.10	2.72	3.10	0.16				0.72			
	1985–1989	0.10	0.10	0.09	0.95	0.95	0.03				0.47			
	1995–1999													
	2000–2002													
Italy	1985–1989	2.44	0.45	0.26	0.11	0.58	0.00				0.01			
	1990–1994													
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Japan[i]	1978–1979	4.12		2.13	0.52		0.00							
	1980–1984	7.01		7.97	1.14		0.02							
	1985–1989	9.18		7.72	0.84		0.01							
	1990–1994	8.15	1.04	1.53	0.19	1.48	0.00	0.00	0.01	0.05	0.01	0.10	0.38	0.83
	1995–1999	5.47		0.79	0.14									
	2000–2002	5.43		0.67	0.12									
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
	1995–1999	0.22	0.04	0.01	0.04	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.16	0.02	0.00	0.03	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Norway[j]	1980–1984	0.68	0.14	0.53	0.77	3.76	0.01				0.34			
	1985–1989	0.76	0.15	0.58	0.76	3.88	0.01				0.35			
	1990–1994	0.20	0.09	0.17	0.85	1.83	0.00	0.00	0.04	0.23				
	1995–1999													
	2000–2002													
Rep.of Korea[k]	1975–1979	0.25		0.12	0.46		0.00							
	1980–1984	0.79	0.14	0.50	0.64	3.58	0.01							
	1985–1989	0.99	0.15	0.65	0.65	4.36	0.01							
	1995–1999													
	2000–2002													
Romania	1995–1999	0.90	0.58	2.59	2.89	4.44	0.00	0.01	0.24	0.60	0.01	0.04	0.56	0.99
	2000–2002	0.89	0.78	1.56	1.75	2.17	0.00	0.00	0.01	0.55	0.00	0.01	0.04	0.97
Russian Fed.	1992–1994		6.74	16.10		2.39	0.02				0.13			
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Slovakia	2000–2002	0.20	0.10	0.16	0.79	1.66	0.00	0.02	0.04	0.16				
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
	1995–1999													
	2000–2002													
South Africa	1975–1979	0.25		0.12	0.46		0.00				0.07			
	1980–1984	0.24		0.08	0.33		0.00				0.09			
	1985–1989	0.23		0.07	0.34									
	1990–1994	0.05	0.03	0.02	0.35	0.72	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.44
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
Switzerland	1995–1999	0.07		0.08	1.20									
	2000–2002	0.04		0.02	0.50									
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
	1995–1999													
	2000–2002													
United Kingdom	1975–1979	8.49		37.40	4.40		0.09							
	1980–1984	9.00		28.20	3.13		0.05							
	1985–1989	9.40		24.00	2.55		0.03							
	1990–1994	5.63		5.60	1.00									
	1995–1999	5.89		1.24	0.21									
	2000–2002	5.70		1.01	0.18									
United States	1975–1979	30.30	14.80	33.00	1.09	2.24								
	1980–1984	28.80	12.70	24.20	0.84	1.90								
	1985–1989	31.70	11.90	19.20	0.60	1.61								
	1990–1994													
	1995–1999	20.00	2.74	2.40	0.12	0.87	0.00	0.00	0.00	0.03				
	2000–2002	22.03	2.12	1.70	0.08	0.80	0.00	0.00	0.00	0.02				

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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
Total[l, m]	1975–1979	63.40		96.30	1.52		0.04				0.42			
	1980–1984	75.50		89.40	1.18		0.02				0.39			
	1985–1989	82.60		66.00	0.80		0.30				0.30			
	1990–1994	46.30	16.40	35.90	0.77	2.18	0.22	0.01	0.02	0.13	0.22	0.36	0.52	0.78
	1995–1999	48.26	7.19	14.59	0.30	2.03	0.00	0.00	0.03	0.12	0.03	0.07	0.23	0.58
	2000–2002	52.87	6.43	10.28	0.19	1.60	0.00	0.00	0.01	0.12	0.01	0.03	0.12	0.56
World[n]	1975–1979	120		170	1.4									
	1980–1984	130		150	1.1									
	1985–1989	130		100	0.8			0.01			0.30			
	1990–1994	120	36	90	0.8	2.5	0.00	0.01	0.02	0.13	0.22	0.36	0.52	0.78
	1995–1999	96	13	37	0.4	2.8	0.00	0.00	0.05	0.12	0.03	0.07	0.22	0.57
	2000–2002	90	9	36	0.4	4.0	0.00	0.00	0.01	0.12	0.02	0.06	0.17	0.60

[a] Data are annual values averaged over the periods indicated.

[b] Data are for research activities conducted by Ontario Hydro and Atomic Energy of Canada Ltd (AECL); for 1975–1987, the data contain a component arising from isotope production, which was then being conducted by AECL.

[c] Includes data for fuel research, a research reactor and radioisotope production.

[d] Data for 1975–1989 are for 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] Data for 1975–1989 are from the Federal Republic of Germany and cover only research and prototype reactors.

[g] Includes only workers employed at the research reactor of the Atomic Energy Institute; some nuclear fuel cycle research may be carried out at other research and university institutes.

[h] Data for workers at research reactors.

[i] Includes exposures to workers at test and research reactors, aboard a nuclear ship, at critical assemblies and at research facilities for nuclear fuel materials.

[j] Includes only workers at the Institute of Energy Technology.

[k] Includes exposures of workers at TRIGA research reactors and other fuel research facilities.

[l] Total of reported data. In the total for the monitored workers, the measurably exposed value for the Russian Federation is included.

[m] The total reported for measurably exposed workers has been increased pro rata to the data for monitored workers to take account of countries that reported the number of monitored workers but not of 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 A-24 Exposures to workers from medical uses of radiation[a]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	2.20	0.83	2.89	1.31	3.46	0.02				0.56			
	1994	5.99	2.28	9.00	1.50	3.96	0.04	0.04	0.05	0.17	0.61	0.63	0.69	0.93
	1995–1999													
	2000–2002													
Australia[c, d]	1975–1979	3.22		1.70	0.53									
	1985–1989	6.21	4.42	0.37	0.06	0.08								
	1990–1994	8.19	5.52	1.04	0.13	0.19	0.00	0.00	0.00	0.01	0.20	0.22	0.27	0.43
	1995–1999													
	2001	8.99		0.72	0.08									
Belarus	2000–2002	3.18	3.18	3.94	1.24	1.24	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.95
Brazil[e]	1985–1989	3.93	1.01	2.99	0.76	2.97	0.01				0.34			
	1990–1994	4.29	0.50	1.40	0.33	2.58	0.00	0.01	0.01	0.05	0.35	0.46	0.63	0.91
	1995–1999[y]	4.68	1.23	5.26	1.12	4.22	0.01	0.03	0.06	0.14				
	2000–2002[y]	7.55	1.47	5.40	0.72	3.73	0.01	0.02	0.04	0.11				
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
	1995–1999	2.81	0.25	0.80	0.29	4.29	0.00	0.00	0.00	0.03	0.00	0.01	0.04	0.22
	2000–2002													
Canada	1975–1979	8.40	4.50	3.23	0.38	0.72	0.00				0.07			
	1980–1984	9.50	2.00	1.71	0.18	0.87	0.00				0.04			
	1985–1989	10.70	2.70	1.75	0.16	0.64	0.00				0.03			
	1990–1994	13.20	2.52	1.35	0.10	0.53	0.00	0.00	0.00	0.02	0.05	0.06	0.11	0.47
	1995–1999	14.03	2.14	1.26	0.09	0.60	0.00	0.00	0.00	0.02	0.05	0.06	0.11	0.46
	2000–2002	14.59	1.91	1.41	0.10	0.75	0.00	0.00	0.00	0.02	0.03	0.06	0.14	0.51
Chile	1995–1999	0.08	0.08	0.10	10.79	10.79	0.01	0.01	0.01	0.30	0.03	0.03	0.03	0.09
	2000–2002	0.15	0.15	0.08	4.39	4.39	0.00	0.00	0.02	0.69	0.00	0.00	0.02	0.35

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
China	1985–1989	78.10	13.30	143.00	1.84	10.80	0.03				0.45			
	1990–1994	12.50	11.70	21.20	1.70	1.80	0.01	0.03	0.05	0.31	0.25	0.34	0.44	0.78
	1995–1999	97.60	63.04	150.89	1.55	2.39	0.01	0.02	0.03	0.31	0.09	0.18	0.27	0.82
	2000	102.91	65.99	121.44	1.18	1.84	0.00	0.01	0.02	0.30	0.07	0.15	0.23	0.95
China - Taiwan Province[f]	1985–1989	3.40		1.49	0.44									
	1990–1994	5.10	0.99	0.74	0.15	0.75								
	1995–1999	6.37	0.49	0.38	0.06	0.79	0.00	0.00	0.00	0.01	0.23	0.27	0.48	0.76
	2000–2002	6.78	0.42	0.41	0.06	0.99	0.00	0.00	0.00	0.01	0.26	0.40	0.54	0.77
Croatia	1990–1994	2.90	1.80	0.50	0.17	0.28								
	1995–1999													
	2000–2002	2.90	0.82	0.50	0.17	0.61	0.00	0.00	0.01	0.03	0.01	0.08	0.27	0.58
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
	1995–1999	0.16	0.16	0.09	0.58	0.58	0.00	0.00	0.00	0.12	0.00	0.00	0.04	0.42
	2000–2002	0.19	0.19	0.17	0.89	0.89	0.00	0.00	0.00	0.33	0.00	0.03	0.03	0.62
Czech Rep.[g]	1975–1979	5.08	1.27	3.16	0.62	2.50	0.00				0.18			
	1980–1984	6.89	2.22	4.48	0.65	2.02	0.00				0.10			
	1985–1989	8.56	2.66	5.84	0.68	2.21	0.00				0.13			
	1990–1994	7.71	3.66	6.04	0.78	1.65	0.00	0.00	0.01	0.16	0.06	0.10	0.18	0.71
	1995–1999	8.03	4.14	7.79	0.97	1.88	0.00	0.01	0.02	0.15	0.09	0.13	0.22	0.47
	2000–2002	9.04	3.14	6.25	0.69	1.99	0.00	0.01	0.02	0.11	0.04	0.11	0.25	0.52
Denmark[h]	1975–1979	4.28		1.01	0.24		0.00							
	1980–1984	4.02		0.64	0.16		0.00				0.02			
	1985–1989	3.82		0.43	0.11		0.00				0.01			
	1990–1994	3.72	1.17	0.48	0.13	0.41	0.00	0.00	0.00	0.02	0.00	0.01	0.07	0.40
	1995–1999	4.17	1.24	0.48	0.11	0.38	0.00	0.00	0.00	0.02	0.00	0.01	0.04	0.37
	2000–2002	4.39	1.09	0.41	0.09	0.38	0.00	0.00	0.00	0.02	0.00	0.00	0.06	0.39
Ecuador[h]	1993–1994	0.66	0.41	0.50	0.77	1.24	0.00	0.01	0.01	0.32				
	1995–1999													
	2000–2002													
El Salvador	2001–2002	0.41	0.41	0.51	1.26	1.26	0.00	0.00	0.00	0.72	0.00	0.00	0.00	0.00

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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	3.88	0.08	0.58	0.15	6.93	0.00				0.46			
	1980–1984	4.37	0.29	0.71	0.16	2.43	0.00				0.15			
	1985–1989	4.82	0.30	0.92	0.19	3.10	0.00				0.28			
	1990–1994	4.71	0.43	1.14	0.24	2.63	0.00	0.00	0.01	0.05	0.27	0.40	0.58	0.91
	1995–1999	4.34	0.66	1.85	0.43	2.79	0.00	0.01	0.02	0.08	0.33	0.44	0.61	0.92
	2000–2002	4.51	0.77	1.70	0.38	2.20	0.00	0.01	0.02	0.07	0.31	0.44	0.62	0.90
France[k]	1975–1979	33.40		39.70	1.19		0.00							
	1980–1984	49.00	6.05	28.30	0.58	4.67	0.00							
	1985–1989	61.80	6.35	20.30	0.33	3.19	0.00							
	1995–1999	87.41		12.74	0.15									
	2000–2002	91.05		8.64	0.09									
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
	1995–1999													
	2000–2002													
Germany[l]	1980–1984	19.20	3.12	2.05	0.11	0.66					0.08			
	1985–1989	20.40	1.17	1.68	0.09	1.44					0.11			
	1995–1999	213.90	23.58	21.82	0.10	0.93	0.00	0.00	0.00	0.03	0.06	0.09	0.19	0.70
	2000–2002	218.30	26.37	16.74	0.08	0.63	0.00	0.00	0.00	0.02	0.04	0.07	0.16	0.61
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
	1995–1999	5.06	0.97	3.55	0.70	3.66	0.01	0.02	0.03	0.10	0.48	0.58	0.73	0.94
	2000–2002	6.43	1.36	3.46	0.54	2.62	0.01	0.01	0.03	0.07	0.39	0.53	0.72	0.92
Hungary	1975–1979	5.96	1.22	2.32	0.39	1.90	0.00				0.11			
	1980–1984	7.49	1.01	1.61	0.22	1.60	0.00				0.09			
	1985–1989	7.26	0.98	1.49	0.21	1.53	0.00				0.08			
	1990–1994	6.76	0.65	0.71	0.10	1.09	0.00	0.00	0.00	0.03	0.04	0.06	0.17	0.67
	1995–1999	7.06	0.41	0.33	0.05	0.94	0.00	0.00	0.00	0.01	0.10	0.10	0.15	0.59
	2000–2002	7.34	2.22	0.99	0.14	0.45	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.32
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
	1995–1999	0.44	0.11	0.09	0.20	0.79	0.00	0.00	0.01	0.04	0.21	0.24	0.37	0.65
	2000–2002	0.42	0.12	0.08	0.18	0.68	0.00	0.00	0.00	0.04	0.07	0.15	0.22	0.58

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
India	1975–1979	6.50	3.64	3.75	0.58	1.03	0.00				0.21			
	1980–1984	8.00	3.97	2.76	0.35	0.70	0.00				0.15			
	1985–1989	10.40	5.42	3.54	0.34	0.65	0.00				0.14			
	1990–1994	10.70	5.59	2.58	0.24	0.42	0.00	0.00	0.01	0.05	0.12	0.18	0.30	0.68
	1995–1999													
	2000–2002													
Indonesia	1975–1979	0.98	0.94	1.59	1.62	1.70	0.00				0.02			
	1980–1984	1.84	1.76	2.94	1.60	1.68	0.00				0.00			
	1985–1989	2.30	2.19	3.84	1.67	1.75	0.00				0.02			
	1995–1999	0.09	0.09	0.06	0.64	0.65	0.00	0.01	0.03	0.18	0.00	0.17	0.44	1.00
	2000–2002	0.20	0.20	0.09	0.46	0.46	0.00	0.00	0.02	0.17	0.00	0.12	0.45	1.00
Ireland	1985–1989	1.46	0.12	0.55	0.38	4.69								
	1991–1994	1.43	0.15	0.09	0.06	0.60	0.00	0.00	0.00	0.01	0.00	0.03	0.11	0.48
	1995–1999													
	2000–2002													
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
	1995–1999	0.55	0.55	0.52	0.94	0.94	0.01	0.01	0.02	0.17	0.25	0.32	0.38	0.80
	2000–2002	0.57	0.57	0.42	0.74	0.74	0.01	0.01	0.02	0.11	0.29	0.35	0.44	0.73
Lithuania	1995–1999	1.70	1.26	2.40	1.41	1.91	0.00	0.00	0.01	0.74	0.02	0.04	0.09	0.98
	2000–2002	1.73	0.76	1.89	1.09	2.49	0.00	0.00	0.02	0.44	0.01	0.03	0.12	0.70
Luxembourg	1995–1999	0.64	0.34	0.33	0.51	0.85	0.01	0.01	0.01	0.06	0.00	0.00	0.00	0.00
	2000–2002	0.69	0.37	0.30	0.44	0.65	0.01	0.01	0.01	0.06	0.00	0.00	0.00	0.00
Malta	1995–1999	0.27	0.01	0.03	0.11	2.38	0.00	0.00	0.00	0.01	0.71	0.71	0.75	0.79
	2000–2002	0.35	0.04	0.05	0.14	1.68	0.00	0.00	0.00	0.01	0.68	0.68	0.74	0.83
Myanmar	1990–1994	0.03	0.03	0.02	0.62	0.63	0.00	0.00	0.00	0.04				
	1995–1999	0.15	0.15	0.05	0.36	0.36	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.02
	2000–2002	0.26	0.26	0.11	0.44	0.44	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.01
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
	1995–1999	11.69	4.65	6.25	0.53	1.34	0.00	0.00	0.01	0.07	0.12	0.16	0.10	0.51
	2000–2002	12.91	4.93	5.53	0.43	1.12	0.00	0.00	0.01	0.06	0.05	0.09	0.20	0.45

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Norway[m]	1990–1992	2.92	0.98	2.29	0.78	2.32	0.01	0.01	0.04	0.14				
	1995–1999													
	2000–2002	3.72	1.05	2.17	0.58	2.07	0.01	0.01	0.03	0.11				
Pakistan	1990–1994	0.64	0.62	2.30	3.60	3.99	0.07	0.09	0.15	0.40	0.60	0.07	0.79	0.93
	1995–1999													
	2000–2002													
Peru	1980–1989	1.37		4.95	3.61									
	1985–1989	1.48		5.10	3.45									
	1994	1.90	1.59	4.94	2.60	3.10	0.06	0.09	0.13	0.42				
	1995–1999	0.03	0.03	0.10	3.14	3.14	0.04	0.08	0.15	0.64	0.33	0.49	0.67	0.93
	2000–2002	0.03	0.03	0.05	1.57	1.57	0.00	0.00	0.02	0.65	0.00	0.00	0.12	0.85
Philippines	1995–1999	2.26	0.08	0.14	0.06	1.41	0.00	0.00	0.00	0.01	0.03	0.09	0.41	0.89
	2000–2002	2.32	0.23	0.18	0.08	0.74	0.00	0.00	0.00	0.02	0.20	0.22	0.31	0.71
Romania	1995–1999	3.70	3.63	4.58	1.24	1.26	0.00	0.00	0.01	0.77	0.03	0.03	0.05	0.87
	2000–2002	6.49	4.52	3.43	0.54	0.84	0.00	0.00	0.00	0.20	0.03	0.04	0.07	0.85
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	
	1995–1999													
	2000–2002	3.72	3.71	6.45	1.79	1.79	0.00	0.01	0.03	0.78				
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
	1995–1999													
	2000–2002	1.87	0.89	0.39	0.21	0.44	0.00	0.00	0.00	0.04	0.01	0.01	0.10	0.46
Spain	1985–1989	34.30	30.90	25.90	0.76	0.84	0.00				0.12			
	1990–1994													
	1995–1999													
	2000–2002	40.24	24.10	16.30	0.41	0.68	0.00	0.00	0.01	0.10	0.08	0.11	0.17	0.59
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
	1995–1999													
	2000–2002													
Sweden	1999	3.04	1.76	0.83	0.27	0.47	0.00	0.00	0.00	0.06	0.00	0.00	0.01	0.35
	2000–2002	3.72	1.39	0.77	0.21	0.56	0.00	0.00	0.00	0.06	0.03	0.03	0.11	0.54

