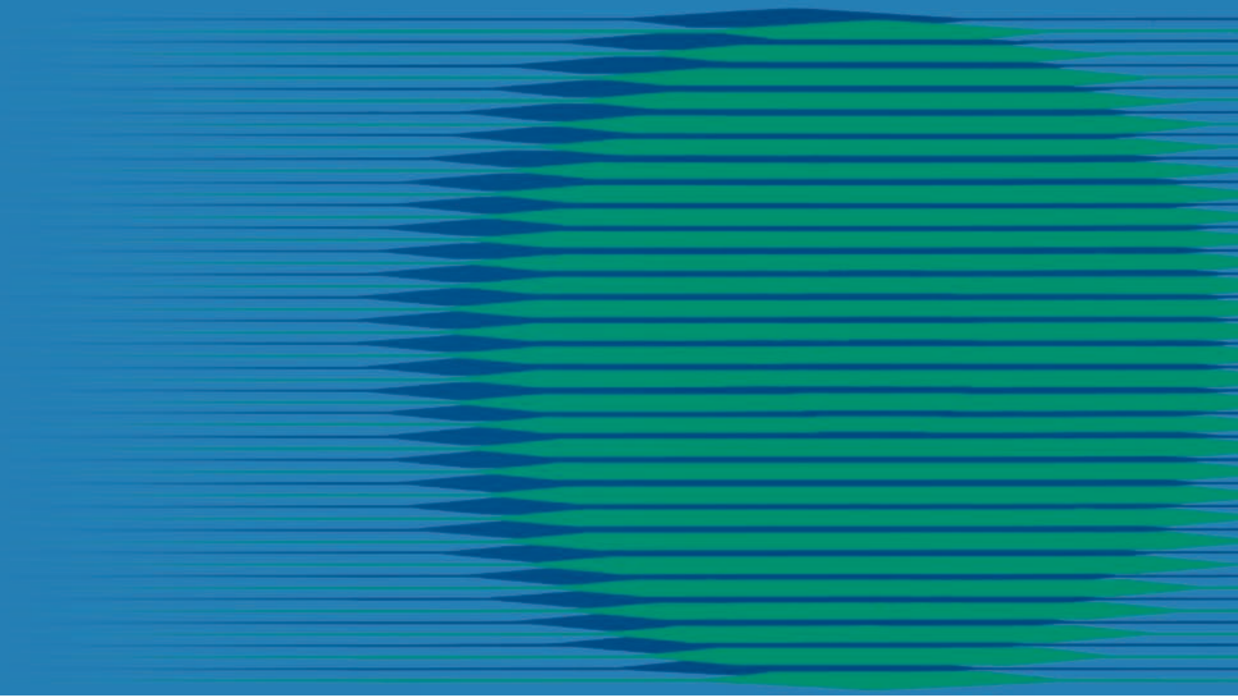
SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCEAR 2008 Report

Volume II: EFFECTS

Scientific Annexes C, D and E



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 II
Scientific Annexes C, D and E

UNITED NATIONS
New York, 2011

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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Volume II

Annex C (Radiation exposures in accidents)

Corrigendum

1. **Page 24, table 3, section headed "Sealed radioactive sources", column headed "Industrial source/installation", first row**

For ^{137}Co source *read* ^{60}Co source

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ANNEX C

RADIATION EXPOSURES IN ACCIDENTS

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INTRODUCTION

1. In the course of the research and development for and the application of atomic energy and nuclear technologies, a number of radiation accidents have occurred. Some of these accidents have resulted in significant health effects and occasionally in fatal outcomes. The application of technologies that make use of radiation is increasingly widespread around the world. Millions of people have occupations related to the use of radiation, and hundreds of millions of individuals benefit from these uses. Facilities using intense radiation sources for energy production and for purposes such as radiotherapy, sterilization of products, preservation of foodstuffs and gamma radiography require special care in the design and operation of equipment to avoid radiation injury to workers or to the public. Experience has shown that such technology is generally used safely, but on occasion controls have been circumvented and serious radiation accidents have ensued.

2. Reviews of radiation exposures from accidents have been presented in previous UNSCEAR reports. The last report containing an exclusive chapter on exposures from accidents was the UNSCEAR 1993 Report [U6].

3. This annex is aimed at providing a sound basis for conclusions regarding the number of significant radiation accidents that have occurred, the corresponding levels of radiation exposures and numbers of deaths and injuries, and the general trends for various practices. Its conclusions are to be seen in the context of the Committee's overall evaluations of the levels and effects of exposure to ionizing radiation.