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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 Rep.	1990–1994	0.80	0.07	2.42	3.03	4.40	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.12
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
United Kingdom[n]	1991	13.70		1.40	0.10									
	1995–1999													
	2001	10.46		1.48	0.14									
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
	1995–1999													
	2000–2002													
Total reported data[o, p]	1975–1979	65.70		54.80	0.84		0.00				0.14			
	1980–1984	104.00		48.30	0.47		0.00				0.08			
	1985–1989	213.00		194.00	0.91		0.02				0.40			
	1990–1994	135.00	54.90	76.70	0.57	1.40	0.01	0.01	0.02	0.10	0.27	0.35	0.46	0.75
	1995–1999	480.25	111.04	222.62	0.46	2.00	0.00	0.01	0.02	0.17	0.13	0.17	0.26	0.61
	2000–2002	577.78	152.00	212.13	0.37	1.40	0.00	0.00	0.01	0.19	0.10	0.14	0.22	0.59
World[q]	1975–1979	630.00		600.00	0.94		0.00				0.11			
	1980–1984	1060.00		720.00	0.68		0.00				0.10			
	1985–1989	1350.00		760.00	0.56		0.00				0.22			
	1990–1994	950.00	350.00	470.00	0.50	1.34	0.00	0.01	0.02	0.09	0.19	0.30	0.44	0.77
		[840]	[330]	[485]	[0.57]	[1.47]	0.00	[0.01]	[0.02]	[0.1]	[0.19]	[0.29]	[0.43]	[0.76]
	1995–1999	6670.00		3300.00	0.50		0.00	0.01	0.02	0.18	0.13	0.35	0.48	0.78
	2000–2002	6670.00		3300.00	0.50		0.00	0.01	0.02	0.19	0.10	0.36	0.48	0.79
Dental radiology														
Argentina	1985–1989	0.07	0.04	0.03	0.46	0.74	0.01				0.42			
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	1.16												
	1985–1989	3.80	1.60	0.02	0.00	0.01								
	1990–1994	3.88	1.58	0.08	0.02	0.05	0.00	0.00	0.00	0.00	0.24	0.24	0.31	0.41
	1995–1999													
	2001	3.73		0.03	0.01									
Belarus	2000–2002	0.11	0.11	0.17	1.49	1.49	0.00	0.00	0.01	0.78	0.00	0.00	0.03	1.00
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
	1995–1999[y]	0.05	0.00	0.00	0.06	0.89	0.00	0.00	0.00	0.01				
	2000–2002[y]	0.06	0.00	0.00	0.02	0.19	0.00	0.00	0.00	0.01				
Bulgaria	1992	0.20	0.00	0.04	0.21		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1995–1999	0.13	0.00	0.03	0.21	12.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	2000–2002													
Canada	1975–1979	13.10	0.97	0.42	0.03	0.44	0.00				0.11			
	1980–1989	19.50	0.94	0.60	0.31	0.64	0.00				0.13			
	1985–1989	24.40	0.94	0.64	0.03	0.68	0.00				0.28			
	1990–1994	26.80	0.20	0.25	0.01	1.24	0.00	0.00	0.00	0.00	0.54	0.62	0.65	0.77
	1995–1999	29.06	0.39	0.23	0.01	0.67	0.00	0.00	0.00	0.00	0.14	0.18	0.29	0.52
	2000–2002	31.33	0.42	0.31	0.01	0.79	0.00	0.00	0.00	0.00	0.37	0.38	0.42	0.53
Chile	1995–1999	0.02	0.02	0.03	1.40	1.40	0.02	0.02	0.03	0.34	0.58	0.58	0.62	0.95
	2000–2002	0.04	0.04	0.06	1.77	1.77	0.00	0.00	0.01	0.57	0.00	0.00	0.03	0.59
China	1995–1999	0.19	0.01	0.01	0.03	0.67	0.00	0.00	0.00	0.00	0.83	0.83	1.07	1.18
- Taiwan Province	2000–2002	0.41	0.01	0.00	0.01	0.24	0.00	0.00	0.00	0.00	0.00	0.52	0.52	0.67
Croatia	1990–1994	0.45	0.03	0.05	0.10	1.67								
	1995–1999													
	2000–2002	0.33	0.08	0.02	0.06	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10
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
	1995–1999	0.02	0.02	0.01	0.39	0.39	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
	2000–2002	0.01	0.01	0.01	0.67	0.67	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Ecuador[h]	1993–1994	0.08	0.05	0.05	0.66	0.93	0.00	0.00	0.01	0.26				
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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}*
El Salvador	2002	0.07	0.07	0.07	1.00	1.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00
Finland	1990–1994	0.18	0.00	0.00	0.00		0.00	0.00	0.00	0.00				
	1995–1999	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
France[k]	1975–1979	6.17		2.61	0.42		0.00							
	1980–1984	11.20	0.74	2.42	0.22	3.25	0.00							
	1985–1989	16.70	0.86	1.97	0.12	2.31	0.00							
	1995–1999	22.48		1.41	0.06									
	2000–2002	24.78		0.88	0.04									
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
	1995–1999	4.54	0.12	0.12	0.03	1.05	0.00	0.00	0.00	0.00	0.26	0.31	0.41	0.75
	2000–2002	3.56	0.10	0.04	0.01	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.52
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
	1995–1999	0.04	0.00	0.01	0.18	2.19	0.00	0.00	0.02	0.04	0.00	0.00	0.57	0.89
	2000–2002	0.04	0.01	0.00	0.13	1.05	0.00	0.00	0.01	0.03	0.00	0.00	0.54	0.84
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								
	1995–1999	0.09	0.00	0.00	0.05	1.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.12	0.02	0.01	0.05	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iceland	1990–1994	0.04	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	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			
	1995–1999	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.20	0.00	0.00	0.00	0.00
	2000–2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
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
	1995–1999													
	2000–2002													
Italy	1985–1989	1.01	0.39	0.07	0.07	0.19	0.00				0.28			
	1995–1999													
	2000–2002													
Japan	1975–1979	0.35	0.08	0.13	0.36	1.68								
	1980–1984	1.75	0.20	0.34	0.20	1.69								
	1985–1989	3.53	0.35	0.56	0.16	1.60								
	1990–1994	5.40	0.45	0.57	0.11	1.29	0.00	0.00	0.00	0.03	0.22	0.29	0.40	0.82
	1995–1999	5.80	0.40	0.45	0.08	1.12	0.00	0.00	0.00	0.02				
	2000–2002	6.64	0.36	0.55	0.08	1.52	0.00	0.00	0.00	0.02				
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
	1995–1999	0.06	0.06	0.02	0.28	0.31	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.31
	2000–2002	0.06	0.06	0.02	0.37	0.37	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.49
Lithuania	1995–1999	0.23	0.09	0.20	0.84	2.98	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.61
	2000–2002	0.41	0.10	0.33	0.82	3.42	0.00	0.00	0.00	0.24	0.00	0.00	0.00	0.36
Luxembourg	1995–1999	0.12	0.06	0.03	0.24	0.48	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
	2000–2002	0.06	0.03	0.02	0.29	0.77	0.00	0.00	0.00	0.09	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				
	1995–1999													
	2000–2002													
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
	1995–1999	4.25	0.51	0.12	0.03	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	4.74	0.37	0.09	0.02	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Norway	1990–1992	0.07	0.00	0.00	0.01	0.28	0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002	0.02	0.00	0.00	0.00	0.00	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
	1995–1999													
	2000–2002													
Philippines	1995–1999	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
	2000–2002	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Romania	1995–1999	0.38	0.38	0.47	1.25	1.26	0.00	0.00	0.00	0.98	0.00	0.00	0.03	1.00
	2000–2002	0.40	0.30	0.28	0.71	1.00	0.00	0.00	0.00	0.43	0.00	0.00	0.02	0.90
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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002	0.31	0.11	0.03	0.10	0.28	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.28
South Africa	1975–1979	2.27	1.06	0.12	0.05	0.11								
	1980–1984	2.82	0.53	1.52	0.54	2.88	0.00				0.64			
	1985–1989	3.33	0.37	4.49	1.35	12.20	0.00				0.18			
	1995–1999													
	2000–2002													
Spain	1985–1989	1.29	1.21	1.56	1.21	1.30	0.01				0.10			
	1990–1994													
	1995–1999													
	2000–2002	11.44	8.39	8.26	0.72	0.98	0.00	0.00	0.01	0.22	0.12	0.15	0.19	0.74
Sweden	1992–1994	0.29		0.01	0.04									
	1999	0.09	0.03	0.00	0.07	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.11	0.02	0.00	0.04	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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[s]	1975–1979	7.09		1.21	0.17		0.00				0.07			
	1980–1984	9.13		0.96	0.11		0.00				0.89			
	1985–1989	10.70		0.26	0.03		0.00				0.02			
	1990–1994	11.00		0.25	0.02		0.00	0.00	0.00	0.00	0.16	0.16	0.20	0.38
	1995–1999	11.84	0.66	0.16	0.01	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.20
	2000–2002	12.71	0.43	0.10	0.01	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.21
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	28.00	0.71
	1995–1999													
	2000–2002													
United Kingdom[n]	1980–1984	20.00		2.00	0.10									
	1985–1989	20.00		2.00	0.10									
	1991	20.00		2.00	0.10									
	1995–1999													
	2001	11.70		0.98	0.08									
United States[t]	1975–1979	215.00		80.00	0.37									
	1980–1984	259.00		60.00	0.23									
	1985–1989	307.00	61.00	12.00	0.04	0.20								
	1995–1999													
	2000–2002													
Total reported data[o, p]	1975–1979	242.00		84.50	0.35		0.00				0.08			
	1980–1984	322.00		68.80	0.21		0.00				0.08			
	1985–1989	391.00		18.50	0.05		0.00				0.12			
	1990–1994	81.40	5.31	3.97	0.05	0.75	0.00	0.00	0.00	0.00	0.28	0.33	0.40	0.64
	1995–1999	79.55	2.77	3.31	0.04	1.19	0.00	0.01	0.01	0.10	0.11	0.11	0.18	0.38
	2000–2002	113.37	11.04	12.26	0.11	1.11	0.00	0.00	0.00	0.11	0.02	0.05	0.09	0.34

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
World[q]	1975–1979	370.00		120.00	0.32									
	1980–1984	500.00		93.00	0.20									
	1985–1989	480.00		25.00	0.05									
	1990–1994	265.00	17.00	16.00	0.06	0.89	0.00	0.00	0.00	0.01	0.24	0.29	0.33	0.56
		[200]	[17]	[13]	[0.04]	[0.77]	0.00	0.00	0.00	[0.01]	[0.2]	[0.24]	[0.28]	[0.48]
	1995–1999	404.00		24.00	0.06		0.00	0.00	0.00	0.01	0.20	0.25	0.30	0.50
	2000–2002	404.00		24.00	0.06		0.00	0.00	0.00	0.01	0.20	0.25	0.26	0.48
Nuclear medicine														
Argentina	1985–1989	0.92	0.25	0.76	0.82	3.08	0.01				0.26			
	1990–1994	0.42	0.23	1.14	2.71	4.91	0.05	0.05	0.08	0.34	0.57	0.59	0.67	0.96
	1995–1999	1.50	0.90	2.28	1.52	2.60	0.02	0.03	0.07	0.29	0.25	0.34	0.55	0.90
	2000–2002	1.55	1.02	2.48	1.60	2.44	0.01	0.03	0.11	0.33	0.05	0.18	0.56	0.91
Australia[c, d]	1975–1979	0.67		0.20	0.30									
	1985–1989	2.72	1.31	0.44	0.16	0.33								
	1990–1994	1.58	0.86	0.64	0.41	0.75	0.00	0.00	0.01	0.14	0.01	0.01	0.09	0.76
	1995–1999													
	2001	1.10		1.20	1.10									
Brazil[e]	1985–1989	0.92	0.25	0.76	0.82	3.08	0.01				0.26			
	1990–1994	0.43	0.19	0.67	1.57	3.50	0.02	0.04	0.08	0.24	0.35	0.49	0.71	0.94
	1995–1999[y]	0.09	1.23	0.20	2.35	0.17	0.02	0.08	0.16	0.27				
	2000–2002[y]	0.05	1.47	0.08	1.49	0.06	0.01	0.06	0.10	0.25				
Bulgaria	1990–1994	0.19		0.20	1.03									
	1995–1999	0.14	0.01	0.05	0.33	6.58	0.00	0.00	0.00	0.06	0.09	0.09	0.15	0.40
	2000–2002													
Canada	1975–1979	0.57	0.41	1.08	1.90	2.63	0.01				0.13			
	1980–1984	0.85	0.55	1.53	1.81	2.80	0.00				0.05			
	1985–1989	1.14	0.83	2.24	1.96	2.71	0.00				0.04			
	1990–1994	1.42	1.00	1.95	1.37	1.96	0.00	0.00	0.04	0.46	0.01	0.03	0.21	0.91
	1995–1999	1.49	1.04	1.90	1.27	1.81	0.00	0.00	0.02	0.46	0.01	0.03	0.13	0.90
	2000–2002	1.60	1.17	2.47	1.55	2.11	0.00	0.00	0.04	0.53	0.01	0.02	0.17	0.93

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Chile	1995–1999	0.06	0.06	0.57	9.27	9.27	0.01	0.02	0.12	0.53	0.05	0.07	0.15	0.26
	2000–2002	0.10	0.08	1.04	10.60	14.78	0.03	0.06	0.27	0.71	0.06	0.09	0.22	0.31
China	1985–1989	6.08	0.71	9.52	1.57	13.30	0.01				0.27			
	1995–1999	5.65	3.62	7.02	1.24	1.94	0.01	0.01	0.03	0.30	0.13	0.21	0.28	0.96
	2000	5.72	3.68	6.65	1.16	1.81	0.00	0.01	0.03	0.30	0.05	0.16	0.26	0.99
China - Taiwan Province	1985–1989	0.38		0.10	0.27									
	1990–1994	0.50	0.23	0.14	0.29	0.63	0.00	0.00	0.00	0.07	0.07	0.10	0.50	0.96
	1995–1999	0.55	0.10	0.07	0.13	0.73	0.00	0.00	0.00	0.03	0.21	0.24	0.32	0.67
	2000–2002	0.65	0.16	0.10	0.16	0.64	0.00	0.00	0.00	0.05	0.00	0.04	0.04	0.58
Croatia	1990–1994	0.06	0.04	0.05	0.80	1.10								
	1995–1999													
	2000–2002	0.27	0.14	0.25	0.92	1.82	0.00	0.01	0.06	0.22	0.03	0.12	0.48	0.87
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
	1995–1999													
	2000–2002													
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
	1995–1999	0.01	0.01	0.01	1.01	1.01	0.00	0.00	0.00	0.66	0.00	0.00	0.00	0.89
	2000–2002	0.01	0.01	0.02	1.59	1.93	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.78
Czech Rep.[g]	1975–1979	0.74	0.22	0.43	0.58	1.83	0.00				0.04			
	1980–1984	1.08	0.67	0.99	0.92	1.48	0.00				0.03			
	1985–1989	1.46	0.75	1.26	0.87	1.68	0.00				0.01			
	1990–1994	0.76	0.70	0.74	0.98	1.05	0.00	0.00	0.01	0.35	0.01	0.04	0.10	0.68
	1995–1999	1.10	1.07	1.72	1.56	1.60	0.00	0.00	0.05	0.52	0.01	0.03	0.21	0.84
	2000–2002	1.16	1.08	1.42	1.23	1.31	0.00	0.00	0.02	0.40	0.00	0.03	0.12	0.77
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
	1995–1999	0.62	0.43	0.50	0.80	1.17	0.00	0.00	0.01	0.31	0.01	0.03	0.10	0.78
	2000–2002	0.66	0.45	0.50	0.76	1.12	0.00	0.00	0.01	0.32	0.00	0.01	0.06	0.78

Country	Period	Monitored workers (10^3)	Measurably exposed workers (10^3)	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
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
	1995–1999													
	2000–2002													
El Salvador	2001–2002	0.01	0.01	0.03	2.58	5.30	0.00	0.00	0.27	0.73	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	0.68	0.13	0.15	0.22	1.15	0.00	0.00	0.00	0.09	0.00	0.00	0.06	0.76
	1995–1999	0.47	0.11	0.13	0.26	1.19	0.00	0.00	0.00	0.11	0.00	0.00	0.05	0.79
	2000–2002	0.45	0.12	0.09	0.21	0.75	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.65
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													
	1995–1999	4.21		1.88	0.45									
	2000–2002	3.85		1.27	0.33									
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			
	1995–1999													
	2000–2002													
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
	1995–1999	0.54	0.23	0.40	0.74	1.77	0.00	0.01	0.03	0.21	0.10	0.16	0.36	0.86
	2000–2002	0.64	0.31	0.39	0.61	1.25	0.00	0.00	0.03	0.16	0.02	0.06	0.32	0.79
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
	1995–1999	0.69	0.17	0.26	0.38	1.60	0.00	0.00	0.01	0.11	0.02	0.05	0.24	0.83
	2000–2002	0.70	0.45	0.76	1.08	1.68	0.00	0.00	0.03	0.35	0.03	0.06	0.23	0.87

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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
	1995–1999	0.08	0.01	0.01	0.15	1.97	0.00	0.00	0.00	0.05	0.00	0.00	0.09	0.92
	2000–2002	0.10	0.02	0.02	0.19	1.21	0.00	0.00	0.00	0.06	0.00	0.00	0.09	0.85
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
	1995–1999													
	2000–2002													
Indonesia	1980–1984	0.01	0.01	0.01	1.23	1.23								
	1985–1989	0.10	0.01	0.02	1.20	1.20								
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
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
	1995–1999	0.14	0.14	0.18	1.31	1.31	0.00	0.01	0.06	0.32	0.00	0.07	0.33	0.90
	2000–2002	0.17	0.17	0.22	1.27	1.27	0.00	0.00	0.04	0.33	0.00	0.04	0.25	0.89
Lithuania	1995–1999	0.08	0.06	0.12	1.59	2.06	0.00	0.00	0.02	0.77	0.00	0.02	0.07	0.90
	2000–2002	0.08	0.05	0.12	1.55	2.58	0.00	0.01	0.02	0.61	0.04	0.11	0.12	0.82
Malta	1995–1999	0.03	0.00	0.00	0.05	0.36	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.71
	2000–2002	0.03	0.01	0.00	0.07	0.46	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.33

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.42		1.21	2.88									
	1990–1994	0.60	0.26	0.73	1.21	4.63	0.03				0.33			
	1997–1999	0.58	0.58	1.90	3.27	3.27	0.01	0.03	0.12	1.00	0.00	0.00	0.00	0.00
	2000–2002	0.42	0.42	1.64	3.95	3.95	0.01	0.04	0.19	0.97	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.02	0.02	0.02	1.26	1.26	0.03	0.03	0.09	0.50				
	1995–1999	0.02	0.02	0.00	0.31	0.31	0.00	0.00	0.00	0.00				
	2000–2002	0.03	0.03	0.00	0.46	0.46	0.00	0.00	0.00	0.00				
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
	1995–1999	4.22	0.95	0.54	0.13	0.59	0.00	0.00	0.00	0.04	0.04	0.07	0.11	0.54
	2000–2002	4.02	0.89	0.55	0.14	0.62	0.00	0.00	0.00	0.04	0.00	0.02	0.04	0.55
Norway	1990–1992	0.24	0.10	0.14	0.59	1.47	0.00	0.00	0.02	0.19				
	1995–1999													
	2000–2002	0.22	0.06	0.05	0.23	0.90	0.00	0.00	0.00	0.08				
Pakistan	1990–1994	0.23	0.22	2.07	8.90	12.60	0.26	0.38	0.55	0.81	0.72	0.82	0.94	1.00
	1995–1999													
	2000–2002													
Peru	1980–1984	0.12		0.43	3.73									
	1985–1989	0.13		0.35	2.75									
	1994	0.03	0.03	0.15	5.00	5.00	0.00	0.00	0.30	0.80				
Philippines	1995–1999	0.13	0.06	0.17	1.35	2.66	0.02	0.03	0.08	0.24	0.30	0.40	0.64	0.91
	2000–2002	0.23	0.12	0.15	0.67	1.28	0.00	0.00	0.01	0.19	0.15	0.17	0.26	0.84
Romania	1995–1999	0.30	0.27	0.86	2.87	3.30	0.01	0.05	0.15	0.85	0.10	0.23	0.44	0.99
	2000–2002	0.25	0.19	0.38	1.54	1.74	0.01	0.03	0.08	0.47	0.08	0.20	0.42	0.95
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
	1995–1999													
	2000–2002	0.28	0.28	0.58	2.09	2.11	0.00	0.00	0.03	0.86				
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
	1995–1999													
	2000–2002	0.14	0.09	0.09	0.63	0.98	0.00	0.00	0.01	0.22	0.00	0.04	0.16	0.76

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.92	0.83	1.61	1.74	1.93	0.01				0.11			
	1995–1999													
	2000–2002	1.86	1.55	3.04	1.64	1.97	0.01	0.02	0.07	0.42	0.10	0.16	0.40	0.90
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
	1995–1999													
	2000–2002													
Sweden	1999	0.29	0.18	0.10	0.34	0.56	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.33
	2000–2002	0.35	0.19	0.14	0.40	0.73	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.62
Syrian Arab Rep.	1990–1994	0.06	0.01	0.03	0.48	3.16	0.00	0.00	0.01	0.00	0.00	0.00	0.15	0.31
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
United Kingdom[n]	1991	1.40		0.30	0.22									
	1995–1999													
	2001	0.49		0.46	0.94									
Total reported data[o, p]	1975–1979	5.66		5.21	0.92		0.00				0.11			
	1980–1984	7.91		5.72	0.72		0.00				0.05			
	1985–1989	15.90		16.60	1.04		0.01				0.17			
	1990–1994	13.50	7.63	12.80	0.95	1.68	0.01	0.02	0.04	0.24	0.24	0.29	0.42	0.81
	1995–1999	22.98	11.26	20.88	0.91	1.85	0.00	0.01	0.04	0.32	0.06	0.10	0.20	0.73
	2000–2002	27.11	14.17	26.14	0.96	1.84	0.00	0.01	0.04	0.31	0.03	0.07	0.19	0.73
World[q]	1975–1979	61.00		62.00	1.01		0.00				0.09			
	1980–1984	81.00		85.00	1.04		0.00				0.03			
	1985–1989	90.00		85.00	0.95		0.00				0.10			
	1990–1994	115.00	65.00	90.00	0.79	1.41	0.00	0.01	0.02	0.21	0.10	0.15	0.27	0.74
		[100]	[60]	[86]	[0.86]	[1.4]	0.00	[0.01]	[0.03]	[0.21]	[0.15]	[0.2]	[0.31]	[0.74]
	1995–1999	117.00		89.00	0.76		0.00	0.01	0.04	0.32	0.06	0.10	0.20	0.73
	2000–2002	120.00		87.00	0.73		0.00	0.01	0.04	0.31	0.03	0.07	0.19	0.73

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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
						Radiotherapy								
Argentina	1985–1989	0.27	0.08	0.28	1.04	3.61	0.00				0.10			
	1990–1994	0.40	0.10	0.25	0.64	2.61	0.01	0.01	0.02	0.10	0.30	0.43	0.51	0.89
	1995–1999	0.98	0.37	0.41	0.42	1.19	0.00	0.01	0.01	0.07	0.10	0.20	0.29	0.58
	2000–2002	1.00	0.28	0.40	0.40	1.43	0.00	0.01	0.02	0.10	0.04	0.19	0.44	0.88
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
	1995–1999													
	2001	1.12		0.16	0.14									
Belarus[aa]	2000–2002	0.68	0. 681	1.22	1.79	1.79	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.78
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
	1995–1999[y]	0.13	0.05	0.21	1.63	3.98	0.02	0.04	0.08	0.22				
	2000–2002[y]	0.04	0.01	0.03	0.74	3.38	0.01	0.01	0.07	0.13				
Bulgaria	1990–1994	0.33		0.48	1.44									
	1995–1999	0.46	0.20	0.34	0.74	2.15	0.00	0.00	0.00	0.28	0.00	0.00	0.01	0.71
	2000–2002													
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
	1995–1999	1.32	0.29	0.20	0.15	0.70	0.00	0.00	0.00	0.02	0.15	0.19	0.27	0.52
	2000–2002	1.87	0.34	0.26	0.14	0.76	0.00	0.00	0.00	0.02	0.20	0.23	0.29	0.52
Chile	1995–1999	0.01	0.01	0.01	1.05	1.05	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.58
	2000–2002	0.01	0.01	0.02	2.40	2.40	0.04	0.04	0.04	0.70	0.33	0.33	0.33	0.93
China	1985–1989	2.54	0.35	3.54	1.39	10.00	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
	1995–1999	6.24	4.00	6.47	1.04	1.62	0.00	0.01	0.02	0.30	0.10	0.19	0.26	1.00
	2000	7.00	4.46	5.60	0.80	1.26	0.00	0.01	0.02	0.29	0.06	0.14	0.22	1.00

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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
	1995–1999	0.46	0.03	0.03	0.06	1.28	0.00	0.00	0.00	0.01	0.47	0.47	0.59	0.80
	2000–2002	0.62	0.03	0.03	0.04	1.00	0.00	0.00	0.00	0.01	0.21	0.38	0.66	0.76
Croatia	1990–1994	0.03	0.03	0.02	0.70	0.90								
	1995–1999													
	2000–2002	0.27	0.10	0.06	0.21	0.55	0.00	0.00	0.00	0.04	0.00	0.00	0.15	0.53
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
	1995–1999													
	2000–2002													
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
	1995–1999	0.02	0.02	0.01	0.71	0.71	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00
	2000–2002	0.04	0.04	0.04	1.03	0.10	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.00
Czech Rep.[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
	1995–1999	0.76	0.73	0.77	1.01	1.05	0.00	0.00	0.01	0.34	0.01	0.04	0.11	0.68
	2000–2002	0.95	0.86	0.71	0.75	0.83	0.00	0.01	0.02	0.15	0.03	0.10	0.25	0.58
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
	1995–1999	0.93	0.16	0.07	0.08	0.45	0.00	0.00	0.00	0.02	0.04	0.10	0.15	0.54
	2000–2002	1.03	0.07	0.02	0.02	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21
Ecuador	1993–1994	0.06	0.05	0.07	1.06	1.44	0.01	0.02	0.04	0.35				
	1995–1999													
	2000–2002													
El Salvador	2001–2002	0.03	0.03	0.06	1.99	1.99	0.00	0.04	0.05	0.79	0.00	0.21	0.26	0.92

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.25	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
	1995–1999	0.31	0.03	0.02	0.05	0.58	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.32
	2000–2002	0.32	0.01	0.00	0.01	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
France[m]	1975–1979	4.77		8.77	1.84		0.01							
	1980–1984	6.01	1.30	6.08	1.01	4.68	0.01							
	1985–1989	6.49	1.23	3.97	0.61	3.22	0.01							
	1990–1994													
	1995–1999	8.29		1.88	0.23									
	2000–2002	7.70		1.08	0.14									
Germany[l]	1980–1984	1.20	0.31	1.09	0.91	3.57					0.24			
	1985–1989	1.03	0.17	0.68	0.66	4.00					0.23			
	1995–1999													
	2000–2002													
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
	1995–1999	0.29	0.02	0.05	0.18	2.72	0.00	0.01	0.01	0.02	0.33	0.60	0.74	0.91
	2000–2002	0.37	0.05	0.07	0.19	1.53	0.00	0.00	0.00	0.02	0.62	0.62	0.62	0.87
Hungary	1975–1979	0.36	0.14	0.73	2.05	5.15	0.03				0.36			
	1980–1984	0.45	0.14	0.61	1.36	4.31	0.02				0.24			
	1985–1989	0.55	0.15	0.61	1.10	3.97	0.01				0.23			
	1990–1994	0.47	0.10	0.33	0.70	3.28	0.01	0.02	0.04	0.14	0.28	0.36	0.59	0.94
	1995–1999	0.44	0.04	0.15	0.33	4.30	0.01	0.01	0.02	0.05	0.45	0.58	0.74	0.94
	2000–2002	0.44	0.07	0.12	0.27	1.62	0.01	0.01	0.01	0.03	0.47	0.62	0.74	0.87
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
	1995–1999	0.02	0.00	0.00	0.08	1.59	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.87
	2000–2002	0.02	0.00	0.00	0.07	0.65	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.52

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
India	1975–1979	2.49	1.43	3.91	1.57	2.73	0.02				0.39			
	1980–1984	2.98	1.53	3.39	1.14	2.22	0.01				0.30			
	1985–1989	4.17	2.28	3.94	0.95	1.73	0.01				0.23			
	1990–1994	4.52	2.35	3.15	0.70	1.34	0.00	0.01	0.03	0.15	0.17	0.26	0.43	0.81
	1995–1999													
	2000–2002													
Indonesia	1975–1979	0.09	0.09	0.19	2.10	2.20								
	1980–1984	0.31	0.30	0.50	1.60	1.68	0.00				0.02			
	1985–1989	0.23	0.22	0.35	1.55	1.63	0.00				0.04			
	1995–1999													
	2000–2002													
Ireland	1985–1989	0.30	0.14	0.15	0.50	1.05								
	1991–1994	0.28	0.07	0.03	0.12	0.43	0.00	0.00	0.00	0.03	0.00	0.00	0.04	0.58
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
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
	1995–1999	0.02	0.02	0.01	0.26	0.26	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.27
	2000–2002	0.02	0.02	0.00	0.24	0.24	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.16
Lithuania	1995–1999	0.12	0.09	0.18	1.50	2.04	0.00	0.01	0.01	0.75	0.00	0.04	0.08	0.87
	2000–2002	0.13	0.06	0.13	1.06	2.50	0.00	0.00	0.01	0.44	0.00	0.00	0.07	0.58
Luxembourg	1995–1999	0.03	0.00	0.00	0.01	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.03	0.00	0.00	0.02	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Malta	1995–1999	0.01	0.00	0.02	1.20	0.27	0.00	0.00	0.00	0.01				
	2000–2002	0.01	0.01	0.00	0.17	0.46	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.55

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.31	0.26	0.88	2.84	3.41	0.03				0.33			
	1990–1994	0.66		0.45	0.68									
	1997–1999	0.61	0.61	1.33	2.18	2.18	0.01	0.01	0.05	1.00	0.00	0.00	0.00	0.00
	2000–2002	0.58	0.58	1.89	3.28	3.28	0.01	0.02	0.06	0.97	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.02	0.02	0.01	0.58	0.58	0.00	0.00	0.00	0.14				
	1995–1999	0.05	0.05	0.01	0.23	0.23	0.00	0.00	0.00	0.19				
	2000–2002	0.10	0.10	0.01	0.15	0.15	0.00	0.00	0.00	0.31				
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
	1995–1999	1.65	0.31	0.14	0.08	0.51	0.00	0.00	0.00	0.01	0.20	0.23	0.33	0.53
	2000–2002	1.81	0.31	0.12	0.06	0.38	0.00	0.00	0.00	0.01	0.09	0.23	0.49	0.49
Norway	2000–2002	0.05	0.01	0.03	0.54	5.50	0.01	0.01	0.02	0.03				
Pakistan	1990–1994	0.13	0.12	1.35	10.50	11.60	0.32	0.45	0.64	0.86	0.68	0.82	0.94	1.00
	1995–1999													
	2000–2002													
Peru	1980–1984	0.09		0.54	6.18									
	1985–1989	0.09		0.48	5.17									
	1994	0.05	0.05	0.24	5.00	5.00	0.00	0.08	0.42	0.88				
	1995–1999	0.04	0.04	0.12	2.98	3.02	0.03	0.04	0.10	0.82	0.23	0.27	0.40	0.96
	2000–2002	0.06	0.06	0.21	3.46	3.46	0.01	0.06	0.21	0.89	0.04	0.21	0.52	0.97
Philippines	1995–1999	0.18	0.02	0.04	0.23	1.60	0.00	0.00	0.00	0.06	0.10	0.10	0.23	0.84
	2000–2002	0.22	0.07	0.03	0.15	0.39	0.00	0.00	0.00	0.02	0.00	0.12	0.28	0.56
Romania	1995–1999	1.29	1.28	2.70	2.10	2.11	0.01	0.01	0.02	0.89				
	2000–2002	0.63	0.54	0.74	1.18	1.73	0.01	0.01	0.02	0.66				
Slovakia	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
	1995–1999													
	2000–2002	0.41	0.41	0.67	1.62	1.64	0.00	0.00	0.01	0.78				
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
	1995–1999													
	2000–2002	0.08	0.08	0.01	0.09	0.10	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.16

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	1.01	0.96	0.88	0.86	0.91	0.00				0.02			
	1995–1999													
	2000–2002	2.15	1.40	1.39	0.65	0.99	0.00	0.00	0.01	0.11	0.35	0.35	0.39	0.70
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
	1995–1999													
	2000–2002													
Sweden	1999	0.29	0.09	0.03	0.12	0.37	0.00	0.00	0.00	0.01	0.00	0.00	0.16	0.30
	2000–2002	0.47	0.17	0.07	0.15	0.43	0.00	0.00	0.00	0.02	0.00	0.06	0.14	0.39
Syrian Arab Rep.	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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
United Kingdom[n]	1991	2.68		0.40	0.15									
	1995–1999													
	2001	2.41		0.17	0.07									
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
	1995–1999													
	2000–2002													
Total reported data[o, p]	1975–1979	9.31		16.50	1.78		0.12				0.30			
	1980–1984	13.30		15.30	1.15		0.01				0.20			
	1985–1989	18.80		16.60	0.88		0.01				0.21			
	1990–1994	19.80	9.41	13.00	0.65	1.38	0.00	0.01	0.03	0.15	0.25	0.34	0.46	0.79
	1995–1999	24.94	8.44	15.20	0.61	1.80	0.00	0.01	0.01	0.23	0.10	0.14	0.21	0.58
	2000–2002	32.53	10.12	15.27	0.47	1.51	0.00	0.01	0.02	0.25	0.08	0.14	0.22	0.52

Country	*Period*	*Monitored workers (10^{3})*	*Measurably exposed workers (10^{3})*	*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}*
World[q]	1975–1979	84.00		190.00	2.23									
	1980–1984	110.00		180.00	1.58									
	1985–1989	110.00		100.00	0.87									
	1990–1994	120.00	48.00	65.00	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]
	1995–1999	264		132	0.51		0.00	0.01	0.02	0.12	0.14	0.23	0.35	0.70
	2000–2002	264		132	0.47		0.00	0.01	0.02	0.11	0.14	0.23	0.34	0.70
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
	1995–1999													
	2001	1.84		0.00	0.00	0.00								
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
	1995–1999[y]	0.04	0.00	0.02	0.59	6.39	0.01	0.03	0.03	0.03				
	2000–2002[y]	0.10	0.01	0.02	0.22	2.27	0.00	0.01	0.02	0.05				
Bulgaria	1990–1994	0.25	0.02	0.06	0.26		0.00	0.00	0.00	0.02				
	1995–1999	0.12	0.01	0.04	0.34	3.65	0.00	0.00	0.00	0.07	0.00	0.00	0.04	0.48
	2000–2002													
Canada	1990–1994	21.30	2.66	1.75	0.08	0.66	0.00	0.00	0.00	0.02	0.08	0.12	0.22	0.57
China - Taiwan Province	1995–1999	0.13	0.01	0.03	0.27	4.48	0.00	0.01	0.01	0.02	0.71	0.82	0.89	1.01
	2000–2002	0.32	0.01	0.01	0.04	1.83	0.00	0.00	0.00	0.00	0.35	0.58	0.58	0.71
Czech Rep.[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	11.60	4.04	9.12	0.78	2.25	0.00				0.10			
	1995–1999													
	2000–2002													
Croatia	2000–2002	0.13	0.01	0.01	0.05	0.48	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.51
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
	1995–1999													
	2000–2002													

Country	Period	Monitored workers (10^3)	Measurably exposed workers (10^3)	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
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
	1995–1999	0.08	0.08	0.02	0.29	0.29	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
	2000–2002	0.05	0.05	0.03	0.71	0.71	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00
Ecuador	1993–1994	0.03	0.03	0.04	1.10	1.10	0.00	0.00	0.00	0.49				
	1995–1999													
	2000–2002													
France	1995–1999	5.85		0.38	0.06									
	2000–2002	5.07		0.17	0.03									
Germany[w]	1990–1994	0.22	0.03	0.02	0.11	0.94	0.00	0.00	0.00	0.02	0.09	0.12	0.22	0.67
	1995–1999	11.24	0.81	0.63	0.06	0.82	0.00	0.00	0.00	0.01	0.04	0.10	0.28	0.71
	2000–2002	8.14	0.59	0.38	0.05	0.68	0.00	0.00	0.00	0.01	0.06	0.08	0.28	0.70
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
	1995–1999													
	2000–2002													
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
	1995–1999	0.27	0.01	0.00	0.01	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23
	2000–2002	0.26	0.02	0.01	0.04	0.46	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.32
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
	1995–1999													
	2000–2002													
Japan	1990–1994	173.00	45.20	66.10	0.38	1.46	0.00	0.01	0.02	0.08	0.17	0.25	0.41	0.80
	1995–1999[z]	196.13	51.03	79.33	0.40	1.55	0.00	0.01	0.02	0.08	0.20	0.30	0.49	0.85
	2000–2002[z]	221.23	57.06	75.85	0.34	1.33	0.00	0.00	0.01	0.08	0.17	0.26	0.43	0.83
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
	1995–1999	0.07	0.07	0.05	0.74	0.74	0.00	0.00	0.01	0.18	0.00	0.04	0.12	0.80
	2000–2002	0.06	0.06	0.07	1.08	1.08	0.00	0.00	0.05	0.28	0.00	0.00	0.28	0.86
Lithuania	1995–1999	0.23	0.12	0.26	1.14	2.14	0.00	0.00	0.00	0.51	0.00	0.00	0.01	0.70
	2000–2002	0.31	0.09	0.29	0.94	3.31	0.00	0.00	0.01	0.29	0.00	0.00	0.04	0.48
Luxembourg	1995–1999	0.02	0.01	0.00	0.20	0.47	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
	2000–2002	0.02	0.01	0.00	0.20	0.49	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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	1997–1999	0.19	0.19	0.37	2.04	2.04	0.00	0.01	0.02	1.07	0.45	0.51	0.61	1.08
	2000–2002	0.05	0.05	0.14	2.83	2.83	0.01	0.01	0.09	0.95	0.07	0.07	0.26	0.98
Myanmar	1990–1994	0.04	0.04	0.03	0.75	0.75	0.01	0.01	0.01	0.14				
	1995–1999													
	2000–2002													
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
	1995–1999	0.15	0.02	0.01	0.06	0.29	0.00	0.00	0.00	0.01	0.00	0.00	0.25	0.50
	2000–2002	0.15	0.02	0.01	0.04	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Norway	1990–1992	1.51	0.43	0.47	0.31	1.09	0.00	0.00	0.01	0.06				
	1995–1999													
	2000–2002	0.22	0.02	0.01	0.04	0.80	0.00	0.00	0.00	0.01				
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
	1995–1999													
	2000–2002													
Romania	1995–1999	0.19	0.19	0.54	2.77	2.77	0.00	0.00	0.01	0.79	0.00	0.00	0.01	0.96
	2000–2002	0.20	0.15	0.24	1.21	1.47	0.00	0.00	0.00	0.42	0.00	0.00	0.02	0.93
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
	1995–1999													
	2000–2002													
Spain	2000–2002	12.59	7.58	5.07	0.40	0.67	0.00	0.00	0.00	0.11	0.09	0.10	0.14	0.55
Sri Lanka	1991– 1994	0.01	0.01	0.09	9.76	12.10	0.19	0.28	0.28	0.39	0.86	0.96	0.96	0.98
	1995–1999													
	2000–2002													
Sweden	1990–1994[x]	7.50		2.38	0.32									
	1999	0.38	0.15	0.06	0.16	0.40	0.00	0.00	0.00	0.03	0.00	0.00	0.10	0.44
	2000–2002	0.60	0.22	0.11	0.17	0.47	0.00	0.00	0.00	0.05	0.00	0.00	0.07	0.50
Switzerland	1990–1994	27.70		1.25	0.05		0.00	0.00	0.00	0.01	0.01	0.04	0.16	0.52
	1995–1999	30.80	2.53	1.15	0.04	0.46	0.00	0.00	0.00	0.01	0.03	0.08	0.22	0.54
	2000–2002	33.43	1.38	0.76	0.02	0.55	0.00	0.00	0.00	0.01	0.02	0.08	0.25	0.63

Country	Period	Monitored workers (10^3)	Measurably exposed workers (10^3)	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 reported data[o, p]	1990–1994	461.00	76.00	98.90	0.21	1.30	0.00	0.00	0.01	0.04	0.15	0.22	0.36	0.74
	1995–1999	246	55	83	0.34	1.50	0.00	0.00	0.01	0.19	0.10	0.13	0.22	0.59
	2000–2002	285	67	83	0.29	1.24	0.00	0.00	0.01	0.15	0.05	0.08	0.16	0.53

[a] Data are annual values averaged over the periods indicated.

[b] 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.

[d] The method of dose recording was different in the two periods for which data were reported, and this may partly account for differences in the data. Average individual doses for 1975–1979 were estimated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category. 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 were assumed to be representative.

[e] The reported results have been estimated by scaling up from a sample of approximately 25% of the monitored workers.

[f] Data include exposures from dental radiography and other medical uses.

[g] Data for 1975–1989 are for Czechoslovakia. Scaling down to 60% would give approximately equivalent data for the Czech Republic.

[h] Where lead aprons were worn, the dosimeters were worn beneath 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, because the reported data covered only 75% of the monitored workers.

[l] The 1980–1989 data are for the German Democratic Republic.

[m] Reported data contain a contribution from radiotherapy.

[n] The reported results have been estimated by scaling up from a sample of approximately 33% of the monitored workers.

[o] The total for measurably exposed workers has been scaled up to take account of those countries that reported the number of monitored workers but not the number of measurably exposed workers.

[p] These data should be interpreted with care, particularly because the countries included in the summations may differ from one period to another, 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 for NR_{15} and SR_{15} are averages of the data reported. In general, these data are less complete than those that form the basis for the summations of the numbers of workers and of the collective doses.

[q] Values shown in square brackets are the world estimates based on the standard method given in Section I.B. However, the Committee identified a more robust method of estimation for this instance based on taking the regional value for the United States to be equivalent to the rest of the OECD. The resulting values are shown without brackets.

[r] Within the period 1990–1994, the data for 1990 relate only to the Federal Republic of Germany.

[s] Data for dentists in private practice only.

[t] Data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative of 1975–1979, 1980–1984 and 1985–1989, respectively.

[u] In the absence of data for 1985–1989, the data for 1990 have been assumed to be representative.

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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

[v] No world estimate has been made, because of the undefined nature of the sectors covered.

[w] Data for 1980–1989 are a combination of data previously reported for the German Democratic Republic and the Federal Republic of Germany.

[x] Values apply to all medical uses of radiation since no division into different categories could be made.

[y] Data represent about 15% of the monitored workers in Brazil.

[z] Data include diagnostic radiology, nuclear medicine and radiotherapy.

[aa] External beam only.

Table A-25 Exposures to workers from diagnostic radiology

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Type of radiology (job category)*	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Belarus	Conventional	2000–2002	3.18	3.18	3.94	1.24	1.24	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.95
	Interventional	2000–2002	0.42	0.42	0.63	1.48	1.48	0.00	0.02	0.04	0.73	0.00	0.16	0.28	1.05
Croatia	Conventional	2000–2002	2.57	0.63	0.28	0.11	0.44	0.00	0.00	0.00	0.02	0.02	0.04	0.16	0.41
	Interventional	2000–2002	0.34	0.19	0.22	0.66	1.16	0.00	0.01	0.03	0.14	0.00	0.13	0.42	0.79
Cyprus	Conventional	1995–1999	0.13	0.13	0.06	0.45	0.45	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
		2000–2002	0.15	0.15	0.13	0.84	0.84	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00
	Interventional	1995–1999	0.03	0.03	0.04	1.04	1.04	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.00
		2000–2002	0.04	0.04	0.04	1.04	1.04	0.00	0.01	0.01	0.37	0.00	0.00	0.00	0.00
Czech Rep.	Conventional	1995–1999	7.87	4.01	4.38	0.56	1.09	0.00	0.01	0.02	0.14	0.10	0.17	0.31	0.72
		2000–2002	8.79	2.93	3.22	0.37	1.10	0.00	0.00	0.01	0.09	0.05	0.15	0.33	0.77
	Interventional	1995–1999	0.16	0.13	0.08	0.51	29.50	0.05	0.08	0.17	0.47	0.06	0.08	0.11	0.14
		2000–2002	0.25	0.21	0.19	0.74	14.95	0.01	0.05	0.21	0.61	0.02	0.06	0.16	0.24
Denmark	Conventional	1995–1999	2.83	0.94	0.32	0.11	0.33	0.00	0.00	0.00	0.02	0.00	0.02	0.04	0.31
		2000–2002	2.85	0.72	0.21	0.07	0.30	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.29
	Interventional	1995–1999	1.33	0.30	0.16	0.12	0.55	0.00	0.00	0.00	0.03	0.00	0.00	0.05	0.48
		2000–2002	1.54	0.37	0.20	0.13	0.53	0.00	0.00	0.00	0.03	0.00	0.00	0.07	0.50
Finland	Conventional	1995–1999	4.23	0.57	1.11	0.26	1.54	0.00	0.00	0.01	0.06	0.00	0.00	0.00	0.00
		2000–2002	4.36	0.64	0.94	0.22	0.55	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.00
	Interventional	1995–1999	0.11	0.09	0.75	7.09	8.12	0.11	0.16	0.31	0.73	0.61	0.70	0.85	1.00
		2000–2002	0.15	0.13	0.75	4.95	5.90	0.09	0.16	0.30	0.68	0.41	0.59	0.79	0.98

Country	*Type of radiology (job category)*	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Greece	Conventional (medical doctors)	1995–1999	1.37	0.30	1.09	0.79	3.17								
		2000–2002	1.72	0.32	0.96	0.56	3.05								
	Conventional (technicians)	1995–1999	2.75	0.35	0.49	0.18	1.42								
		2000–2002	3.28	0.44	0.35	0.11	0.83								
	Conventional (others)	1995–1999	0.24	0.04	0.07	0.28	1.78								
		2000–2002	0.40	0.08	0.09	0.22	1.16								
	Interventional (cardiologist)	1995–1999	0.35	0.18	1.63	4.62	7.89								
		2000–2002	0.42	0.26	1.68	3.97	6.43								
	Interventional (other[a] medical doctors)	1995–1999	0.17	0.02	0.04	0.24	1.76								
		2000–2002	0.30	0.11	0.16	0.54	1.63								
	Interventional (nurses)	1995–1999	0.12	0.07	0.17	1.42	2.66								
		2000–2002	0.22	0.11	0.16	0.70	1.42								
	Interventional (others)	1995–1999	0.06	0.03	0.07	1.01	2.58								
		2000–2002	0.10	0.04	0.06	0.67	1.66								
Hungary	Conventional	1995–1999	6.13	0.37	0.29	0.05	0.93	0.00	0.00	0.00	0.01	0.10	0.10	0.15	0.55
		2000–2002	6.07	2.04	0.91	0.15	0.45	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.32
	Interventional	1995–1999	1.88	0.04	0.04	0.02	0.96	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.56
		2000–2002	2.07	0.18	0.08	0.04	0.44	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.29
Kuwait	Conventional	1995–1999	0.42	0.42	0.26	0.62	0.62	0.00	0.00	0.01	0.14	0.00	0.01	0.08	0.65
		2000–2002	0.44	0.44	0.21	0.48	0.48	0.00	0.00	0.01	0.10	0.05	0.05	0.17	0.62
	Interventional	1995–1999	0.14	0.14	0.26	1.95	1.95	0.04	0.06	0.07	0.26	0.49	0.62	0.68	0.94
		2000–2002	0.13	0.13	0.21	1.63	1.63	0.03	0.05	0.06	0.15	0.53	0.65	0.71	0.85
Lithuania	Conventional (medical doctors)	1995–1999	0.42	0.31	0.67	1.60	2.16	0.00	0.00	0.02	0.74	0.01	0.01	0.07	0.89
		2000–2002	0.42	0.19	0.46	1.10	2.47	0.00	0.00	0.01	0.45	0.01	0.02	0.05	0.62
	Conventional (nurses)	1995–1999	1.18	0.87	2.06	1.48	1.71	0.00	0.00	0.01	0.74	0.00	0.01	0.05	1.03
		2000–2002	1.17	0.46	1.44	1.06	2.33	0.00	0.00	0.01	0.39	0.01	0.02	0.08	0.65
	Interventional (cardiologist)	1995–1999	0.04	0.03	0.15	4.24	4.89	0.04	0.10	0.19	0.88	0.24	0.40	0.54	0.98
		2000–2002	0.05	0.04	0.15	3.20	3.51	0.00	0.01	0.14	0.90	0.00	0.03	0.32	0.99
	Interventional (nurses)	1995–1999	0.06	0.05	0.09	1.39	2.08	0.00	0.00	0.01	0.70	0.00	0.00	0.03	0.84
		2000–2002	0.09	0.07	0.21	2.26	3.03	0.00	0.02	0.09	0.74	0.03	0.09	0.33	0.92