4. The Committee's evaluations of public, occupational and medical diagnostic exposures are mostly concerned with chronic exposures of various population groups at levels that are well below the thresholds for early acute (deterministic) health effects. In contrast, accidents can involve relatively high exposures, above such thresholds, and it is necessary to consider separately the early acute health effects, which essentially occur only in accidents and which are clearly attributable to radiation exposure. In addition, a few accidents have led to elevated exposures among larger populations, usually by releasing radioactive material into the environment; the Committee has attempted to assess the contribution such accidents have made to overall population radiation exposures.

5. The scope of this annex was to include "a survey of accidents whereby exposure to radioactive material affected workers or members of the public in a fashion that results in acute (i.e. deterministic) health effects." Selected accidents of significant public interest and/or involving environmental contamination were also to be considered. Thus, for the purpose of this annex, radiation accidents are defined as unintended events in which at least one person experienced early acute health effects that required some degree of medical intervention, and unintended events that caused significant population exposures due to environmental contamination.

6. It should be noted that the Committee has not considered accidents that may have been significant from a technical point of view (e.g. failures in safety systems at nuclear power plants) but that did not lead to radiation exposures. Moreover, it is not the purpose of this annex, and indeed it is outside the remit of the Committee, to investigate the root causes of the accidents, analyse accident progressions, conduct probabilistic risk assessments and forecast trends. Nevertheless, in order to provide a better qualitative appreciation of the range of characteristics and common features of the accidents that have occurred, the Committee has provided brief summaries of selected accidents, their circumstances and their health consequences, and has described overall trends when possible.

7. Accidents were selected for inclusion in the text and/or tables if information about the accident was available in published literature in medicine, radiation protection or dosimetry, or other relevant scientific or government literature, or in publications of the International Atomic Energy Agency (IAEA) or the World Health Organization (WHO). Malicious acts (intentional as opposed to accidental), with one exception of topical interest (see paragraph 124), are not included in this compilation, nor are accidents that occurred during nuclear weapons testing. During the fifty-fifth session of the Scientific Committee, it was agreed that no descriptions of accidents occurring after July 2007 would be included in this annex.

8. The IAEA and WHO publish important documents related to accidents for which they have provided assistance in response; these documents contain extensive descriptions of the event, dose assessments, health consequences and medical treatment. Accident catalogues are maintained by the Institute of Biophysics, Moscow, Russian Federation; by SEARCH in Ulm, Germany; by the Curie Institute, Paris, France; and by REAC/TS in Oak Ridge, Tennessee, United States of America. Table 1

provides a summary of accidents recorded for the territory of the former Soviet Union, some of which are described in this report [M4].

9. The Committee considers it likely that most of the serious accidents at nuclear facilities have been reported. In contrast, it considers it probable that many smaller industrial accidents, accidents with "orphan" sources, accidents in academic or research work and very many accidents in the medical uses of radiation have not been reported. There may be various reasons for this, including cultural and professional attitudes, fear of prosecution and ineffective regulatory regimes. In any case, it is clear that this review of accidents cannot be considered comprehensive.

10. Nevertheless the Committee considers that its assessment does provide a depiction of the number of significant radiation accidents that have occurred, the corresponding levels of radiation exposures and numbers of deaths and injuries, and the general trends for various practices, as a basis for evaluating the contribution made by accidents to overall radiation exposures and effects.

11. The review of selected radiation accidents has six sections:

- Section I covers criticalities and other operational accidents occurring at nuclear facilities, including accidents resulting in releases to the environment.
- Section II describes accidents involving sources, accelerators and X-ray devices used in industrial facilities.
- Section III provides examples of accidents associated with orphan sources and devices.
- Section IV describes accidents involving sources and radiation-generating devices used in academic and research environments.
- Section V provides examples of medical accidents involving sources, radiation-generating devices and nuclear medicine.
- Section VI addresses other accidents, principally those connected with the transport and movement of radioactive and nuclear materials in land, air, sea, undersea and space vehicles.
- Section VII summarizes information about accidents in various practices.

I. ACCIDENTS AT NUCLEAR FACILITIES

12. Accidents at nuclear facilities are considered in two categories: those related to nuclear weapons programmes and those not related to nuclear weapons programmes. Each category is considered in three subsections:

- *Criticality accidents.* These are generally considered significant owing to the potential loss of special nuclear material, serious contamination of the workplace, the possibility of off-site contamination and, in some cases, serious medical consequences. A large number of such accidents have occurred, although most of them took place in the early research and development of nuclear weapons technologies. This annex summarizes only those criticality accidents that led to serious medical consequences, and tables 2a and 2b summarize information on the 23 criticality accidents that have been reported.
- *Other accidents with only on-site consequences.* These have occurred during operations at nuclear facilities, and affected principally on-site workers. Some also involved the release of radioactive material to the outside environment and possible exposure of off-site populations. Tables 2a and 2b summarize key information on eight such accidents (other than criticality accidents) that led to early health effects among operators, plant staff or emergency response personnel, but had no significant off-site exposures of the general population or environment.
- *Accidents with releases to the environment and potentially significant population exposures.* Tables 2a and 2b summarize key information on seven accidents (including one criticality accident) at nuclear facilities that resulted in significant exposures of the general public.

A. Accidents related to nuclear weapons programmes

1. Criticality accidents

13. Of the 23 criticality accidents in total that have been reported, 17 occurred at facilities related to nuclear weapons programmes, which are listed in table 2a and briefly described below.

14. *United States, Los Alamos National Laboratory, 1945.* Three serious accidents have occurred at Los Alamos National Laboratory in Los Alamos, New Mexico. The first occurred in August 1945 when a critical assembly was being created by stacking tungsten carbide bricks around a plutonium core. The experimenter was moving the final block into place when he noted the neutron count indicating that the addition of the last brick would make the assembly supercritical. As he withdrew his hand, the final brick slipped and fell into the centre, creating the criticality. His dose[1] was estimated at 5.1 Gy from

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[1] Dose, unless otherwise specified, refers to whole-body dose.

a yield of 10^{16} fissions. He died 28 days after the exposure. An army guard assigned to the building but not directly involved with the experiment received a dose estimated at 0.5 Gy [L1].

15. *United States, Los Alamos National Laboratory, 1946.* In May 1946, the plutonium core described above was being used in a demonstration of the techniques for creating a metal critical assembly using beryllium as a reflector. The individual conducting the demonstration was holding the top cell with his left thumb and inadvertently allowed one edge of the upper hemisphere to come into contact with the lower hemisphere. He attempted to place a screwdriver under part of the upper hemisphere not in contact with the lower hemisphere. The screwdriver slipped, resulting in a criticality excursion with an estimated yield of 3×10^{15} fissions. The individual conducting the experiment died nine days after the exposure, following a dose estimated at 21 Gy. Seven other individuals in the room received doses ranging from 0.37 to 3.6 Gy [L1].

16. *United States, Argonne National Laboratory, 1952.* In June 1952, an accident occurred at Argonne National Laboratory in Argonne, Illinois, in a light water moderated core in which 6.8 kg of ^{235}U oxide was embedded in strips of polystyrene plastic. The system became critical following an attempt to replace the control rod when the normal amount of water was in the core. Four individuals received radiation doses of 1.36, 1.27, 0.6 and 0.09 Gy [L1].

17. *Former Soviet Union, Mayak Complex, 1953.* In March 1953, a criticality excursion occurred at the Mayak Complex in Chelyabinsk involving seven 40 L tanks of unfavourable geometry used for the mixing, dilution, sample storage and transfer of plutonium nitrate derived from irradiated reactor fuel. No radiation monitoring equipment was available to workers; therefore the seriousness of the event was not recognized. The estimated yield was 2.5×10^{17} fissions. An operator received about 10 Gy whole-body dose, but this was very non-uniform (more than 30 Gy to the legs). He survived a moderate degree of acute radiation syndrome (ARS) but amputation of both legs was necessary. The dose to a second operator was about 1.5–2.0 Gy and she survived a mild degree of ARS [G5, L1, V1].

18. *Former Soviet Union, Mayak Complex, 1957.* In April 1957, a second event occurred involving a tank used for oxalate purification and filtration of highly enriched uranium solutions. An unsafe geometry resulted in a criticality with a fission yield estimated at 2×10^{17}. The operator, who remained in the area for approximately ten minutes, died 12 days later, having received a whole-body dose estimated at about 10 Gy (based on an analysis of the ^{24}Na levels in his blood). Five other workers experienced ARS of different severities depending on the doses received, which ranged from 2.0 to 6.0 Gy [G5, L1, V1].

19. *Former Soviet Union, Mayak Complex, 1958.* In January 1958, a third event occurred that was related to the use of a test tank built for determining critical parameters for solutions of uranium. After a test, a team of four persons decided to speed the draining of a solution. The combination of the solution geometry in the tank and neutron reflection by the workers' bodies resulted in a criticality involving approximately 2.3×10^{17} fissions. Three of the four persons died within one week, with doses estimated to have been in the range 40–50 Gy. The fourth person, who had been 3 m away from the tank, received a dose estimated at 6 Gy and presented symptoms of ARS and of visual impairment. She survived, although long-term health problems related to organs on the left side of her body were observed, including skin fibrosis, kidney sclerosis and cataracts [B11, G5, K2, L1, V1].