Country	*Type of radiology (job category)*	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Luxembourg	Conventional	1995–1999	0.64	0.34	0.33	0.51	0.85	0.01	0.01	0.01	0.06	0.00	0.00	0.00	0.00
		2000–2002	0.69	0.37	.	0.44	0.65	0.01	0.01	0.01	0.06	0.00	0.00	0.00	0.00
	Interventional	1995–1999	0.03	0.00	0.00	0.19	1.36	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.00
		2000–2002	0.03	0.01	0.01	0.28	1.06	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00
Malta	Conventional	1995–1999	0.19	0.01	0.02	0.12	2.68	0.00	0.00	0.00	0.00				
		2000–2002	0.20	0.02	0.01	0.05	0.53	0.00	0.00	0.00	0.01	0.00	0.00	0.28	0.44
	Interventional	1995–1999	0.08	0.01	0.00	0.05	0.93	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.06
		2000–2002	0.15	0.01	0.04	0.26	3.22	0.00	0.00	0.00	0.01				
Netherlands	Conventional	1995–1999	8.42	3.39	3.13	0.37	0.92	0.00	0.01	0.01	0.07	0.00	0.00	0.01	0.16
		2000–2002	9.40	3.57	2.73	0.29	0.78	0.00	0.00	0.01	0.06	0.00	0.00	0.02	0.18
	Interventional	1995–1999	3.27	1.27	1.22	0.37	2.47	0.00	0.00	0.01	0.08	0.00	0.00	0.00	0.04
		2000–2002	3.52	1.36	1.02	0.29	2.04	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.03
Peru	Conventional	1995–1999	0.03	0.03	0.10	3.14	3.14	0.04	0.08	0.15	0.64	0.00	0.00	0.00	0.00
	Interventional	2000–2002	0.03	0.03	0.05	1.57	1.57	0.00	0.00	0.02	0.65	0.00	0.00	0.00	0.00
		2002	0.01	0.01	0.03	3.91	3.91	0.00	0.00	0.29	1.00	0.00	0.00	0.00	0.00
Philippines	Conventional	1995–1999	2.22	0.07	0.11	0.05	1.37	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
		2000–2002	2.20	0.19	0.15	0.07	0.76	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
	Interventional	1995–1999	0.04	0.01	0.03	0.79	2.16	0.00	0.00	0.02	0.11	0.00	0.00	0.00	0.00
		2000–2002	0.13	0.04	0.02	0.17	0.60	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Romania	Conventional	1995–1999	3.70	3.63	4.58	1.24	1.26	0.00	0.00	0.01	0.77	0.03	0.03	0.05	0.87
		2000–2002	6.40	4.43	3.43	0.54	0.84	0.00	0.00	0.00	0.20	0.03	0.04	0.07	0.85
	Interventional	2000–2002	0.09	0.09	0.33	3.58	3.58	0.01	0.03	0.14	0.94	0.03	0.09	0.34	0.99
Slovakia	Conventional	2000–2002	3.60	3.59	6.45	1.79	1.79	0.00	0.01	0.03	0.78	0.00	0.00	0.00	0.00
	Interventional	2000–2002	0.12	0.12	0.45	3.72	3.79	0.04	0.08	0.18	0.90	0.00	0.00	0.00	0.00
United Kingdom	Conventional	2001	10		0.703	0.07									
	Interventional	2001	0.640		0.140	0.21									

[a] Orthopaedists, surgeons, gastroenterologists and auxiliary staff of similar categories.

Table A-26 Exposures to workers from nuclear medicine according to job category

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Job category*	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Croatia	Technicians	1995-1999	0.12	0.08	0.18	1.49	2.35	0.00	0.02	0.12	0.31	0.04	0.17	0.62	0.91
		2000–2002	0.07	0.03	0.02	0.34	0.94	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.74
	Medical doctors	2000–2002	0.08	0.04	0.05	0.58	1.35	0.00	0.00	0.02	0.18	0.00	0.00	0.20	0.78
Cyprus	Technicians	1995–1999	0.01	0.01	0.01	0.83	0.83	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00
		2000–2002	0.01	0.01	0.01	1.78	1.78	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.00
	Medical doctors	1995–1999	0.01	0.01	0.01	1.30	1.30	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.00
		2000–2002	0.01	0.01	0.01	1.33	1.33	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00
Czech Rep.	Technicians and nurses	1995–1999	0.79	0.77	1.25	1.59	1.63	0.00	0.00	0.05	0.53	0.00	0.01	0.21	0.85
		2000–2002	0.81	0.76	1.04	1.29	1.36	0.00	0.00	0.02	0.42	0.01	0.03	0.12	0.78
	Medical doctors	1995–1999	0.32	0.30	0.47	1.48	1.54	0.00	0.01	0.04	0.50	0.02	0.07	0.19	0.83
		2000–2002	0.35	0.32	0.38	1.08	1.18	0.00	0.00	0.02	0.34	0.00	0.03	0.13	0.75
Finland	Technicians	1995–1999	0.38	0.09	0.11	0.29	1.22	0.00	0.00	0.00	0.12	0.00	0.00	0.05	0.80
		2000–2002	0.36	0.11	0.09	0.25	0.81	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.66
	Medical doctors	1995–1999	0.09	0.01	0.01	0.14	0.94	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.71
		2000–2002	0.09	0.01	0.00	0.05	0.32	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.29
Greece	Technicians	1995–1999	0.26	0.12	0.23	0.89	2.03								
		2000–2002	0.28	0.15	0.20	0.73	1.41								
	Medical doctors	1995–1999	0.18	0.08	0.13	0.71	1.53								
		2000–2002	0.21	0.11	0.12	0.58	1.08								
	Nurses	1995–1999	0.04	0.01	0.02	0.48	1.41								
		2000–2002	0.08	0.03	0.05	0.59	1.49								
	Others	1995–1999	0.06	0.02	0.02	0.33	1.38								
		2000–2002	0.07	0.02	0.02	0.23	0.75								
Kuwait	Technicians	1995–1999	0.04	0.04	0.05	1.51	1.51	0.00	0.01	0.04	0.45	0.00	0.04	0.19	0.93
		2000–2002	0.04	0.04	0.07	1.72	1.72	0.00	0.01	0.06	0.48	0.00	0.07	0.26	0.94
	Nurses and others	1995–1999	0.11	0.11	0.13	1.24	1.24	0.00	0.01	0.07	0.28	0.00	0.09	0.39	0.89
		2000–2002	0.13	0.13	0.15	1.14	1.14	0.00	0.00	0.04	0.29	0.00	0.03	0.25	0.87

Country	*Job category*	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Lithuania	Technicians	1995–1999	0.04	0.03	0.06	1.65	1.98	0.00	0.00	0.01	0.82	0.00	0.00	0.04	0.94
		2000–2002	0.04	0.03	0.06	1.50	2.24	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.83
	Medical doctors	1995–1999	0.02	0.01	0.03	1.40	2.01	0.00	0.01	0.02	0.69	0.00	0.09	0.13	0.86
		2000–2002	0.02	0.01	0.02	1.10	1.94	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.71
	Nurses	1995–1999	0.02	0.01	0.03	1.67	2.29	0.00	0.00	0.02	0.77	0.00	0.00	0.08	0.85
		2000–2002	0.02	0.01	0.03	1.95	3.12	0.02	0.06	0.08	0.60	0.15	0.38	0.44	0.86
Malta	Technicians	1995–1999	0.01	0.00	0.00	0.17	0.62								
		2000–2002	0.00	0.00	0.00	0.38	0.51								
	Nurses	1995–1999	0.02	0.00	0.00	0.02	0.36								
		2000–2002	0.03	0.00	0.00	0.02	0.42								
Netherlands	Technicians	1995–1999	3.53	0.57	0.25	0.07	0.46	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02
		2000–2002	3.22	0.43	0.20	0.06	0.49	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02
	Medical doctors	1995–1999	0.69	0.39	0.31	0.45	0.79	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.05
		2000–2002	0.79	0.47	0.34	0.43	0.73	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.06
Sweden	Doctors	1999	0.04	0.02	0.01	0.22	0.43	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.27
		2000–2002	0.04	0.02	0.01	0.29	0.67	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.66
	Nurses and others	1999	0.19	0.11	0.07	0.37	0.64	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.39
		2000–2002	0.24	0.13	0.1	0.4	0.76	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.63
	Preparing personnel	1999	0.06	0.04	0.02	0.3	0.41	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.12
		2000–2002	0.06	0.04	0.03	0.46	0.68	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.58
United Kingdom	Technicians	2001	0.358		0.23	0.63									
	Medical doctors	2001	0.068		0.19	0.28									
	Nurses	2001	0.064		0.04	0.70									

Table A-27 Exposures to workers from all medical uses of radiation[a]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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}
Argentina	1985–1989	3.45	1.20	3.74	1.08	3.12	0.13				0.48			
	1990–1994	6.81		10.39	1.53	3.99	0.04	0.04	0.05	0.18	0.6	0.62	0.68	0.93
	1995–1999	2.48	1.27	2.69	1.08	2.12	0.01	0.02	0.04	0.18	0.18	0.27	0.42	0.74
	2000–2002	2.55	1.30	2.88	1.13	2.22	0.01	0.02	0.07	0.22	0.05	0.19	0.50	0.90
Australia[c, d]	1975–1979	6.23		3.45	0.55									
	1985–1989	15.80	8.96	1.11	0.07	0.12	0.00				0.04			
	1990–1994	14.77		2.01	0.14	0.23	0.00	0.00	0.00	0.02	0.14	0.15	0.21	0.54
	2001	16.78		2.11	0.13									
Belarus	2000–2002	3.98	3.29	5.33	1.34	1.62								
Brazil[e]	1985–1989	76.00	23.00	115.00	1.51	4.96								
	1990–1994	6.39		3.37	0.53	3.32	0.00	0.01	0.02	0.07	0.43	0.54	0.70	0.93
	1995–1999	4.99	2.53	5.69	1.14	2.25	0.01	0.04	0.06	0.14				
	2000–2002	7.80	2.96	5.53	0.71	1.87	0.01	0.02	0.05	0.11				
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
	1995–1999	3.66	0.48	1.26	0.35	2.65								
Canada	1975–1979	39.60	11.80	10.40	0.26	0.88	0.00				0.08			
	1980–1984	51.70	7.88	8.30	0.16	1.05	0.00				0.04			
	1985–1989	62.90	10.80	9.18	0.15	0.85	0.00				0.06			
	1990–1994	63.65	6.82	5.65	0.09	0.83	0.00	0.00	0.00	0.02	0.07	0.09	0.21	0.67
	1995–1999	45.91	3.86	3.60	0.08	0.93	0.00	0.00	0.01	0.13	0.09	0.11	0.20	0.60
	2000–2002	49.39	3.83	4.46	0.09	1.16	0.00	0.00	0.01	0.14	0.15	0.17	0.26	0.62
Chile	1995–1999	0.17	0.17	0.71	4.20	4.20	0.04	0.05	0.16	1.56	0.66	0.68	0.79	1.88
	2000–2002	0.29	0.28	1.20	4.09	4.36	0.07	0.10	0.33	2.67	0.39	0.42	0.61	2.18
China	1985–1989	86.80	14.40	156.00	1.80	10.90	0.03				0.43			
	1990–1994	13.96		22.90	1.64	1.76	0.01	0.03	0.05	0.32	0.24	0.33	0.43	0.77
	1995–1999	109.49	70.66	164.38	1.50	2.33	0.01	0.01	0.03	0.30	0.11	0.19	0.27	0.93
	2000–2002	115.63	74.12	133.69	1.16	1.80	0.00	0.01	0.02	0.30	0.06	0.15	0.24	0.98

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
China - Taiwan Province	1980–1984	3.08		1.77	0.57									
	1985–1989	3.98		1.96	0.49									
	1990–1994	6.01	1.35	0.93	0.15	0.69	0.00	0.00	0.00	0.01	0.02	0.02	0.08	0.16
	1995–1999	7.71	0.63	0.52	0.07	0.83	0.00	0.00	0.00	0.01	0.49	0.53	0.67	0.88
	2000–2002	8.77	0.63	0.55	0.06	0.87	0.00	0.00	0.00	0.01	0.16	0.38	0.47	0.70
Croatia	1990–1994	3.44	1.89	0.62	0.18	0.33								
	2000–2002	3.90	1.15	0.84	0.22	0.73	0.00	0.00	0.01	0.06	0.01	0.04	0.18	0.52
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	0.3	0.86
	1995–1999	0.30	0.30	0.14	0.47	0.47	0.00	0.00	0.00	0.22	0.00	0.00	0.01	0.26
	2000–2002	0.30	0.30	0.27	0.90	0.91	0.00	0.00	0.00	0.32	0.00	0.01	0.01	0.28
Czech Rep.[f]	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	11.60	4.04	9.12	0.78	2.25	0.00				0.10			
	1990–1994	9.40		7.82	0.83	1.51	0.00	0.00	0.01	0.19	0.05	0.09	0.16	0.69
	1995–1999	9.89	5.94	10.28	1.04	1.73	0.00	0.00	0.03	0.34	0.04	0.07	0.18	0.66
	2000–2002	11.14	5.08	8.38	0.75	1.65	0.00	0.01	0.02	0.22	0.02	0.08	0.21	0.62
Denmark	1975–1979	6.13		3.32	0.54		0.00				0.22			
	1980–1984	6.02		2.08	0.35		0.00				0.10			
	1985–1989	6.04		1.18	0.20		0.00				0.01			
	1990–1994	5.28	1.76	1.04	0.20	0.59	0.00	0.00	0.00	0.05	0.01	0.02	0.09	0.60
	1995–1999	5.72	1.82	1.05	0.18	0.58	0.00	0.00	0.00	0.12	0.02	0.05	0.10	0.56
	2000–2002	6.08	1.61	0.93	0.15	0.58	0.00	0.00	0.00	0.11	0.00	0.00	0.04	0.46
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
El Salvador	2001–2002	0.52	0.52	0.67	1.29	1.30	0.00	0.01	0.08	0.64	0.00	0.05	0.07	0.23
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
	1995–1999	5.24	0.80	2.00	0.38	2.52	0.00	0.00	0.01	0.05	0.08	0.11	0.17	0.51
	2000–2002	5.38	0.91	1.79	0.33	1.97	0.00	0.00	0.01	0.04	0.08	0.11	0.16	0.42

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	40.90		49.30	1.21		0.00							
	1980–1984	59.20	8.06	36.00	0.61	4.46	0.00							
	1985–1989	73.70	0.42	25.10	0.34	3.06	0.00							
	1995–1999	128.25		18.29	0.14		0.00							
	2000–2002	132.44		12.04	0.09		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	158.60	22.20	29.54	0.34	1.18	0.00				0.14			
	1985–1989	209.60	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
	1995–1999	229.67	24.51	22.57	0.10	0.92	0.00	0.00	0.00	0.01	0.12	0.17	0.29	0.72
	2000–2002	230.00	27.06	17.16	0.07	0.63	0.00	0.00	0.00	0.01	0.03	0.05	0.18	0.61
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	0.7	0.93
	1995–1999	5.93	1.22	4.01	0.68	3.28	0.00	0.01	0.02	0.09	0.23	0.34	0.60	0.90
	2000–2002	7.47	1.72	3.92	0.52	2.28	0.00	0.00	0.02	0.07	0.26	0.30	0.55	0.86
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
	1995–1999	8.550	0.628	0.745	0.087	1.186	0.00	0.00	0.01	0.04	0.11	0.15	0.23	0.52
	2000–2002	8.852	2.778	1.881	0.213	0.677	0.00	0.00	0.01	0.08	0.10	0.14	0.20	0.48
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
	1995–1999	0.53	0.12	0.10	0.19	1.56	0.00	0.00	0.00	0.04	0.07	0.08	0.15	0.81
	2000–2002	0.54	0.13	0.10	0.18	1.34	0.00	0.00	0.00	0.04	0.02	0.05	0.10	0.65
India	1975–1979	9.58	5.22	7.89	0.82	1.51	0.00				0.30			
	1980–1984	11.60	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

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	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			
	1995–1999	0.09	0.09	0.06	0.63	0.63	0.00	0.10	0.12	0.19	0.00	0.09	0.22	0.50
	2000–2002	0.20	0.20	0.09	0.46	0.46	0.00	0.00	0.01	0.08	0.00	0.06	0.22	0.50
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	0.07	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	55.30	21.70	35.70	0.65	1.65								
	1980–1984	111.00	34.20	44.00	0.40	1.29								
	1985–1989	142.00	38.60	46.60	0.33	1.21								
	1990–1994	178.40	45.67	66.63	0.37	1.46	0.00	0.01	0.02	0.08	0.17	0.25	0.41	0.80
	1995–1999	201.92	51.43	79.78	0.40	1.55	0.00	0.00	0.01	0.05	0.20	0.30	0.49	0.85
	2000–2002	227.88	57.42	76.40	0.34	1.33	0.00	0.00	0.01	0.05	0.17	0.26	0.43	0.83
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
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
	1995–1999	0.85	0.85	0.78	0.92	0.92	0.00	0.00	0.02	0.15	0.05	0.09	0.17	0.62
	2000–2002	0.88	0.88	0.73	0.83	0.83	0.00	0.00	0.02	0.16	0.06	0.08	0.19	0.63
Lithuania	1995–1999	2.35	1.61	3.16	1.34	1.96	0.00	0.00	0.01	0.63	0.00	0.02	0.05	0.81
	2000–2002	2.65	1.05	2.76	1.04	2.63	0.00	0.00	0.01	0.40	0.01	0.03	0.07	0.59
Luxembourg	1995–1999	0.80	0.41	0.36	0.45	0.89	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
	2000–2002	0.79	0.41	0.32	0.40	0.77	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
Malta	1995–1999	0.32	0.02	0.05	0.16	2.50	0.00	0.00	0.00	0.01	0.36	0.36	0.38	0.75
	2000–2002	0.39	0.05	0.05	0.13	1.09	0.00	0.00	0.00	0.03	0.23	0.23	0.25	0.57
Mexico	1985–1989	0.73	0.52	2.09	2.86	4.02	0.03				0.24			
	1990–1994	1.27		1.18	0.93									
	1995–1999	1.38	1.38	3.60	2.60	2.60	0.01	0.02	0.06	1.02	0.15	0.17	0.20	0.36
	2000–2002	1.04	1.04	3.67	3.53	3.53	0.01	0.02	0.11	0.96	0.02	0.02	0.09	0.33
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
	1995–1999	0.22	0.22	0.07	0.31	0.31	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.02
	2000–2002	0.38	0.38	0.13	0.35	0.35	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.01

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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	0.6	0.84
	1995–1999	21.97	6.45	7.06	0.32	1.09	0.00	0.00	0.00	0.03	0.07	0.09	0.16	0.42
	2000–2002	23.63	6.52	6.30	0.27	0.97	0.00	0.00	0.00	0.02	0.03	0.07	0.15	0.30
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	1.58		7.03	4.46									
	1985–1989	1.70		7.14	4.20									
	1990–1994	1.98	1.67	5.34	2.70	3.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1995–1999	0.07	0.07	0.22	3.06	3.10	0.04	0.06	0.13	0.73	0.28	0.38	0.53	0.95
	2000–2002	0.09	0.09	0.26	2.80	2.80	0.01	0.03	0.12	0.77	0.02	0.11	0.32	0.91
Philippines	1995–1999	2.61	0.16	0.35	0.14	2.22	0.01	0.01	0.02	0.08	0.15	0.20	0.43	0.88
	2000–2002	2.83	0.42	0.36	0.13	0.85	0.00	0.00	0.00	0.06	0.12	0.17	0.28	0.70
Portugal	1985–1989	3.83	0.97	2.01	0.52	2.06	0.00							
Romania	1995–1999	5.86	5.75	9.15	1.56	1.59	0.00	0.01	0.04	0.86	0.03	0.06	0.13	0.95
	2000–2002	7.97	5.70	5.08	0.64	0.89	0.00	0.01	0.02	0.44	0.03	0.06	0.13	0.91
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
	1995–1999													
	2000–2002	4.00	4.00	7.44	1.86	1.86								
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
	2000–2002	2.40	1.17	0.52	0.22	0.44	0.00	0.00	0.00	0.07	0.00	0.01	0.06	0.41
South Africa	1975–1979	8.76	5.49	0.57	0.06	0.10	0.00				0.08			
	1980–1984	10.70	4.13	7.37	0.69	1.79	0.01				0.52			
	1985–1989	12.10	2.64	9.53	0.79	3.61	0.00				0.23			
Spain	1985–1989	37.70	34.00	29.30	0.78	0.86	0.00				0.12			
	2000–2002	68.28	43.01	34.06	0.50	0.79	0.00	0.01	0.02	0.13	0.11	0.13	0.20	0.69
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	0.20	0.77

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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}
Sweden	1975–1979	11.50	1.29	2.84	0.25	2.21	0.01							
	1980–1984	12.80	1.38	2.53	0.20	1.83	0.00							
	1985–1989	13.20	3.66	3.13	0.24	0.86	0.00							
	1990–1994	7.79		2.39	0.31									
	1999	4.09	2.20	1.02	0.25	0.46	0.00	0.00	0.00	0.05	0.00	0.00	0.02	0.35
	2000-2002	5.26	1.99	1.09	0.21	0.55	0.00	0.00	0.00	0.06	0.02	0.03	0.10	0.54
Switzerland	1975–1979	21.50		6.20	0.29		0.00				0.12			
	1980–1984	30.10		4.97	0.17		0.00				0.09			
	1985–1989	36.10		1.83	0.05		0.00				0.03			
	1990–1994	38.68		1.50	0.04		0.00	0.00	0.00	0.01	0.04	0.06	0.17	0.50
	1995–1999	42.64	3.20	1.31	0.03	0.41	0.00	0.00	0.00	0.01	0.03	0.07	0.19	0.50
	2000–2002	46.14	1.81	0.86	0.02	0.47	0.00	0.00	0.00	0.00	0.02	0.07	0.22	0.58
Syrian Arab Rep.	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
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	39.00		28.00	0.71									
	1985–1989	40.00		8.40	0.21									
	1990–1994	37.81		4.10	0.11									
	2000–2002	25.06		3.09	0.12									
United States[j]	1975–1979	485		460	0.95									
	1980–1984	584		410	0.70									
	1985–1989	734	267	280	0.38	1.05								
Utd. 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
Total reported data[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	205	0.29	1.30	0.00	0.00	0.01	0.05	0.21	0.28	0.41	0.77
	1995–1999	894	224	375	0.42	1.67	0.00	0.01	0.02	0.24	0.13	0.16	0.25	0.64
	2000–2002	1030	252	344	0.33	1.37	0.00	0.01	0.02	0.18	0.06	0.11	0.21	0.61

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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
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				0.1			
	1985–1989	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	0	[0.01]	[0.07]	[0.15]	[0.22]	[0.35]	[0.7]
	1995–1999	7440		3540	0.48		0.00	0.00	0 01	0.05	0.13	0.20	0.33	0 70
	2000–2002	7440		3540	0.48		0.00	0.00	0 01	0.05	0.13	0.20	0.33	0 70

[a] Data are annual values averaged over the periods indicated.