20. *United States, Y-12 plant, 1958.* In June 1958, a criticality accident occurred at the Y-12 plant in Oak Ridge, Tennessee, during recovery of enriched uranium from various solid wastes. Prior to the accident and unbeknown to anyone, uranyl nitrate had been collecting in a vessel because of a leaking valve. When an operator opened the vessel to drain water into a 55 gallon (208 L) drum, the water was preceded by the enriched uranium solution. The unsafe geometry in the drum resulted in a criticality excursion with an estimated yield of 6×10^{16} fissions. A second excursion occurred 15 seconds later. Eight male workers (aged 25 to 56 years) were exposed, with five of the men receiving whole-body doses of between 2.36 and 3.65 Gy. Three others received doses of below 0.7 Gy. Long-term follow-ups with annual medical evaluations were conducted [A1].

21. *United States, Los Alamos National Laboratory, 1958.* In December 1958, a third accident at Los Alamos National Laboratory occurred during an annual physical inventory when process streams were interrupted in a unit used to purify and concentrate plutonium from slag, crucible and other lean residues from recovery processes. Dilute aqueous and organic solutions from two vessels were washed into a single large vessel. The addition of a nitric acid wash to the tank is believed to have separated the liquid phases, resulting in an excursion when a stirrer was activated. The excursion had a yield of 1.5×10^{17} fissions. The accident resulted in the death of the operator 36 hours after exposure, with a dose to the upper torso estimated at approximately 120 Gy. Two other individuals suffered no ill effects after doses estimated at 1.34 and 0.53 Gy [L1].

22. *United States, National Reactor Testing Station, 1961.* In January 1961, a serious event occurred at the National Reactor Testing Station in Idaho Falls, Idaho, involving a direct-cycle boiling water reactor of 3 MW gross thermal power. The reactor used enriched uranium fuel plates clad in aluminium, and was water moderated and cooled. After a routine shutdown for maintenance, a three-man crew was assigned the task of reassembling the control rod drives and preparing the reactor for start-up the following day. The best available evidence suggests that the central control rod was manually pulled out too fast, causing the power to rise. A subsequent steam explosion destroyed the reactor and instantly killed two men; the third man died two hours after the accident as a result of a head injury [L1].

23. *Former Soviet Union, Siberian Chemical Complex, 1961.* In August 1961, an accident occurred at the Siberian Chemical Complex in Seversk at an experimental facility used for purifying enriched (22.6%) uranium hexafluoride. The main cylinder lacked sufficient cooling, and another vessel was bypassed. The criticality alarm system was activated, and personnel evacuated the facility. Radiation surveys in the area using portable gamma monitoring instruments did not indicate abnormal radiation levels, and work resumed, resulting in a second criticality. The yield of each pulse was estimated to be 10^{16} fissions. The process operator received a dose estimated at 2 Gy and experienced mild symptoms related to ARS [L1, V1].

24. *United States, Hanford Facility, 1962.* In April 1962, an accident at a Recuplex System Process Plant in Richland, Washington, occurred as a result of the following set of conditions: cleaning the floor of a solvent extraction hood; a product receiver tank that could overflow into the hood; a temporary line running from the hood floor to a transfer tank; and the apparent improper operation of valves. A criticality excursion occurred followed by supercriticality for 37.5 hours as the power steadily decreased. The total excursion yield was 8×10^{17} fissions. Of the 22 individuals in the building, only three received significant doses of radiation ranging from 0.10 to 1.1 Gy [L1].

25. *Former Soviet Union, Arzamas-16 Nuclear Centre, 1963.* In March 1963, a criticality excursion occurred at the Arzamas-16 Nuclear Centre in Sarov in a system using plutonium with a deuteride reflector. The accident was due to the inadvertent closure of the assembly by the operator. Two individuals received doses estimated at 3.7 and 5.5 Gy. Both experienced a mild form of ARS and survived more than 25 years after the exposure. Four other persons received doses that were medically insignificant [L1].