[b] 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, because the reported data included only about 70% of the exposed workforce.

[d] The method of dose recording was different in the two periods for which data were reported, and this may partly account for differences in the 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. 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 estimated by scaling up from a sample of approximately 25% of the monitored workers.

[f] Data for 1975-1989 are for Czechoslovakia.

[g] Reported doses are overestimates, because the dosimeter was calibrated in terms of the skin surface dose and was worn above the apron when one was used. For X-ray diagnostic radiology, preliminary studies indicate that the overestimate may be by a factor 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 period 1990–1994, the data for 1990 relate only to the Federal Republic of Germany.

[i] Reported data have been estimated by scaling up from a sample of approximately 33% of the monitored workers.

[j] Data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative of 1975–1979, 1980–1984 and 1985–1989, respectively.

[k] Figures quoted are rounded values.

[l] The total for measurably exposed workers has been estimated by scaling up to take account of those countries that reported the number of monitored workers but not the number of measurably exposed workers. Reported data contain a contribution from radiotherapy.

[m] These data should be interpreted with care, particularly because the countries included in the summations may differ from one period to another, depending on whether data were reported. Consequently, direct comparison between data for different periods is invalid. It should also be noted that the data for NR_{15} and SR_{15} are averages of the data reported. In general, these data are less complete than those included in the summations for the numbers of workers and the collective doses. Values shown in brackets are the world estimates based on the standard method given in Section III.A.3. However, the Committee identified a more robust method of estimation for this instance based on taking the regional value for the United States to be equivalent to the rest of the OECD. The resulting values are shown without brackets.

Table A-28 Exposures to workers from various industrial uses of radiation[a]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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
	1995–1999	0.04	0.02	0.01	0.28	0.63	0.00	0.00	0.01	0.09	0.00	0.00	0.11	0.66
	2000–2002	0.03	0.02	0.02	0.53	0.92	0.00	0.00	0.01	0.22	0.00	0.00	0.09	0.71
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
	1995–1999													
	2001													
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
	1995–1999													
	2000–2002													
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
	1995–1999	1.27	0.40	1.22	0.96	1.33	0.00	0.00	0.01	0.21	0.04	0.11	0.24	
	2000	1.40	0.89	0.88	0.63	0.58	0.01	0.01	0.01	0.29	0.34	0.36	0.42	
China - Taiwan Province	1995–1999	0.13	0.00	0.01	0.08	10.45	0.00	0.00	0.00	0.00	0.98	0.98	0.98	0.98
	2000–2002	0.24	0.01	0.02	0.07	1.94	0.00	0.00	0.00	0.02	0.00	0.00	0.29	0.92
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
	1995–1999													
	2000–2002													
Czech Rep.	1995–1999	0.03	0.03	0.02	0.83	0.95	0.00	0.01	0.01	0.18	0.00	0.08	0.08	0.44
	2000–2002	0.03	0.03	0.02	0.81	0.86	0.01	0.01	0.01	0.15	0.27	0.27	0.27	0.49
Denmark	1995–1999	0.27	0.06	0.03	0.10	0.47	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.50
	2000–2002	0.22	0.04	0.03	0.13	0.77	0.00	0.00	0.00	0.04	0.00	0.00	0.11	0.65
Ecuador	1993–1994	0.01	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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[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
	1995–1999													
	2000–2002													
Greece	1995–1999	0.01	0.00	0.00	0.00									
	2000–2002	0.00	0.00	0.00	0.00									
Hungary	1995–1999	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
	2000–2002	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Indonesia	1995–1999	0.03	0.03	0.01	0.26	0.26	0.00	0.00	0.00	0.13	0.00	0.00	0.00	1.00
	2000–2002	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	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
	1995–1999													
	2000–2002													
Japan	1990–1994	54.90	1.79	4.95	0.09	2.76	0.00	0.00	0.00	0.01	0.43	0.55	0.74	0.93
	1995–1999		1.14	2.24	0.71	1.96	0.00	0.01	0.04	0.17	0.11	0.20	0.46	0.89
	2000–2002	3.00	1.07	1.76	0.59	1.67	0.00	0.01	0.03	0.14	0.09	0.18	0.41	0.86
Kuwait	1995–1999	0.14	0.14	0.32	2.20	2.24	0.01	0.04	0.16	0.40	0.11	0.24	0.62	0.95
	2000–2002	0.12	0.12	0.27	2.34	2.34	0.01	0.05	0.15	0.37	0.16	0.36	0.65	0.94
Mexico	1990–1994	0.06		0.03	0.48									
	1997–1999	0.06	0.06	0.14	2.40	2.40	0.01	0.01	0.01	1.00	0.58	0.58	0.58	1.00
	2000–2002	0.06	0.06	0.10	1.60	1.60	0.00	0.00	0.00	0.85	0.00	0.00	0.00	0.93
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
	1995–1999	0.01	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00				
	2000–2002	0.01	0.01	0.00	0.07	0.00	0.00	0.00	0.00	0.00				
Philippines	2000–2002	0.01	0.01	0.00	0.09	0.16	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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	2000–2002	1.37	0.57	0.57	0.42	1.01	0.01	0.01	0.02	0.06	0.35	0.42	0.56	0.78
Syrian Arab Rep.	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
	1995–1999													
	2000–2002													
Total reported data[u]	1990–1994	57.20	2.45	5.96	0.10	2.28	0.00	0.00	0.00	0.01	0.41	0.52	0.70	0.91
	1995–1999	2.01	1.88	4.00	2.00	2.13	0.00	0.01	0.02	0.20	0.20	0.24	0.34	0.80
	2000–2002	6.55	2.85	3.67	0.56	1.29	0.00	0.01	0.02	0.16	0.11	0.14	0.25	0.63
Industrial radiography														
Argentina	1985–1989	0.05	0.01	0.03	0.59	2.70								
	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
	1995–1999	0.71	0.24	0.35	0.50	1.56	0.00	0.01	0.02	0.14	0.16	0.22	0.40	1.00
	2000–2002	0.70	0.33	0.35	0.50	1.20	0.00	0.00	0.02	0.17	0.00	0.00	0.15	0.80
Australia	1985–1989	0.40	0.26	0.40	1.01	1.52	0.01	0.00			0.11			
	1990–1994	2.51	1.02	0.47	0.19	0.46	0.00	0.02	0.01	0.04	0.04	0.12	0.29	0.73
	1995–1999													
	2001	0.45		0.09	0.20									
Belarus	2000-2002	1.35	1.35	4.59	3.41	3.41	0.00	0.00	0.16	1.00	0.00	0.00	0.27	0.84
Brazil[f, n]	1985–1989				3.30	14.50								
	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
	1995–1999	0.33	0.09	0.28	0.86	2.97	0.00	0.01	0.04	0.17				
	2000–2002	0.37	0.06	0.16	0.42	2.66	0.00	0.00	0.03	0.11				
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
	1995–1999	0.64	0.24	0.63	0.98	3.79	0.01	0.01	0.03	0.29	0.11	0.18	0.33	0.82
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	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
	1995–1999	2.47	1.33	7.77	3.14	5.80	0.05	0.10	0.20	0.40	0.41	0.59	0.81	0.98
	2000–2002	2.88	1.48	7.74	2.69	5.24	0.04	0.08	0.18	0.39	0.30	0.50	0.77	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
	1995–1999	18.59	12.00	23.72	1.28	1.97	0.01	0.02	0.03	0.31	0.12	0.22	0.31	0.98
	2000–2002	16.99	10.87	18.18	1.07	1.67	0.00	0.01	0.02	0.30	0.06	0.14	0.21	1.00
China - Taiwan Province	1985–1989	1.01		1.53	1.52									
	1990–1994	2.39	1.09	0.91	0.38	0.84								
	1995–1999	1.23	0.45	1.96	1.59	4.28	0.02	0.04	0.09	0.23	0.37	0.54	0.74	0.97
	2000–2002	1.18	0.48	1.86	1.58	3.92	0.02	0.04	0.10	0.26	0.27	0.44	0.72	0.96
Croatia	1990–1994	0.04	0.02	0.05	1.43	2.50								
	1995–1999													
	2000–2002	0.09	0.04	0.09	1.25	3.06	0.03	0.04	0.07	0.18	0.56	0.64	0.79	0.92
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
	1995–1999													
	2000–2002													
Cyprus	1995–1999	0.01	0.01	0.00	0.34	0.34	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.06
	2000–2002	0.02	0.02	0.01	0.92	0.91	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.53
Czech Rep.[v]	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
	1995–1999	0.81	0.77	1.58	1.96	2.07	0.01	0.03	0.10	0.44	0.12	0.25	0.49	0.87
	2000–2002	0.75	0.66	1.20	1.59	1.83	0.01	0.03	0.09	0.33	0.14	0.26	0.52	0.87

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.24		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
	1995–1999	0.36	0.20	0.37	1.02	1.83	0.00	0.01	0.05	0.29	0.00	0.06	0.34	0.84
	2000–2002	0.31	0.16	0.33	1.06	2.11	0.00	0.01	0.06	0.26	0.06	0.17	0.46	0.86
Ecuador	1993–1994	0.02	0.01	0.03	1.16	2.36	0.00	0.00	0.04	0.38				
	1995–1999													
	2000–2002													
El Salvador	2002	0.01	0.01	0.03	2.77	2.77	0.00	0.00	0.14	0.71	0.00	0.00	0.00	0.00
Estonia	1995–1999	0.03	0.03	0.07	2.63	2.63	0.02	0.05	0.11	0.66	0.22	0.31	0.47	0.92
	2000–2002	0.03	0.03	0.05	1.72	1.72	0.00	0.02	0.06	0.55	0.00	0.14	0.29	0.83
Iceland	1990–1994	0.02	0.00		0.00		0.00	0.00	0.00	0.00				
	1995–1999	0.03	0.00	0.00	0.09	1.09	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.89
	2000–2002	0.04	0.00	0.00	0.06	0.61	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.24
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
	1995–1999	0.40	0.09	0.08	0.20	0.89	0.00	0.00	0.00	0.07	0.00	0.00	0.04	0.63
	2000–2002	0.36	0.13	0.11	0.30	0.84	0.00	0.00	0.00	0.10	0.00	0.00	0.03	0.66
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							
	1995–1999													
	2000–2002													
Gabon	1992–1994	0.00	0.00	0.08	20.48	20.48	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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]	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
	1995–1999													
	2000–2002													
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
	1995–1999	0.27	0.05	0.12	0.44	2.30	0.00	0.00	0.03	0.12	0.03	0.12	0.44	0.92
	2000–2002	0.25	0.07	0.18	0.73	2.64	0.00	0.01	0.04	0.17	0.04	0.20	0.49	0.94
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
	1995–1999	0.94	0.18	0.42	0.45	2.36	0.00	0.00	0.02	0.12	0.10	0.15	0.41	0.94
	2000–2002	0.98	0.38	0.89	0.91	2.31	0.01	0.02	0.05	0.18	0.17	0.29	0.54	0.90
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
	1995–1999													
	2000–2002													
India	1980–1984	2.93	1.39	9.00	3.07	6.50	0.06				0.55			
	1985–1989	4.23	2.12	13.20	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
	1995–1999													
	2000–2002													
Indonesia	1980–1984	0.14	0.02	0.22	1.53	10.80	0.03				0.45			
	1985–1989	0.43	0.03	0.40	0.95	14.90	0.06				0.10			
	1990–1994													
	1995–1999	0.29	0.06	0.11	0.39	1.71	0.01	0.01	0.03	0.06	0.29	0.46	0.74	0.99
	2000–2002	0.36	0.13	0.33	0.92	2.16	0.01	0.03	0.07	0.14	0.14	0.43	0.75	0.97

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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*
Ireland	1980–1984	0.07	0.04	0.05	0.75	1.39								
	1985–1989	0.05	0.03	0.06	1.41	2.57	0.01				0.15			
	1990–1994	0.09	0.02	0.03	0.35	1.58	0.00	0.00	0.03	0.12	0.00	0.00	0.35	0.79
	1995–1999													
	2000–2002													
Japan	1980–1984	3.31	1.58	5.67	1.71	3.59	0.02							
	1985–1989	2.83	1.08	3.35	1.19	3.09	0.01							
	1990–1994	4.35	1.41	4.00	0.83	2.57	0.01	0.02	0.05	0.15	0.24	0.38	0.62	0.93
	1995–1999	3.14	1.14	2.24	0.71	1.96	0.00	0.01	0.04	0.17	0.11	0.20	0.46	0.89
	2000–2002	3.00	1.07	1.76	0.59	1.67	0.00	0.01	0.03	0.14	0.09	0.18	0.41	0.86
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
	1995–1999	0.14	0.14	0.32	2.20	2.24	0.01	0.04	0.16	0.40	0.11	0.24	0.62	0.95
	2000–2002	0.12	0.12	0.27	2.34	2.34	0.01	0.05	0.15	0.37	0.16	0.36	0.65	0.94
Lithuania	1995–1999	0.06	0.05	0.22	3.70	4.57	0.03	0.10	0.20	0.82	0.21	0.43	0.63	0.98
	2000–2002	0.08	0.05	0.14	1.78	2.99	0.01	0.01	0.05	0.61	0.08	0.08	0.26	0.82
Luxembourg	1995–1999	0.03	0.02	0.02	0.69	1.27	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
	2000–2002	0.02	0.02	0.03	1.10	1.29	0.00	0.00	0.01	0.36	0.00	0.00	0.00	0.00
Malta	1995–1999	0.01	0.00	0.00	0.11	0.42	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.48
	2000–2002	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
Mexico	1985–1989	0.82	0.49	5.10	6.23	10.50	0.10				0.67			
	1990–1994	0.87		4.83	5.58									
	1997–1999	0.75	0.75	7.58	10.15	10.15	0.13	0.21	0.37	1.00	0.58	0.67	0.79	1.00
	2000–2002	0.84	0.84	7.31	8.75	8.75	0.12	0.27	0.59	0.97	0.40	0.60	0.87	1.00
Myanmar	1994	0.00	0.00	0.00	0.75	0.75	0.00	0.00	0.00	0.50				
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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
Netherlands[i]	1980–1984	0.97		0.34	0.35		0.00				0.13			
	1985–1989	1.02		0.48	0.47		0.00				0.20			
	1990–1994	1.00	0.64	1.52	1.52	2.38	0.01	0.02	0.07	0.33	0.19	0.25	0.50	0.92
	1995–1999	1.01	0.60	1.18	1.17	2.04	0.00	0.01	0.06	0.30	0.09	0.12	0.43	0.93
	2000–2002	0.88	0.59	0.93	1.06	1.60	0.00	0.01	0.05	0.25	0.13	0.17	0.41	0.86
New Zealand	1980–1984	0.15		0.35	2.33									
	1995–1999													
	2000–2002													
Norway	1980–1984	0.80	0.44	0.79	0.99	1.81	0.00				0.04			
	1985–1989	0.82	0.40	0.62	0.76	1.56	0.00				0.10			
	1990–1994	1.11	0.26	0.31	0.28	1.19	0.00	0.00	0.01	0.09				
	1995–1999													
	2000–2002	0.76	0.12	0.20	0.26	1.55	0.00	0.00	0.01	0.05				
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
	1995–1999													
	2000–2002													
Peru	1994	0.04	0.03	0.18	5.00	6.73	0.00	0.00	0.11	0.20				
	1995–1999													
	2000–2002													
Philippines	1995–1999	0.26	0.05	0.11	0.43	1.99	0.00	0.00	0.01	0.11	0.00	0.10	0.23	0.90
	2000–2002	0.29	0.10	0.43	1.47	4.39	0.03	0.04	0.05	0.15	0.65	0.75	0.83	0.99
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
	1995–1999													
	2000–2002													
Romania	1995–1999	1.52	0.71	3.63	2.39	5.08	0.01	0.04	0.16	0.44	0.14	0.30	0.67	0.99
	2000–2002	1.02	0.80	2.80	2.75	3.48	0.01	0.02	0.10	0.67	0.11	0.16	0.38	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
	1995–1999													
	2000–2002	0.42	0.42	0.67	1.60	1.66	0.00	0.00	0.01	0.77				

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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
	1995–1999													
	2000–2002	0.12	0.04	0.07	0.55	1.64	0.00	0.01	0.02	0.12	0.19	0.25	0.51	0.89
South Africa	1975–1979	0.57	0.31	0.11	0.19	0.35								
	1980–1984	0.75	0.45	2.38	3.18	5.30	0.05				0.44			
	1985–1989	0.72	0.32	1.68	2.33	5.29	0.03				0.36			
	1995–1999													
	2000–2002													
Spain	1985–1989	0.82	0.66	1.23	1.50	1.87	0.02				0.32			
	1995–1999													
	2000–2002	1.07	0.65	1.77	1.66	2.73	0.02	0.04	0.09	0.24	0.30	0.45	0.69	0.93
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
	1995–1999													
	2000–2002													
Sweden	1975–1979	0.77	0.19	0.49	0.63	2.56	0.01				0.16			
	1980–1984	0.66	0.17	0.38	0.57	2.27	0.00				0.06			
	1985–1989	0.64	0.25	0.28	0.43	1.12	0.00				0.15			
	1999	0.22	0.10	0.07	0.31	0.67	0.00	0.00	0.00	0.11	0.00	0.00	0.08	0.61
	2000–2002	0.23	0.08	0.13	0.58	1.65	0.00	0.01	0.01	0.06	0.46	0.50	0.50	0.77
Syrian Arab Rep.	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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
United Kingdom[j]	1980–1984	1.82		3.60	1.98		0.02							
	1985–1989	4.82	4.08	5.67	1.18	1.39	0.01				0.43			
	1990–1994	5.10	2.49	3.86	0.76	1.55	0.01	0.01	0.03	0.11				
	1995–1999													
	2000–2002													

Country	Period	Monitored workers (10^3)	Measurably exposed workers (10^3)	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 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
	1995–1999													
	2000–2002													
United States[l, m]	1975–1979	17.00		50.00	2.94									
	1980–1984	27.00		80.00	2.96									
	1985–1989	23.00	12.00	39.00	1.70	3.25								
	1990–1994	5.60	3.75	18.30	3.27	5.68	0.03	0.10	0.20	0.42	0.29	0.60	0.82	0.98
	1995–1999	3.57	2.68	14.77	4.13	5.51	0.04	0.14	0.27	0.53				
	2000–2002	3.28	2.75	17.68	5.36	6.40	0.06	0.19	0.33	0.59				
USSR	1975–1979	2.27		30.00	13.20									
	1980–1984	2.53		20.20	7.98									
	1985–1989	2.63		17.20	6.55									
Total reported data[u]	1975–1979	24.00		89.50	3.74		0.04				0.39			
	1980–1984	42.10		125.00	2.98		0.03				0.42			
	1985–1989	49.90		98.70	1.98		0.03				0.44			
	1990–1994	47.40	22.67	73.20	1.54	3.23	0.02	0.04	0.08	0.23	0.30	0.49	0.70	0.93
	1995–1999	38.11	22.04	67.73	1.78	3.07	0.01	0.03	0.08	0.28	0.14	0.23	0.41	0.82
	2000–2002	38.21	22.56	66.04	1.73	2.93	0.01	0.03	0.08	0.28	0.18	0.28	0.47	0.80
World[u]	1975–1979	72.00		190.00	2.61									
	1980–1984	116.00		230.00	1.98									
	1985–1989	108.00		160.00	1.44									
	1990–1994	106.00	53.00	170.00	1.58	3.17	0.01	0.03	0.07	0.27	0.23	0.36	0.57	0.89
	1995–1999	110.16	50.00	163.20	1.48	3.26	0.01	0.03	0.06	0.28	0.23	0.34	0.57	0.90
	2000–2002	113.46	50.00	168.10	1.48	3.36	0.01	0.03	0.05	0.27	0.21	0.35	0.57	0.90
Luminizing														
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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}*
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
	1995–1999													
	2000–2002													
China - Taiwan Province	1995–1999	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.03	0.00	0.00	0.01	0.80	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.90
France	1975–1979	0.07		0.38	5.30						0.66			
	1980–1984	0.04		0.24	5.52		0.14				0.55			
	1985–1989	0.03		0.18	6.84		0.17				0.52			
	1990–1994													
	1995–1999													
	2000–2002													
India[o]	1980–1984	0.07	0.03	0.08	1.16	2.78	0.01				0.16			
	1985–1989	0.15	0.06	0.19	1.26	3.37	0.02				0.54			
	1990–1994													
	1995–1999													
	2000–2002													
Romania[p]	1995–1999	0.00	0.00	0.00	0.15	0.52	0.00	0.00	0.00	0.08	0.00	0.00	0.00	1.00
South Africa	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
	1995–1999													
	2000–2002													
Switzerland	1975–1979	0.21		2.31	11.20		0.25				0.53			
	1980–1984	0.13		1.02	7.82		0.14				0.39			
	1985–1989	0.16		0.68	4.31		0.04				0.18			
	1995–1999	0.35	0.35	0.72	2.04	2.06	0.01	0.03	0.11	0.51	0.06	0.17	0.46	0.92
	2000–2002	0.22	0.21	0.18	0.80	0.86	0.01	0.02	0.02	0.22	0.16	0.28	0.33	0.75
United Kingdom	1975–1979[w]	0.09		0.40	4.32									
	1975–1979[x]	0.25		1.50	5.89		0.12				0.65			
	1980–1984	0.33		1.10	3.33		0.06				0.40			
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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 reported data[u]	1975–1979	0.51		3.77	7.44		0.18				0.58			
	1980–1984	0.27		1.34	5.01		0.08				0.37			
	1985–1989	0.54		1.45	2.71		0.03				0.31			
	1990–1994	0.08		0.03	0.38		0.00	0.00	0.01	0.10	0.00	0.00	0.09	0.50
	1995–1999	0.37	0.35	0.72	1.93	2.04	0.00	0.01	0.04	0.20	0.02	0.06	0.15	0.64
	2000–2002	0.25	0.21	0.18	0.72	0.86	0.00	0.01	0.01	0.11	0.08	0.14	0.16	0.82
Radioisotope production														
Argentina	1975–1979	0.17		0.67	4.05									
	1980–1984	0.22		0.45	2.10									
	1985–1989	0.18		0.44	2.47									
	1990–1994	0.16	0.14	0.38	2.47	2.69	0.02	0.04	0.12	0.52	0.22	0.31	0.49	0.93
	1995–1999	0.13	0.12	0.31	2.46	2.70	0.01	0.03	0.12	0.62	0.07	0.17	0.36	0.89
	2000–2002	0.14	0.13	0.33	2.40	2.51	0.02	0.04	0.11	0.66	0.13	0.24	0.46	0.96
Australia	1990–1994	0.09		0.26	2.99		0.03	0.09	0.27		0.18	0.52	0.93	
	1995–1999													
	2000–2002													
Belarus	2000–2002	0.01	0.01	0.02	1.83	1.83	0.00	0.00	0.00	0.72	0.00	0.00	0.00	0.87
Brazil[n]	1995–1999	0.08	0.00	0.01	0.16	0.75	0.00	0.00	0.00	0.01				
	2000–2002	0.04	0.00	0.00	0.10	0.55	0.00	0.00	0.00	0.01				
Canada[q]	1975–1979	0.05	0.03	0.12	2.67	3.84	0.02				0.14			
	1980–1984	0.03	0.03	0.19	5.83	7.28	0.09				0.41			
	1985–1989	0.30	0.16	0.48	1.61	2.94	0.01				0.18			
	1990–1994	0.40	0.23	0.57	1.44	2.45	0.00	0.02	0.08	0.35	0.05	0.17	0.48	0.93
	1995–1999	0.33	0.14	0.19	0.57	1.30	0.00	0.00	0.01	0.17	0.00	0.00	0.12	0.80
	2000–2002	0.55	0.23	0.24	0.44	0.86	0.00	0.00	0.00	0.14	0.00	0.00	0.05	0.84
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	0.96
	1995–1999	1.29	0.94	4.89	3.78	4.74	0.06	0.09	0.14	0.40	0.45	0.55	0.65	0.84
	2000–2002	0.57	0.46	2.58	4.53	5.46	0.08	0.13	0.21	0.50	0.46	0.60	0.74	0.89
China - Taiwan Province	2001–2002	0.01	0.00	0.00	0.63	0.83	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.48

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Czech Rep.[v]	1975–1979	0.18		0.50	2.76		0.02				0.19			
	1980–1984	0.33		0.60	1.80		0.02				0.30			
	1985–1989	0.40		0.81	2.05		0.04				0.42			
	1990–1994	0.10	0.08	0.09	0.89	1.14	0.00	0.00	0.03	0.32	0.00	0.00	0.18	0.72
	1995–1999													
	2000–2002													
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													
	1995–1999	0.04	0.03	0.10	2.47	3.96	0.02	0.06	0.18	0.51	0.13	0.33	0.65	0.95
	2000–2002	0.05	0.03	0.09	1.91	2.86	0.02	0.03	0.11	0.40	0.20	0.28	0.56	0.94
Greece	1995–1999	0.05	0.01	0.03	0.55	2.51	0.00	0.00	0.04	0.15	0.00	0.00	0.48	0.95
	2000–2002	0.05	0.02	0.04	0.76	2.06	0.00	0.00	0.03	0.24	0.00	0.00	0.25	0.92
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
	1995–1999	0.11	0.05	0.14	1.25	2.60	0.00	0.01	0.06	0.35	0.02	0.09	0.39	0.94
	2000–2002	0.12	0.07	0.23	2.05	3.20	0.01	0.04	0.16	0.44	0.05	0.23	0.64	0.98
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	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													
	1995–1999													
	2000–2002													
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
	1995–1999	0.41	0.27	0.81	1.98	3.05	0.02	0.05	0.12	0.35	0.19	0.37	0.62	0.95
	2000–2002	0.41	0.33	0.55	1.37	1.71	0.01	0.02	0.08	0.29	0.12	0.25	0.56	0.90
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
	1995–1999													
	2000–2002													
Peru	1994	0.03	0.02	0.13	5.00	5.21	0.08	0.20	0.32	0.84				
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
Rep. 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			
	1995–1999													
	2000–2002													
Romania	1995–1999	0.07	0.04	0.24	3.62	5.48	0.05	0.10	0.23	0.53	0.33	0.50	0.77	0.97
	2000–2002	0.07	0.06	0.10	1.44	2.75	0.00	0.03	0.10	0.29	0.00	0.22	0.57	0.92

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
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									
	1997–1999	1.16		1.16	1.00									
	2000–2002	1.13		0.83	0.73									
United States[l, m]	1975–1979	20.00		40.00	2.00									
	1980–1984	29.00		30.00	1.03									
	1985–1989	30.00	17.00	25.00	0.83	1.47								
	1990–1994	4.45	2.00	6.92	1.56	4.69	0.02	0.05	0.07	0.16	0.49	0.75	0.88	0.97
	1995–1999	2.12	0.92	4.74	2.35	5.31	0.04	0.08	0.12	0.22				
	2000–2002	1.89	1.14	3.62	1.97	3.20	0.03	0.06	0.11	0.24				
Total reported data[u]	1975–1979	21.60		48.30	2.23		0.10				0.18			
	1980–1984	31.50		37.30	1.18		0.05				0.23			
	1985–1989	33.20		32.70	0.98		0.03				0.23			
	1990–1994	7.98	4.46	14.60	1.83	3.28	0.02	0.05	0.09	0.25	0.39	0.60	0.78	0.95
	1995–1999	5.79	2.53	12.62	2.18	4.98	0.02	0.04	0.10	0.33	0.15	0.25	0.50	0.91
	2000–2002	5.02	2.48	8.64	1.72	3.49	0.01	0.03	0.08	0.34	0.10	0.18	0.38	0.87

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
World[u]	1975–1979	57.00		130.00	2.25									
	1980–1984	82.00		100.00	1.26									
	1985–1989	88.00		98.00	1.12									
	1990–1994	24.00	16.00	47.00	1.93	2.95	0.02	0.04	0.10	0.41	0.25	0.42	0.64	0.94
	1995–1999	28.80	20.00	57.60	2.00	2.88	0.02	0.05	0.11	0.56	0.25	0.42	0.72	0.98
	2000–2002	34.56	19.00	62.21	1.80	3.27	0.02	0.05	0.10	0.55	0.25	0.42	0.70	0.98
Well logging														
Australia	1990–1994	4.71	1.66	0.17	0.04	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.10
	1995–1999													
	2000–2002													
Brazil[n]	1995–1999	0.02	0.00	0.00	0.20	0.85	0.00	0.00	0.00	0.03				
	2000–2002	0.00	0.00	0.00	0.03	0.50	0.00	0.00	0.00	0.01				
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
	1995–1999	1.06	0.42	0.51	0.48	1.21	0.00	0.00	0.01	0.15	0.01	0.04	0.20	0.76
	2000–2002	1.43	0.60	0.71	0.50	1.15	0.00	0.00	0.01	0.14	0.05	0.11	0.24	0.72
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
	1995–1999													
	2000–2002													
China - Taiwan Province	1995–1999	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Croatia	1990–1994	0.08	0.01	0.01	0.13	1.00								
	1995–1999													
	2000–2002	0.07	0.00	0.00	0.05	0.56	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.58
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Czech Rep.[v]	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	106.00	0.24	2.05	2.26	0.00	0.01	0.08	0.73	0.00	0.07	0.26	0.96
	1995–1999	0.07	0.07	0.19	2.63	2.66	0.00	0.00	0.12	0.84	0.00	0.01	0.30	0.97
	2000–2002	0.07	0.06	0.22	3.28	3.33	0.02	0.04	0.21	0.79	0.10	0.16	0.52	0.97
Ecuador	1993–1994	0.11	0.11	0.16	1.45	1.45	0.00	0.00	0.01	0.66				
	1995–1999													
	2000–2002													
Iceland	1990–1994	0.01	0.00		0.00		0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
Indonesia	1980–1984	0.14	0.04	0.12	0.82	3.07								
	1985–1989	0.56	0.45	0.84	1.51	1.89								
	1995–1999	0.07	0.07	0.08	1.07	1.12	0.00	0.00	0.01	0.58	0.00	0.00	0.05	0.85
	2000–2002	0.19	0.10	0.31	1.64	3.10	0.01	0.01	0.05	0.44	0.13	0.16	0.34	0.97
Kuwait	1992–1994	0.03	0.00	0.01	0.20	3.20	0.00	0.00	0.01	0.01	0.00	0.00	0.45	0.45
	1995–1999	0.01	0.01	0.00	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.01	0.01	0.00	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	1985–1989	0.36	0.01	0.00	0.01	0.32								
	1990–1994	0.48		0.07	0.15									
	1997–1999	0.27	0.27	0.39	1.42	1.42	0.00	0.00	0.03	1.00	0.02	0.04	0.16	1.00
	2000–2002	0.26	0.26	0.47	1.80	1.80	0.00	0.00	0.01	0.89	0.00	0.01	0.02	0.97

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Myanmar	1994	0.00	0.00	0.00	0.65	0.65	0.00	0.00	0.00	0.50				
	1995–1999	0.01	0.01	0.00	0.17	0.17	0.00	0.00	0.00	0.00				
	2000–2002	0.01	0.01	0.01	0.63	0.63	0.00	0.00	0.00	0.00				
Norway	1990–1992	0.35	0.03	0.00	0.01	0.15	0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002	0.02	0.00	0.00	0.00	0.00	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				
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
Romania	1995–1999	0.08	0.08	0.30	3.86	3.86	0.00	0.02	0.20	0.99	0.00	0.06	0.39	1.00
	2000–2002	0.16	0.16	0.42	2.58	2.58	0.00	0.00	0.12	0.94	0.00	0.00	0.27	0.99
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
	1995–1999													
	2000–2002	0.01	0.01	0.01	1.61	1.61	0.00	0.00	0.00	1.00				
Slovenia	1993–1994	0.00	0.00	0.00	1.54	1.54	0.00	0.00	0.00	0.67				
	1995–1999													
	2000–2002													
South Africa	1975–1979	0.04	0.01	0.00	0.01	0.03								
	1980–1984	0.04	0.02	0.06	1.61	3.76								
	1985–1989	0.04	0.01	0.05	1.49	4.55								
	1995–1999													
	2000–2002													
Spain	2000–2002	0.05	0.03	0.03	0.57	0.97	0.01	0.01	0.01	0.14	0.10	0.10	0.14	0.74
United States[t]	1975–1979	7.60		10.30	1.36						0.30			
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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 reported data[u]	1975–1979				1.32		0.01				0.27			
	1980–1984				1.17		0.00				0.10			
	1985–1989				1.07		0.00				0.04			
	1990–1994	8.43	3.87	3.06	0.36	0.79	0.00	0.00	0.01	0.12	0.08	0.14	0.27	0.79
	1995–1999	1.61	0.94	1.48	0.92	1.56	0.00	0.00	0.05	0.51	0.00	0.02	0.16	0.65
	2000–2002	2.31	1.25	2.18	0.94	1.75	0.00	0.01	0.04	0.40	0.04	0.06	0.17	0.66
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
	1995–1999	0.04	0.02	0.01	0.20	0.41	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.38
	2000–2002	0.05	0.03	0.01	0.10	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canada	1975–1979	0.58	0.19	0.17	0.30	0.91	0.00				0.10			
	1980–1984	0.88	0.23	0.40	0.45	1.76	0.00				0.04			
	1985–1989	1.00	0.53	1.06	1.06	2.00	0.00				0.07			
	1990–1994	0.99	0.40	0.77	0.77	1.94	0.00	0.01	0.05	0.17	0.03	0.10	0.50	0.89
	1995–1999	0.78	0.21	0.35	0.45	1.63	0.00	0.00	0.02	0.12	0.02	0.04	0.31	0.83
	2000–2002	0.89	0.42	0.44	0.49	1.12	0.00	0.00	0.02	0.12	0.00	0.01	0.26	0.71
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
	1995–1999	1.05	0.15	0.57	0.54	1.44	0.00	0.00	0.01	0.01	0.00	0.00	0.09	0.09
	2000–2002													
China - Taiwan Province	1995–1999	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecuador	1993– 1994	0.01	0.00	0.00	0.00		0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002													
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
	1995–1999	0.12	0.01	0.01	0.06	1.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.77
	2000–2002	0.18	0.01	0.01	0.04	0.72	0.00	0.00	0.00	0.01	0.00	0.00	0.32	0.63

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Greece	1995–1999	0.02	0.00	0.00	0.00									
	2000–2002	0.02	0.00	0.00	0.12									
Mexico	1997–1999	0.23	0.23	0.48	2.07	2.07	0.01	0.03	0.05	1.00	0.18	0.26	0.36	1.00
	2000–2001	0.22	0.22	0.62	2.86	2.86	0.01	0.02	0.04	0.95	0.26	0.31	0.36	0.99
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								
	1995–1999	0.06	0.02	0.03	0.46	1.68	0.00	0.01	0.03	0.07	0.13	0.27	0.60	0.87
	2000–2002	0.15	0.03	0.06	0.37	1.63	0.00	0.01	0.03	0.06	0.00	0.44	0.75	1.00
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
	1995–1999													
	2000–2002													
Romania	1995–1999	0.02	0.00	0.00	0.30	1.48	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.63
	2000–2002	0.01	0.01	0.00	0.14	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
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			
	1995–1999													
	2000–2002													
United Kingdom	1985–1989	0.50		0.25	0.50									
	1990–1994													
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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[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													
	1995–1999													
	2000–2002													
Total reported data[u]	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
	1995–1999	2.34	0.64	1.45	0.62	2.25	0.00	0.01	0.01	0.17	0.04	0.07	0.17	0.57
	2000–2002	1.54	0.72	1.13	0.73	1.58	0.00	0.00	0.01	0.16	0.04	0.11	0.24	0.48
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
	1995–1999													
	2001	2.14		0.02	0.04									
Brazil[n]	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
	1995–1999	0.10	0.02	0.03	0.32	1.70	0.00	0.01	0.01	0.04				
	2000–2002	0.04	0.01	0.01	0.19	1.20	0.00	0.00	0.01	0.05				
Bulgaria	1990–1994	0.14		0.14	1.04									
	1995–1999													
	2000–2002													
Chile	1995–1999	0.20		0.39	1.95									
	2000–2002	0.27		0.53	2.00									
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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
China - Taiwan Province	1990–1994	2.29	0.65	0.56	0.25	0.86								
	1995–1999	5.63	0.21	0.26	0.05	1.21	0.00	0.00	0.00	0.01	0.15	0.26	0.57	0.87
	2000–2002	7.77	0.16	0.34	0.04	2.02	0.00	0.00	0.00	0.01	0.48	0.54	0.69	0.91
Croatia	1990–1994	0.15	0.05	0.01	0.07	0.20								
	1995–1999													
	2000–2002	0.25	0.02	0.01	0.03	0.46	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.39
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
	1995–1999													
	2000–2002													
Czech Rep.	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
	1995–1999													
	2000–2002													
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
	1995–1999	2.41	0.24	0.08	0.03	0.34	0.00	0.00	0.00	0.01	0.00	0.08	0.16	0.40
	2000–2002	2.45	0.16	0.07	0.03	0.39	0.00	0.00	0.00	0.01	0.00	0.00	0.17	0.55
Ecuador	1993–1994	0.03	0.03	0.06	2.63	2.63	0.02	0.04	0.08	0.84				
	1995–1999													
	2000–2002													
El Salvador	2002	0.03	0.03	0.03	0.94	0.94	0.00	0.00	0.00	0.19				
Estonia	1995–1999	0.04	0.04	0.08	1.92	2.03	0.00	0.00	0.04	0.69	0.00	0.03	0.16	0.92
	2000–2002	0.17	0.17	0.19	1.12	1.13	0.00	0.00	0.03	0.32	0.00	0.02	0.15	0.72
Finland	1995–1999	0.01	0.01	0.04	4.08	5.28	0.02	0.06	0.28	0.76	0.07	0.18	0.58	0.94
	2000–2002	0.02	0.01	0.06	3.98	4.44	0.02	0.09	0.29	0.76	0.12	0.31	0.68	1.01
France	1995–1999	26.99		19.01	0.70									
	2000–2002	29.11		20.94	0.72									
Germany[h]	1990–1994	45.20	14.40	38.50	0.85	2.67	0.01	0.02	0.05	0.15	0.21	0.37	0.61	0.91
	1995–1999	50.16	10.87	28.69	0.57	2.51	0.01	0.01	0.03	0.11	0.00	0.00	0.00	0.00
	2000–2002	42.14	12.08	23.74	0.56	1.97	0.00	0.01	0.03	0.12	0.00	0.00	0.00	0.00
Greece	1995–1999	0.06	0.00	0.01	0.11	2.54	0.00	0.00	0.01	0.02	0.00	0.00	0.50	0.91
	2000–2002	0.10	0.02	0.03	0.30	1.23	0.00	0.00	0.01	0.06	0.00	0.16	0.26	0.77

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	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
	1995–1999	0.38	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41
	2000–2002	0.40	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.34
Indonesia	1995–1999	0.21	0.21	0.01	0.06	0.06	0.00	0.00	0.00	0.02	0.00	0.00	0.15	0.95
	2000–2002	0.49	0.49	0.03	0.06	0.06	0.00	0.00	0.00	0.03	0.00	0.00	0.06	0.92
Japan	1990–1994	60.70	3.29	7.52	0.12	2.29	0.00	0.00	0.01	0.02	0.27	0.37	0.55	0.88
	1995–1999o	69.56	2.67	5.06	0.07	1.91	0.00	0.00	0.00	0.01	0.26	0.34	0.57	0.88
	2000–2002o	72.35	3.38	6.63	0.09	2.03	0.00	0.00	0.00	0.01	0.38	0.46	0.63	0.88
Kuwait	1992–1994	0.03	0.00	0.01	0.11	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1995–1999	0.01	0.01	0.01	1.15	1.15	0.00	0.03	0.08	0.15	0.00	0.34	0.66	0.82
	2000–2002	0.02	0.02	0.02	1.53	1.53	0.00	0.05	0.09	0.23	0.00	0.40	0.60	0.89
Lithuania	1995–1999	0.06	0.03	0.07	1.19	2.46	0.00	0.00	0.01	0.50	0.00	0.00	0.04	0.75
	2000–2002	0.05	0.01	0.05	1.12	4.52	0.01	0.01	0.02	0.24	0.15	0.24	0.29	0.60
Luxembourg	1995–1999	0.22	0.09	0.04	0.20	0.53	0.00	0.00	0.00	0.03	0.00	0.05	0.13	0.40
	2000–2002	0.22	0.09	0.05	0.23	0.57	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.16
Myanmar	1995–1999	0.02	0.02	0.01	0.69	0.69	0.00	0.00	0.00	0.11				
	2000–2002	0.03	0.03	0.02	0.76	0.76	0.00	0.00	0.00	0.41				
Mexico	1990–1994	0.30		0.27	0.91									
	1997–1999	0.32	0.32	0.75	2.37	2.37	0.00	0.00	0.01	1.00	0.13	0.16	0.31	1.00
	2000–2001	0.05	0.05	0.19	4.27	4.27	0.03	0.08	0.16	1.00	0.20	0.34	0.51	1.05
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
	1995–1999	2.13	0.36	0.14	0.06	0.37	0.00	0.00	0.00	0.01	0.00	0.03	0.09	0.42
	2000–2002	2.18	0.45	0.15	0.07	0.33	0.00	0.00	0.00	0.01	0.05	0.05	0.09	0.40
Norway	1990–1992	0.86	0.03	0.02	0.02	0.62	0.00	0.00	0.00	0.04				
	1995–1999													
	2000–2002	0.21	0.01	0.01	0.04	0.52	0.00	0.00	0.00	0.01				
Peru	1994	0.10	0.09	0.05	0.50	0.55	0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Philippines	1995–1999	1.14	0.02	0.03	0.02	1.56	0.00	0.00	0.00	0.01				
	2000–2002	2.00	0.04	0.02	0.01	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
	1995–1999													
	2000–2002													
Romania	1995–1999	0.03	0.01	0.00	0.05	9.18	0.02	0.02	0.08	0.18	0.65	0.70	0.88	0.99
	2000–2002	0.05	0.05	0.00	0.04	1.79	0.00	0.00	0.03	0.61	0.00	0.00	0.15	0.91
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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
Spain	2000–2002	3.18	1.96	1.64	0.52	0.84	0.00	0.00	0.01	0.14	0.11	0.15	0.23	0.68
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
	1995–1999													
	2000–2002													
Sweden	1990–1994	1.09		0.48	0.44									
	1995–1999													
	2000–2002													
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
	1995–1999	2.65	0.19	0.24	0.09	1.29	0.00	0.00	0.01	0.02	0.08	0.17	0.49	0.81
	2000–2002	2.56	0.15	0.19	0.08	1.28	0.00	0.00	0.00	0.02	0.03	0.07	0.46	0.84
Russian Fed.	1992–1994	2.99	2.99	6.08	2.03		0.00				0.04			
	1995–1999													
	2000–2002													
United Kingdom	1990–1994	13.30	7.14	6.78	0.51	0.95	0.00	0.00	0.02	0.10				
	1995–1999													
	2003	4.63		1.79	0.39									

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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 reported data[u]	1990–1994	143.00	34.40	65.10	0.45	1.89	0.00	0.01	0.02	0.07	0.21	0.34	0.56	0.86
	1995–1999	164.48	15.31	54.99	0.33	3.59	0.00	0.01	0.03	0.19	0.08	0.15	0.33	0.72
	2000–2002	172.90	19.37	56.78	0.33	2.93	0.00	0.01	0.03	0.19	0.08	0.15	0.29	0.67

[a] Data are annual values averaged over the periods indicated.

[b] Values of *NR* are for the monitored workforce.

[c] Insufficient data are available for these categories to make a reliable estimate of worldwide exposure.

[d] Reported data include a contribution from industrial radiography.

[e] The total for measurably exposed workers has been estimated by scaling to take account of countries reporting numbers of monitored workers but not of measurably exposed workers.

[f] Reported data relate to approximately 25% of the monitored workers.

[g] Reported data include a contribution from industrial irradiation.

[h] Within the period 1990–1994, the data for 1990 relate only to the Federal Republic of Germany. Earlier data are a combination of data previously reported for the German Democratic Republic and the Federal Republic of Germany.

[i] Reported data (covering about 80% of the workforce) have been scaled up 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 National Radiological Protection Board. The total number of radiographers in the United Kingdom is somewhat larger. Data for 1985–1989 are for classified workers only.

[k] Reported data include a contribution from other industrial uses (gauges).

[l] Calculation of *SR* distribution ratios are based on data from 1993 and 1994.

[m] Data from NRC reports [U29, U30, U31, U32, U33, U34, U36, U37].

[n] Data for the periods 1995–1999 and 2000–2002 represent about 15% of the monitored workers in Brazil.

[o] Data include luminizing, radioisotope production, well logging and accelerator operation. Doses from industrial irradiation are not considered.

[p] All reported doses are from internal exposure only.

[q] Before 1989, radioisotope production was undertaken by Atomic Energy of Canada Ltd (AECL), and separate statistics for this group of workers are not available. The average data tabulated for 1985–1989 are those for 1989, when production was transferred from AECL. 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 contributed about 50% of the dose.

[s] Neutrons contribute about 15–25% to the reported doses.

[t] Data are for licensees of the USDOE only. The effective doses include a neutron component.

[u] These data should be interpreted with care, particularly because the countries included in the summations may differ from one period to another, depending on whether data were reported. Consequently, direct comparison between data for different periods is invalid. It should also be noted that the data for NR_{15} and SR_{15} are averages of the data reported. In general, these data are less complete than those included in the summations for the numbers of workers and the collective doses.

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*

[v] Data for 1975-1989 are for Czechoslovakia.

[w] Luminizing using paint.

[x] Luminizing using tritium.

Table A-29 Exposures to workers from all industrial uses of radiation[a]
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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
	1995–1999	0.92	0.40	0.68	0.74	0.74	0.00	0.06
	2000–2002	0.92	0.51	0.71	0.77	0.77	0.01	0.03
Australia	1975–1979	2.21		0.92	0.41			
	1985–1989	7.10	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
	1995–1999							
	2000–2002	2.60	0.00	0.11	0.04			
Belarus	2000-2002	1.36	1.36	4.61	3.39	3.39		
Brazil	1985–1989	15.00	3.10	24.00	1.60	7.69		
	1990–1994	1.44	0.43	1.47	1.02	3.40	0.01	0.40
	1995–1999[i]	0.53	0.12	0.33	0.62	2.77	0.00	
	2000–2002[i]	0.45	0.06	0.16	0.36	2.54	0.00	
Bulgaria	1990–1994	0.83	0.17	0.74	0.89	3.70	0.00	0.02
	1995–1999	0.64	0.24	0.63	0.98	2.60		
	2000–2002							
Canada	1975–1979	2.15	1.14	5.14	2.39	4.51	0.02	0.42
	1980–1984	3.38	1.60	6.75	2.00	4.22	0.02	0.34
	1985–1989	3.84	2.27	9.38	2.44	4.13	0.02	0.39
	1990–1994	4.57	2.51	9.83	2.15	3.92	0.03	0.34
	1995–1999	4.64	2.11	8.83	1.90	4.18	0.01	0.11
	2000–2002	5.74	2.72	9.13	1.59	3.35	0.01	0.09
Chile	1995–1999	0.20		0.39	1.95			
	2000–2002	0.27		0.53	2.00			
China	1990–1994	4.76	4.25	6.80	1.43	1.60	0.01	0.24
	1995–1999	22.20	13.49	30.40	1.37	2.25	0.02	0.15
	2000–2002	18.96	12.23	21.64	1.14	1.77	0.03	0.29

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*NR_{15}[b]*	*SR_{15}*
					Monitored workers	*Measurably exposed workers*		
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		
	1995–1999	7.04	0.66	2.23	0.32	3.39	0.00	0.25
	2000–2002	9.27	0.65	2.22	0.24	3.42	0.00	0.13
Croatia	1990–1994	0.26	1.00	0.07	0.27	0.88		
	1995–1999							
	2000–2002	0.41	0.06	0.10	0.24	1.75	0.01	0.19
Cuba	1990–1994	0.33	0.33	0.41	1.25	1.25	0.00	0.02
	1995–1999							
	2000–2002							
Cyprus	1995–1999	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.02	0.02	0.01	0.67	0.67	0.00	0.00
Czech Rep.[j]	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		2.85	1.22	1.58	0.00	0.06
	1995–1999	0.90	0.86	1.79	1.98	2.08	0.00	0.04
	2000–2002	0.85	0.75	1.44	1.70	2.27	0.01	0.17
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
	1995–1999	3.04	0.49	0.48	0.16	0.98	0.00	0.00
	2000–2002	2.99	0.36	0.43	0.14	1.21	0.00	0.02
Ecuador	1990–1994	0.17	0.15	0.25	1.49	1.72	0.00	
	1995–1999							
	2000–2002							
Estonia	1995–1999	0.07	0.07	0.15	2.18	2.21	0.01	0.11
	2000–2002	0.20	0.20	0.25	1.21	1.22	0.00	0.00

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*NR_{15}[b]*	*SR_{15}*
					Monitored workers	*Measurably exposed workers*		
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
	1990–1994	1.19	0.13	0.16	0.13	1.20	0.00	0.04
	1995–1999	0.57	0.13	0.23	0.41	1.77	0.01	0.05
	2000–2002	0.61	0.19	0.27	0.44	1.44	0.01	0.08
France	1975–1979							
	1980–1984							
	1985–1989	9.90		24.00	2.42			
	1995–1999	26.99		19.01	0.70			
	2000–2002	29.11		20.94	0.72			
Gabon	1990–1994	0.01	0.01	0.08	20.48	20.48	1.00	1.00
	1995–1999							
	2000–2002							
Germany[d]	1985–1989	58.60	14.70	25.60	0.44	1.74	0.01	0.29
	1990–1994	51.90	16.59	47.90	0.92	2.89	0.01	0.23
	1995–1999	50.16	10.87	28.69	0.57	2.51	0.01	0.00
	2000–2002	42.14	12.08	23.74	0.56	1.97	0.00	0.00
Greece	1990–1994	0.24	0.03	0.06	0.26	2.50	0.00	0.20
	1995–1999	0.35	0.06	0.15	0.43	0.43	0.00	0.02
	2000–2002	0.32	0.09	0.22	0.68	0.68	0.00	0.02
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
	1995–1999	1.45	0.23	0.57	0.39	2.43	0.00	0.04
	2000–2002	1.52	0.45	1.13	0.74	2.53	0.00	0.07
Iceland	1990–1994	0.03	<0,01	0.00	0.00	0.00	0.00	
	1995–1999	0.03	0.00	0.00	0.09	1.09	0.00	0.00
	2000–2002	0.04	0.00	0.00	0.06	0.61	0.00	0.00

Country	Period	Monitored workers (10^3)	Measurably exposed workers (10^3)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		NR_{15}[b]	SR_{15}
					Monitored workers	Measurably exposed workers		
India	1990–1994	5.08	2.80	7.95	1.57	2.84	0.02	0.34
	1995–1999							
	2000–2002							
Indonesia	1980–1984	0.02	0.01	0.01	0.75	1.25		
	1985–1989	0.03	0.03	0.03	1.12	1.12		
	1995–1999	0.39	0.16	0.20	0.51	1.23	0.00	0.10
	2000–2002	0.59	0.27	0.65	1.10	2.40	0.00	0.09
Ireland	1985–1989	0.74	0.06	0.08	0.11	1.37	0.00	0.09
	1991–1994	0.13	0.23	0.03	0.23	1.32	0.00	
	1995–1999							
	2000–2002							
Italy[e]	1985–1989	1.98	0.44	0.87	0.44	1.97	0.00	0.35
	1995–1999							
	2000–2002							
Japan	1975–1979	27.60	3.93	8.93	0.32	2.27	0.01	
	1980–1984	29.00	4.06	11.00	0.38	2.70	0.00	
	1985–1989	32.00	3.06	8.48	0.27	2.77	0.00	
	1990–1994	120.00	6.49	16.50	0.14	2.54	0.00	0.31
	1995–1999	72.70	3.81	7.31	0.10	1.92	0.00	0.48
	2000–2002	75.35	4.46	8.39	0.11	1.88	0.00	0.57
Kuwait	1990–1994	0.19	0.03	0.62	3.26	22.96	0.00	0.00
	1995–1999	0.31	0.31	0.65	2.08	2.11	0.01	0.06
	2000–2002	0.26	0.26	0.56	2.18	2.18	0.01	0.08
Lithuania	1995–1999	0.12	0.08	0.29	2.38	3.63	0.02	0.11
	2000–2002	0.12	0.06	0.19	1.53	3.28	0.01	0.12
Luxembourg	1995–1999	0.25	0.11	0.06	0.26	0.59	0.00	0.00
	2000–2002	0.25	0.11	0.08	0.33	0.74	0.00	0.00
Malta	1995–1999	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	1985 –1989	1.63	0.51	5.23	3.21	10.20	0.05	0.66
	1990–1994	1.69	0.51	5.20	3.07			
	1995–1999	1.63	1.63	9.34	5.73	5.73	0.03	0.30
	2000–2002	1.42	1.42	8.69	6.10	4.29	0.03	0.17

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*NR_{15} [b]*	*SR_{15}*
					Monitored workers	*Measurably exposed workers*		
Myanmar	1990–1994	0.01	0.01	0.00	0.00	0.00	0.00	
	1995–1999	0.03	0.03	0.01	0.53	0.53	0.00	
	2000–2002	0.04	0.04	0.03	0.73	0.73	0.00	
Netherlands	1980–1984	1.71		0.63	0.37		0.00	0.34
	1985–1989	2.27		0.88	0.39		0.00	0.15
	1990–1994	4.09	1.38	2.68	0.65	1.95	0.01	0.19
	1995–1999	3.62	1.25	2.16	0.60	1.73	0.00	0.10
	2000–2002	3.63	1.40	1.69	0.47	1.21	0.00	0.08
New Zealand	1980–1984	0.28		0.43	1.50			
	1995–1999							
	2000–2002							
Norway	1980–1984	1.21	0.51	0.85	0.70	1.67	0.00	0.04
	1985–1989	1.44	0.51	0.68	0.47	1.35	0.00	0.09
	1990–1994	2.33	0.31	0.33	0.14	1.06	0.00	
	1995–1999							
	2000–2002	0.98	0.14	0.21	0.21	1.51	0.00	
Pakistan	1990–1994	0.13	0.12	0.62	4.66	5.00	0.11	0.63
	1995–1999							
	2000–2002							
Peru	1990–1994	0.26	0.23	0.40	1.54	1.75	0.01	
	1995–1999							
	2000–2002							
Philippines	1995–1999	1.15	0.02	0.29	0.25	12.76	0.00	0.00
	2000–2002	2.00	0.04	0.31	0.11	8.57	0.01	0.33
Poland	1990–1994	2.25	2.09	3.83	1.71	1.84	0.01	0.15
	1995–1999							
	2000–2002							
Portugal	1985–1989	0.63	0.52	0.18	0.28	0.34		
	1995–1999							
	2000–2002							
Romania	1995–1999	1.71	0.84	4.17	2.45	4.95	0.01	0.22
	2000–2002	1.33	1.10	3.34	2.51	3.03	0.00	0.02

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*NR_{15} [b]*	*SR_{15}*
					Monitored workers	*Measurably exposed workers*		
Russian Fed.	1990–1994	2.99	2.99	6.08	2.03	2.03	0.00	0.04
	1995–1999							
	2000–2002							
Slovakia	1990–1994	0.89	0.36	0.91	1.03	2.50	0.00	0.10
	1995–1999							
	2000–2002	0.43	0.42	0.68	1.60	1.60	0.00	
Slovenia	1990–1994	0.81	0.58	0.30	0.37	0.52	0.00	0.10
	1995–1999							
	2000–2002	0.12	0.04	0.07	0.58	1.75	0.00	0.01
South Africa	1975–1979	2.01	0.79	0.21	0.11	0.27	0.00	0.05
	1980–1984	2.90	1.18	2.11	2.11	5.17	0.03	0.41
	1985–1989	2.30	0.55	5.71	4.41	10.50	0.00	0.69
	1990–1994	0.12	0.08	0.27	2.31	3.60	0.03	0.27
	1995–1999							
	2000–2002							
Spain	1985–1989	3.02	2.00	3.98	1.32	1.60	0.01	0.02
	1995–1999							
	2000–2002	5.67	3.20	4.01	0.71	1.25	0.01	0.22
Sri Lanka	1990–1994	0.06	0.03	0.04	0.73	1.54	0.01	0.49
	1995–1999							
	2000–2002							
Sweden	1990–1994	1.09		0.48	0.44			
	1995–1999	0.22	0.10	0.07	0.32	0.70	0.00	0.00
	2000–2002	0.23	0.08	0.13	0.57	1.63	0.00	0.46
Switzerland	1975–1979	11.70		10.20	0.87		0.01	0.31
	1980–1984	12.90		5.92	0.46		0.00	0.14
	1985–1989	13.60		4.08	0.30		0.00	0.08
	1990–1994	2.77		0.33	0.12		0.00	0.18
	1995–1999	3.00	0.54	0.96	0.32	1.78	0.00	0.07
	2000–2002	2.79	0.36	0.37	0.13	1.04	0.00	0.09

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*NR_{15}*[b]	*SR_{15}*
					Monitored workers	*Measurably exposed workers*		
Syrian Arab Rep.	1990–1994	0.07	0.01	0.02	0.28	2.50	0.00	0.00
	1995–1999							
	2000–2002							
Thailand	1990–1994	2.31	0.25	1.81	0.78	7.18	0.02	0.68
	1995–1999							
	2000–2002							
United Kingdom	1980–1984	28.00		26.00	0.93			
	1985–1989	18.80	15.10	21.00	1.12	1.39	0.01	
	1990–1994	19.60	10.27	13.00	0.67	1.27	0.00	
	1995–1999	1.16		1.16	1.00			
	2000–2002	5.76		2.62	0.46			
United Rep. Tanzania	1990–1994	0.03	0.02	0.08	2.46	3.56	0.00	0.00
	1995–1999							
	2000–2002							
United States[f]	1975–1979	202.00		290.00	1.44			
	1980–1984	305.00		380.00	1.25			
	1985–1989	274.00	101.00	150.00	0.55	1.49		
	1990–1994	10.04	5.75	25.20	2.51	4.39	0.03	0.34
	1995–1999	5.69	3.60	19.51	3.43	5.42	0.04	
	2000–2002	5.17	3.89	21.30	4.12	5.48	0.04	
USSR	1975–1979	7.78		126.00	16.20			
	1980–1984	9.85		122.00	12.40			
	1985–1989	12.80		104.00	8.15			
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
	1995–1999	212	42	141	0.66	3.33	0.01	
	2000–2002	222	47	136	0.61	2.87	0.20	

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*NR_{15} [b]*	*SR_{15}*
					Monitored workers	*Measurably exposed workers*		
World estimate[h]	1975–1979	530	290	870	1.64	3.00	0.01	0.35
	1980–1984	690	300	940	1.36	3.20	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]
	1995-1999	790		315	0.4			
	2000-2002	869		348	0.40			

[a] Data are annual values averaged over the periods indicated.

[b] Values of NR_{15} are for the monitored workforce.

[c] Includes exposures of workers at the research reactor and in research establishments.

[d] Within the period 1990–1994, the data for 1990 relate only to the Federal Republic of Germany.

[e] The reported number of workers is small compared with the numbers in comparable industrialized countries, which suggests that the data are incomplete.

[f] Calculation of *SR* distribution ratios is based on data from 1993 and 1994.

[g] The total for measurably exposed workers has been estimated by scaling up to take account of those countries that reported the number of monitored workers but not the number of measurably exposed workers.

[h] Values shown in brackets are the world estimates based on the standard method given in Section III.A.3. However, the Committee identified a more robust method of estimation for this instance based on taking the regional value for the United States to be equivalent to the rest of the OECD. The resulting values are shown without brackets.

[i] Data for the periods 1995–1999 and 2000–2002 represent about 15% of the monitored workers in Brazil.

[j] Data for 1975-1989 are for Czechoslovakia.

Table A-30 Exposures to workers from miscellaneous uses of radiation[a]

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.55		0.06	0.10									
	1985–1989	2.22	0.94	0.07	0.03	0.07	0.00				0.00			
	1990–1994	0.62	0.21	0.02	0.04	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23
	1995–1999													
	2001	3.08		0.04	0.13									
Belarus	2000–2002	0.05	0.05	0.12	2.47	2.47	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00
Brazil[e,x]	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
	1995–1999	0.68	10.80	0.01	0.08	0.49	0.01	0.03	0.06	0.14				
	2000–2002	0.40	9.00	0.01	0.14	0.59	0.01	0.02	0.04	0.11				
Bulgaria[f]	1992	0.25		0.25	1.00									
	1995–1999	0.10	0.02	0.04	0.38	2.19	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.51
	2000–2002													
Canada[g]	1975–1979	5.01	0.89	0.69	0.14	0.78	0.00				0.09			
	1980–1984	7.40	1.02	0.80	0.11	0.78	0.00				0.04			
	1985–1989	9.51	1.62	1.05	0.11	0.65	0.00				0.09			
	1990–1994	14.70	1.51	0.76	0.05	0.50	0.00	0.00	0.00	0.01	0.03	0.06	0.14	0.44
	1995–1999	17.62	1.87	1.34	0.08	0.72	0.00	0.00	0.00	0.02	0.04	0.06	0.16	0.53
	2000–2002	17.80	2.15	1.48	0.08	0.69	0.00	0.00	0.00	0.02	0.06	0.07	0.15	0.55
China - Taiwan Province	1985–1989	0.71		0.04	0.06									
	1990–1994	1.10	0.22	0.15	0.14	0.69	0.00	0.00	0.00	0.02	0.18	0.18	0.23	0.47
	1995–1999	1.98	0.07	0.02	0.01	0.28	0.00	0.00	0.00	0.00	0.25	0.25	0.25	0.36
	2000–2002	2.34	0.09	0.02	0.01	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Czech Rep.[h]	1975–1979	0.08		0.04	0.45		0.00				0.23			
	1980–1984	0.18		0.18	0.97		0.02				0.58			
	1985–1989	0.21		0.12	0.56		0.00				0.03			
	1990–1994	0.86	0.60	0.57	0.66	0.93	0.00	0.00	0.01	0.16	0.04	0.06	0.13	0.46
	1995–1999													
	2000–2002													
El Salvador	2001–2002	0.01	0.01	0.01	0.75	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estonia	1995–1999	0.01	0.01	0.00	0.71	0.71	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.54
	2000–2002	0.02	0.01	0.01	0.70	0.80	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.54
Finland[i]	1980–1984	0.95	0.02	0.04	0.04	1.63	0.00				0.06			
	1985–1989	1.18	0.03	0.05	0.05	1.68	0.01				0.11			
	1990–1994	1.33	0.08	0.22	0.17	2.79	0.00	0.00	0.01	0.03	0.21	0.42	0.64	0.92
	1995–1999	1.46	0.07	0.11	0.08	1.74	0.00	0.00	0.00	0.02	0.14	0.23	0.49	0.87
	2000–2002	1.30	0.05	0.10	0.08	1.82	0.00	0.00	0.00	0.01	0.31	0.44	0.55	0.87
France	1985–1989	3.80	0.09	0.20	0.05	2.22	0.00							
	1995–1999	4.19		0.09	0.02									
	2000–2002	3.07		0.10	0.03									
Germany[j,k,l]	1975–1979	0.22	0.01	0.02	0.10	2.79	0.00				0.19			
	1980–1984	0.21	0.00	0.00	0.02	0.93	0.00				0.00			
	1985–1989	21.31	1.06	1.54	0.12	3.48	0.00				0.17			
	1990–1994	26.60	0.90	0.88	0.03	0.98	0.00	0.00	0.00	0.01	0.08	0.14	0.30	0.70
	1995–1999	25.09	1.21	1.13	0.05	0.89	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	2000–2002	25.02	1.49	0.92	0.04	0.55	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
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
	1995–1999	0.30	0.01	0.02	0.07	2.39	0.00	0.00	0.01	0.01	0.30	0.30	0.70	0.89
	2000–2002	0.27	0.02	0.05	0.19	3.00	0.00	0.00	0.00	0.02	0.54	0.70	0.70	0.96

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	0.22	0.01	0.02	0.10	2.79	0.00				0.19			
	1980–1984	0.21	0.00	0.00	0.02	0.93	0.00				0.00			
	1985–1989	0.21	0.01	0.01	0.04	2.02	0.00				0.00			
	1990–1994	0.39	0.01	0.01	0.04	0.95	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.62
	1995–1999	0.34	0.02	0.01	0.04	0.96	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.60
	2000–2002	0.34	0.03	0.02	0.06	0.61	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.60
India[n]	1980–1984	1.01	0.17	0.29	0.29	1.74	0.00				0.24			
	1985–1989	1.92	0.47	0.45	0.24	0.97	0.00				0.07			
	1990–1994	2.06	0.54	0.44	0.21	0.81	0.00	0.00	0.00	0.05	0.07	0.09	0.16	0.59
	1995–1999													
	2000–2002													
Indonesia	1980–1984	0.28	0.19	0.25	0.92	1.33	0.02				0.37			
	1985–1989	0.66	0.64	0.48	0.72	0.75	0.00				0.11			
	1995–1999													
	2000–2002													
Italy	1985–1989	0.66	0.09	0.05	0.08	0.63	0.00				0.00			
	1995–1999													
	2000–2002													
Japan	1980–1984	21.40	0.79	0.49	0.02	0.62	0.00							
	1985–1989	27.60	0.69	0.46	0.02	0.67	0.00							
	1990–1994	59.20	0.86	0.86	0.01	1.01	0.00	0.00	0.00	0.00	0.20	0.28	0.40	0.73
	1995–1999	70.79	1.17	0.97	0.01	0.83	0.00	0.00	0.00	0.00	0.03	0.09	0.29	0.73
	2000–2002	74.19	1.69	0.93	0.01	0.58	0.00	0.00	0.00	0.00	0.06	0.10	0.25	0.64
Lithuania	1995–1999	0.06	0.03	0.06	1.04	1.36	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.63
	2000–2002	0.09	0.00	0.06	0.72	1.20	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.06
Luxembourg	2000–2002	0.00	0.00		0.00	0.07								
Mexico	1997–1999	0.87	0.87	0.75	0.85	0.85	0.00	0.00	0.01	1.00	0.03	0.05	0.15	1.00
	2000–2001	0.56	0.56	0.80	1.43	1.43	0.00	0.00	0.00	0.89	0.00	0.00	0.03	0.94
Myanmar	1990–1994	0.02	0.02	0.02	1.18	1.18	0.00	0.03	0.04	0.23				
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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
	1995–1999	1.72	0.24	0.08	0.04	0.32	0.00	0.00	0.00	0.01	0.00	0.08	0.19	0.41
	2000–2002	1.35	0.18	0.06	0.04	0.31	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.29
Norway[o]	1980–1984	0.42	0.03	0.01	0.03	0.55	0.00				0.00			
	1985–1989	0.45	0.03	0.03	0.06	0.90	0.00				0.48			
	1990–1994	0.56	0.09	0.02	0.04	0.24	0.00	0.00	0.00	0.01				
	1995–1999													
	2000–2002	0.68	0.03	0.02	0.03	0.65	0.00	0.00	0.00	0.01				
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
	1995–1999													
	2000–2002													
Portugal	1985–1989	0.78	0.37	0.33	0.42	0.88								
	1995–1999													
	2000–2002													
Romania	1995–1999	0.13	0.06	0.14	1.11	2.25	0.00	0.00	0.06	0.47	0.00	0.05	0.38	0.97
	2000–2002	0.06	0.04	0.10	1.62	1.99	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.93
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
	1995–1999													
	2000–2002	0.42	0.41	0.65	1.54	1.49	0.00	0.01	0.03	0.73				
South Africa	1975–1979	0.23	0.04	0.00	0.01	0.04	0.00				0.00			
	1980–1984	0.36	0.09	0.47	1.29	5.12	0.02				0.45			
	1985–1989	0.43	0.07	0.21	0.49	3.02	0.00				0.10			
	1995–1999													
	2000–2002													
Spain	2000–2002	4.60	2.22	0.75	0.16	0.34	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.24
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
	1995–1999													
	2000–2002													
Sweden	1990–1994	2.38		0.12	0.05									
	1999	0.87	0.20	0.05	0.06	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.15
	2000–2002	1.14	0.23	0.07	0.07	0.23	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.31

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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[p]	1975–1979	7.44		5.91	0.79		0.01							
	1980–1984	8.48		3.44	0.41		0.00							
	1985–1989	8.83		2.88	0.33		0.00							
	1990–1994	9.44		2.17	0.23		0.00	0.00	0.01	0.05	0.02	0.06	0.22	0.61
	1995–1999	9.76	2.63	1.55	0.16	0.59	0.00	0.00	0.00	0.03	0.00	0.01	0.11	0.52
	2000–2002	10.28	1.19	0.77	0.07	0.67	0.00	0.00	0.00	0.02	0.00	0.01	0.13	0.59
Syrian Arab Rep.	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
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
United Kingdom	1980–1984	12.50		1.30	0.10		0.00				0.00			
	1985–1989	1.17	0.49	0.38	0.32	0.78	0.00							
	1990–1994	1.26	0.32	0.21	0.17	0.67	0.00	0.00	0.01	0.02				
	1997–1999													
	2000–2001	10.00		0.60	0.06									
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
	1995–1999													
	2000–2002													
United States[q]	1975–1979	0.02		18.00	0.72									
	1980–1984	0.03		15.00	0.58									
	1985–1989	0.02		6.00	0.35	0.86								
	1995–1999													
	2000–2002													
Total reported data[r]	1975–1979	38.60		23.50	0.61		0.00				0.19			
	1980–1984	66.00		20.40	0.31		0.00				0.11			
	1985–1989	85.70		13.60	0.16		0.00				0.07			
	1990–1994	125.40	6.58	7.41	0.06	1.13	0.00	0.00	0.00	0.01	0.09	0.15	0.28	0.62
	1995–1999	135.95	19.27	6.38	0.05	0.33	0.00	0.00	0.01	0.16	0.05	0.07	0.19	0.58
	2000–2002	157.05	19.44	7.67	0.05	0.39	0.00	0.00	0.00	0.13	0.07	0.10	0.13	0.54

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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
World[s]	1975–1979	140.00		74.00	0.55									
	1980–1984	180.00		43.00	0.24									
	1985–1989	160.00		22.00	0.14									
	1990–1994	310.00	30.00	33.00	0.11	1.10	0.00	0.00	0.00	0.02	0.07	0.11	0.22	0.55
	1995–1999	372.00	29.00	36.00	0.10	1.24	0.00	0.00	0.00	0.01	0.09	0.10	0.20	0.60
	2000–2002	446.40	30.00	38.00	0.09	1.27	0.00	0.00	0.00	0.02	0.09	0.12	0.21	0.67
Veterinary medicine														
Australia[c,d]	1975–1979	0.39		0.06	0.14		0.00				0.00			
	1985–1989	2.07	0.89	0.02	0.01	0.02	0.00				0.00			
	1990–1994	2.66	0.88	0.07	0.03	0.07	0.00	0.00	0.00	0.00	0.16	0.16	0.16	0.30
	1995–1999													
	2001	4.03		0.04	0.01									
Brazil[e, x]	1990–1994	0.02	0.00	0.00	0.25	1.39	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.78
	1995–1999	0.01		0.01	1.63		0.02	0.04	0.08	0.22				
	2000–2002	0.00		0.00	0.74		0.01	0.01	0.07	0.13				
Canada	1975–1979	0.77	0.24	0.17	0.22	0.73	0.00				0.11			
	1980–1984	1.27	0.22	0.16	0.13	0.74	0.00				0.03			
	1985–1989	1.52	0.31	0.17	0.11	0.56								
	1990–1994	2.14	0.29	0.13	0.06	0.46	0.00	0.00	0.00	0.01	0.00	0.02	0.05	0.38
	1995–1999	7.48	0.59	0.30	0.04	0.54	0.00	0.00	0.00	0.01	0.15	0.16	0.18	0.43
	2000–2002	8.30	0.49	0.33	0.04	0.66	0.00	0.00	0.00	0.01	0.14	0.15	0.15	0.38
China - Taiwan Province	1995–1999	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Croatia	1995–1999													
	2000–2002	0.05	0.01	0.01	0.13	0.53	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.39
Cyprus	1990–1994	0.00	0.00	0.00	0.70	0.88	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.87
	1995–1999													
	2000–2002	0.05	0.01	0.01	0.13	0.53	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.39

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Czech Rep.[h]	1975 –1979	0.17		0.10	0.59									
	1980 –1984	0.23		0.14	0.62									
	1985 –1989	0.25		0.13	0.52									
	1990 –1994	0.23	0.18	0.18	0.75	0.97	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.37
	1995–1999													
	2000–2002													
Denmark	1975–1979	0.49		0.02	0.05		0.00				0.00			
	1980–1984	0.52		0.03	0.06		0.00				0.17			
	1985–1989	0.71		0.02	0.03									
	1990–1994	0.94	0.06	0.02	0.02	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.55
	1995–1999	1.16	0.07	0.03	0.02	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
	2000–2002	1.26	0.07	0.02	0.02	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.32
Estonia	1995–1999	0.01	0.01	0.00	0.45	0.47	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.31
	2000–2002	0.02	0.02	0.01	0.67	0.72	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.26
Finland	1980–1984		0.01	0.01		1.20					0.00			
	1985–1989		0.02	0.03		1.20								
	1990–1994	0.19	0.04	0.06	0.29	1.50	0.00	0.00	0.01	0.09	0.00	0.00	0.30	0.84
	1995–1999	0.28	0.05	0.06	0.21	1.16	0.00	0.00	0.00	0.07	0.00	0.03	0.17	0.74
	2000–2002	0.29	0.04	0.07	0.23	1.56	0.00	0.00	0.01	0.06	0.00	0.10	0.38	0.84
France[t]	1985–1989	1.19	0.09	0.02	0.17	2.30	0.00							
	1995–1999	3.13		0.24	0.08									
	2000–2002	3.94		0.18	0.05									
Germany	1995–1999	7.45	0.92	0.60	0.08	0.68	0.00	0.00	0.00	0.02	0.02	0.03	0.12	0.56
	2000–2002	10.15	1.44	0.61	0.06	0.45	0.00	0.00	0.00	0.01	0.04	0.06	0.13	0.45
Greece	1995–1999	0.00	0.00	0.00	0.08	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.01	0.00	0.00	0.07	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	1975–1979	0.08	0.01	0.05	0.55	5.07	0.01				0.42			
	1980–1984	0.14	0.01	0.03	0.20	2.78	0.00				0.24			
	1985–1989	0.06	0.00	0.01	0.10	1.56	0.00	0.00	0.00	0.03	0.00	0.00	0.16	0.74
	1990– 1994													
	1995–1999	0.06	0.00	0.00	0.04	0.96	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.78
	2000–2002	0.58	0.01	0.00	0.04	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78
Iceland	1990– 1994	0.01	0.00		0.00		0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002													
India	1975–1979	0.06	0.02	0.01	0.17	0.51	0.00				0.00			
	1980–1984	0.08	0.03	0.16	0.20	0.61	0.00				0.00			
	1985–1989	0.09	0.03	0.02	0.20	0.53	0.00				0.20			
	1995–1999													
	2000–2002													
Ireland	1985–1989	0.04	0.00	0.00	0.02	0.33								
	1995–1999													
	2000–2002													
Japan[u]	1985–1989	18.00		1.40	0.08									
	1990–1994	1.38	0.20	0.15	0.11	0.71	0.00	0.00	0.00	0.02				
	1995–1999													
	2000–2002													
Luxembourg	1995–1999	0.01	0.01	0.00	0.14	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000–2002	0.02	0.01	0.00	0.13	0.36	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	0.61	0.61	0.00	0.00	0.00	0.00				
	1995–1999													
	2000–2002													
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
	1995–1999	1.76	0.54	0.15	0.09	0.28	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.23
	2000–2002	2.60	0.69	0.16	0.06	0.24	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.16
Norway	2000–2002	0.30	0.04	0.05	0.17	1.33	0.00	0.00	0.01	0.03				
Romania	2000–2002	0.01	0.01	0.01	0.46	0.76	0.00	0.00	0.04	0.15	0.00	0.00	0.38	0.93

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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
	1995–1999													
	2000–2002	0.02	0.02	0.04	1.53	1.51	0.00	0.00	0.00	0.89				
Slovenia	1990–1994	0.01	0.01	0.01	0.76	0.76	0.00	0.00	0.00	0.05				
	1995–1999													
	2000–2002	0.04	0.02	0.01	0.19	0.36	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.30
South Africa	1975–1979	0.42	0.28	0.01	0.03	0.05	0.00				0.42			
	1980–1984	0.61	0.20	0.12	0.20	0.60	0.00				0.06			
	1985–1989	0.75	0.13	0.24	0.32	1.89	0.00				0.07			
	1990–1994	0.75	0.13	0.24	0.32	0.89	0.00				0.07			
	1995–1999													
	2000–2002													
Sweden	1992–1994	0.68		0.08	0.12									
	1999	0.38	0.16	0.07	0.19	0.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.34
	2000–2002	0.51	0.13	0.05	0.11	0.42	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.45
Switzerland	1975–1979	0.44		0.12	0.27		0.00				0.03			
	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
	1995–1999	1.40	0.11	0.03	0.02	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31
	2000–2002	1.73	0.10	0.02	0.01	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26
United Kingdom	1985–1989	4.00		0.40	0.10									
	1990–1994	0.30	0.08	0.02	0.06	0.21	0.00	0.00	0.00	0.00				
	1995–1999													
	2001	10.00		2.00	0.20									

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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[v]	1975–1979	18.10	6.20	14.00	0.77	2.26								
	1980–1984	21.00	12.00	13.00	0.62	1.08								
	1985–1989	85.00	38.00	36.00	0.42	0.95								
	1990–1994													
	1995–1999													
	2000–2002													
Total reported data[r]	1975–1979	19.70		14.40	0.73		0.00				0.12			
	1980–1984	23.80		13.50	0.57		0.00				0.03			
	1985–1989	96.40		37.10	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
	1995–1999	23.14	2.46	1.50	0.06	0.61	0.00	0.00	0.01	0.05	0.01	0.02	0.04	0.34
	2000–2002	43.95	3.10	3.62	0.08	1.17	0.00	0.00	0.01	0.08	0.01	0.02	0.07	0.37
World[s]	1975–1979	48.00		25.00	0.52									
	1980–1984	65.00		26.00	0.40									
	1985–1989	160.00		52.00	0.32									
	1990–1994	45.00	13.00	8.00	0.18	0.62	0.00	0.00	0.00	0.03	0.02	0.13	0.24	0.60
	1995–1999	103.50	32.00	17.25	0.17	0.54	0.00	0.00	0.00	0.03	0.02	0.10	0.20	0.50
	2000–2002	119.03	31.00	18.20	0.15	0.59	0.00	0.00	0.00	0.03	0.02	0.10	0.20	0.50
Other occupational groups														
Australia	2001	3.98		0.10	0.02									
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
	1995–1999													
	2000–2002													
China - Taiwan Province	1990–1994	1.99	0.68	1.02	0.51	1.49								
	1995–1999	2.94	0.29	0.23	0.08	0.88	0.00	0.00	0.00	0.02	0.15	0.25	0.43	0.80
	2000–2002	3.57	0.23	0.17	0.05	0.77	0.00	0.00	0.00	0.01	0.17	0.19	0.36	0.73
Croatia	2000–2002	0.34	0.07	0.02	0.07	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08
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
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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}
Cyprus	1990–1994	0.01	0.01	0.01	0.61	0.94	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.77
	1995–1999													
	2000–2002													
Czech Rep.	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
	1995–1999	0.62	0.51	0.58	0.94	1.14	0.00	0.01	0.04	0.20	0.03	0.13	0.34	0.72
	2000–2002	0.70	0.44	0.40	0.57	0.89	0.00	0.00	0.02	0.12	0.00	0.07	0.24	0.65
Denmark	1990–1994	0.17	0.00	0.00	0.01	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60
	1995–1999	0.16	0.00	0.00	0.01	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99
	2000–2002													
Ecuador	1993–1994	0.05	0.05	0.06	1.04	1.05	0.00	0.00	0.00	0.50				
	1995–1999													
	2000–2002													
Finland	1995–1999	0.03	0.00	0.00	0.11									
	2000–2002	0.04	0.01	0.00	0.05	0.29	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.42
France	1990–1994	0.84	0.54	3.46	4.10	6.36	0.07	0.13	0.28	0.64				
	1995–1999	8.58		0.13	0.02									
	2000–2002	7.44		0.14	0.02									
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
	1995–1999													
	2000–2002													
Greece	1990–1994	0.25	0.03	0.07	0.29	2.42	0.00	0.00	0.10	0.06	0.27	0.34	0.53	0.89
	1995–1999	0.18	0.02	0.04	0.21	2.33	0.00	0.01	0.01	0.04	0.18	0.37	0.59	0.88
	2000–2002	0.30	0.05	0.10	0.34	2.12	0.00	0.01	0.02	0.06	0.07	0.35	0.56	0.89
Kuwait	1995–1999	0.10	0.10	0.02	0.21	0.22	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.37
	2000–2002	0.10	0.07	0.04	0.37	0.39	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.31
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
	1995–1999	2.18	0.44	0.19	0.09	0.35	0.00	0.00	0.00	0.01	0.12	0.14	0.22	0.45
	2000–2002	1.93	0.86	0.12	0.06	0.19	0.00	0.00	0.00	0.01	0.08	0.10	0.12	0.38
Norway	2000–2002	0.23	0.04	0.04	0.20	1.02	0.00	0.00	0.01	0.05				
Lithuania	1995–1999	0.04	0.02	0.07	1.97	3.95	0.01	0.03	0.05	0.59	0.05	0.25	0.34	0.83
	2000–2002	0.12	0.02	0.11	0.88	5.20	0.00	0.00	0.02	0.17	0.00	0.00	0.19	0.39

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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	1994	0.04	0.04	0.02	0.60	0.60	0.00	0.00	0.00	0.23				
	1995–1999													
	2000–2002													
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
	1995–1999													
	2000–2002													
Slovenia	1990–1994	0.06	0.06	1.15	17.70	17.70	0.60	0.75	0.91	0.94	0.88	0.99	1.00	1.00
	1995–1999													
	2000–2002	0.59	0.30	0.07	0.12	0.23	0.00	0.00	0.00	0.01	0.32	0.38	0.38	0.51
Spain	2000–2002	0.79	0.18	0.32	0.41	1.79	0.00	0.01	0.02	0.08	0.12	0.24	0.55	0.87
Sweden	1999	0.26	0.06	0.02	0.09	0.35	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.48
	2000–2002	0.49	0.12	0.07	0.14	0.58	0.00	0.00	0.00	0.08	0.00	0.00	0.18	0.64
Switzerland	1995–1999	0.41	0.04	0.01	0.02	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19
	2000–2002	0.41	0.01	0.00	0.01	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30
United Kingdom[y]	2003	13.14	0.03	2.37	0.18		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
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
	1995–1999[w]	20.00	2.74	2.40	0.12	0.87	0.00	0.00	0.00	0.03				
	2000–2002[w]	22.03	2.12	1.70	0.08	0.80	0.00	0.00	0.00	0.02				
Total reported data[r]	1990–1994	9.37		9.56	1.03		0.02	0.03	0.06	0.20	0.33	0.42	0.57	0.88
	1995–1999	35.50	4.20	3.69	0.10	0.88	0.00	0.01	0.01	0.10	0.06	0.13	0.21	0.63
	2000–2002	56.21	4.56	5.77	0.10	1.26	0.00	0.00	0.01	0.05	0.06	0.10	0.20	0.48

[a] Data are annual values averaged over the periods indicated. 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] Values of NR_5 are for the monitored workforce. Values for the exposed workforce can also be estimated where data were provided for both the monitored and the measurably exposed workers.

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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

[c] For 1975–1989, the numbers of workers and the collective doses reported for about 70% of the exposed workforce have been extrapolated for the entire country.

[d] The method of dose recording was different in the two periods for which data were reported, and this may partly account for differences in the 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. 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 are based on a sample of approximately 25% of the monitored workers.

[f] Reported data include a contribution from veterinary medicine.

[g] Data are mainly from universities but exclude exposures at accelerators and at teaching establishments where little research is undertaken.

[h] Data for 1975–1989 are for Czechoslovakia.

[i] Includes all research institutes except research reactors and accelerators. No data are available on exposures in tertiary education.

[j] Within the period 1990–1994, the data for 1990 relate only to the Federal Republic of Germany.

[k] For 1976–1980, the data are for all universities and technical colleges in non-medical fields. For 1981–1989, the data are for all research and educational faculties except for those associated with the medical and nuclear sciences.

[l] Data include exposures arising in research and training in the natural sciences and technology, including research centres.

[m] Includes technological education only (i.e. not medicine, science, philosophy, etc.).

[n] Includes data from educational and research institutes.

[o] Data for 1980–1989 are solely for the University of Oslo.

[p] May include some data for research related to the nuclear fuel cycle.

[q] Data are for NRC licensees only.

[r] These data should be interpreted with care, particularly because the countries included in the summations may differ from one period to another, 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 for *NR* and *SR* are averages of the data reported. In general, these data are less complete than those that form the basis for the summations of numbers of workers and collective doses.

[s] Estimates are extrapolations of regional values based on the gross national product. Because of insufficient data, the estimates of NR and SR are averages of the reported data; however, these may be considered representative for worldwide exposure.

[t] The number of workers and the collective dose have been estimated by scaling up by a factor of 1.33, since the reported data covered only 75% of the monitored workers.

[u] For 1985–1989 the data are for holding assistants; 1.06 man Sv of the collective dose arose in conducting radiographic examinations and 0.34 man Sv in fluoroscopy. The level of exposure is related to some 2.4 million radiographs; about 5% of the examinations were of large animals, the remaining 95% of small animals.

[v] Values for 1985 are based on extrapolation of earlier data.

[w] Data refer to general research.

[x] Data represent about 15% of the monitored workers.

[y] Data refer to nuclear power station workers.

Table A-31 Exposures to workers from military activities[a]
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country	*Period*	*Monitored workers* (10^3)	*Measurably exposed workers* (10^3)	*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			
	1995–1999													
	2000–2002													
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									
	1995–1999													
	2000–2002													
Total reported[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									
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
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		0.05							
	1985–1989	6.24		11.6	1.86		0.019							
	1990–1994	9.78		8.0	0.82		0.00							
	1995–1999													
	2000–2002													
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						
	1995–1999													
	2000–2002													
Total reported[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	0.82									
	1995–1999													
	2000–2002													

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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 military activities														
Canada	1995–1999	1.54	0.17	0.08	0.05	0.50	0.00	0.00	0.00	0.01	0.05	0.05	0.08	0.35
	2000–2002	1.81	0.79	0.05	0.03	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
Czech Rep.	1995–1999	0.06	0.06	0.07	1.07	1.08	0.00	0.00	0.04	0.24	0.00	0.00	0.29	0.70
	2000–2002	0.06	0.04	0.04	0.64	0.91	0.00	0.00	0.01	0.14	0.00	0.00	0.10	0.54
France	1990–1994	5.70	0.73	1.31	0.23	1.78	0.00	0.00	0.01	0.13				
	1995–1999													
	2000–2002													
Netherlands	1990–1994	0.15	0.02	<0.1	0.01	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	1995–1999	0.16	0.01	0.01	0.04	0.85	0.00	0.00	0.00	0.00	0.00	0.25	0.25	0.25
	2000–2002	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Romania	1995–1999	0.03	0.03	0.09	3.34	0.13	0.00	0.00	0.18	1.00				
	2000–2002	0.02	0.02	0.05	2.40	0.13	0.00	0.00	0.00	1.00				
United Kingdom	1975–1979	11.90		35.80	3.00		0.04							
	1980–1984	12.80		26.30	2.06		0.03							
	1985–1989	12.20		14.60	1.19		0.01							
	1990–1994	13.90		9.20	0.66		0.00	0.00	0.02					
	1995–1999	14.09		3.59	0.26									
	2000–2002	13.79		3.36	0.24									
United States	1975–1979	92.50	55.80	101.00	1.09	1.81								
	1980–1984	104.00	61.50	56.00	0.54	0.91								
	1985–1989	115.00	73.00	69.00	0.60	0.95								
	1990–1994	119.00	29.30	22.00	0.19	0.76								
	1995–1999[h]	115.87	19.85	14.89	0.13	0.75	-	-	-	0.03				
	2000–2002[h]	100.31	16.57	12.86	0.13	0.78	-	-	-	0.03				

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*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*
Total reported	1975–1979	104.00		137.00	1.30									
	1980–1984	116.00		82.00	0.71									
	1985–1989	127.00		84.00	0.66									
	1990–1994	139.00		33.00	0.24									
	1995–1999	131.75	20.11	18.73	0.14	0.93								0.43
	2000–2002	116.14	17.43	16.36	0.14	0.94								0.31

[a] Data are annual values averaged over the periods indicated.

[b] Actual effective doses are typically less than 50% of the tabulated values, which are those measured by the dosimeter.

[c] Values for this period are averages for the year 1979.

[d] Includes exposures of employees of the USDOE 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] Value used is the average for 1992–1994 taken from reference [U21].

[g] Data are reported for on-board and shore-based personnel. Shore-based personnel may include both civilian and service personnel. Since the early 1980s, dosimeters have been issued only to on-board personnel whose duties at sea require them and to personnel designated as classified persons on shore.

[h] Data from the USDOE website (http://rems.eh.doe.gov) [U23].