26. *United States, Wood River Junction Chemical Process Plant, 1964.* In July 1964, an accident occurred at the Wood River Junction Chemical Process Plant in Rhode Island. The facility's function was to recover highly enriched uranium from scrap metal left over from the production of fuel elements. A variety of chemical procedures were involved in the overall process. On the day prior to the accident, a plant evaporator failed to operate properly, making it necessary to disassemble it for cleaning. During the cleaning process, a plug of uranium nitrate crystals was discovered in the connecting line. The crystals were dissolved with steam and drained into polyethylene bottles that were identical to those that normally held a very low concentration of fissile material. The bottles were labelled as high-concentration solutions. On the day of the accident the operator mistakenly poured the contents of a high-concentration bottle into the make-up vessel, which already contained 41 L of sodium carbonate solution that was being agitated by a stirrer. A critical state was reached when nearly all the uranium had been transferred. The excursion of 1.0×10^{17} to 1.1×10^{17} fissions created a flash of light and the loss of approximately 20% of the solution on to the ceiling, walls and operator. The radiation dose to the operator was estimated to be approximately 100 Gy. He died 49 hours after the exposure. Two workers who entered the room received doses of 1 and 0.6 Gy [K1, L1].

27. *Former Soviet Union, Russian Federal Nuclear Centre, 1968.* In April 1968, two technicians failed to reposition the lower reflector of an assembly prior to initiating a new test at the Russian Federal Nuclear Centre in Chelyabinsk. There was no criticality alarm system installed at the time, and health physics support was not present. The two technicians received estimated neutron/gamma doses of 5–10 and 20–40 Gy. The technician who received the higher dose died three days later, and the other technician died after 54 days [L1].

28. *Former Soviet Union, Mayak Complex, 1968.* In December 1968, a fourth event occurred at the Mayak plutonium extraction facility during a test of a new extraction process when an unusually high plutonium concentration and the presence of organic material were detected in the solution. When the solution was poured into a vessel of unsafe geometry, the operator saw a flash, the criticality alarm was activated and all personnel evacuated the facility. The shift supervisor later returned and attempted to pour some liquid into a drain, resulting in a second criticality. The first excursion yielded 10^{16} fissions and the second 10^{15} fissions. The shift supervisor died on day 34 of very severe ARS. The operator survived ARS of moderate severity, but subsequently both legs and one arm were amputated [V1, V4].

29. *Former Soviet Union, Siberian Chemical Complex, 1978.* In December 1978, another event at the complex occurred in a section of a glovebox line where plutonium metal ingots were being packed into storage boxes. The box design was deficient and it was possible to load more than one ingot into a box. A criticality excursion occurred when four ingots were loaded into a single box. The yield was 3×10^{15} fissions. One ingot was physically ejected and the operator removed the other ingots manually. The operator received a dose estimated at 2.5 Gy to the whole body and about 70 Gy to the hands; he experienced ARS of moderate severity, but amputation to above the elbows was necessary. Eyesight impairment occurred some time later. Seven other workers received doses estimated at between 0.05 and 0.6 Gy [B11, L1, V1].

30. *Russian Federation, Arzamas-16 Nuclear Centre, 1997.* In June 1997, a second criticality accident occurred at Arzamas-16 during experimental manipulation of a critical assembly. A technician was working alone in the assembly area when a component from the upper reflector slipped from his hand and fell on to the lower assembly containing the enriched uranium core. There was a flash of light, and the technician realized that a criticality had occurred. He left the experiment hall and reported the accident to his supervisors and colleagues. Initial estimates suggested a whole-body dose of 45 Gy from neutrons and 3.5 Gy from

gamma rays. The technician was promptly hospitalized. He died 66.5 hours after the exposure, despite prompt and intensive medical care [I5, L1].

2. Other accidents with only on-site consequences

31. Of the eight accidents (other than criticality accidents) in total that occurred during the operation of nuclear facilities and that led to early health effects among operators, plant staff or emergency response personnel, but had no off-site consequences for health or the environment, five occurred at facilities associated with nuclear weapons programmes and are listed in table 2a. A brief description of one of these is provided here to illustrate the nature of such events.

32. *United States, Hanford Facility, 1976.* In August 1976, a 64-year-old chemical operator was injured by a chemical explosion of an ion exchange column used for recovery of ^{241}Am at the Hanford Facility in Richland, Washington. The operator sustained chemical burns of the face, eyes, neck and right shoulder, as well as lacerations and embedded foreign bodies in these areas. He was heavily contaminated externally with ^{241}Am and inhaled an estimated 40.7 MBq of the radionuclide. Aggressive medical therapy began immediately, including on-site decontamination and administration of calcium- and zinc-DTPA. Chelation therapy continued for many months and was responsible for a significant reduction in the ^{241}Am body burden. The estimated cumulative doses three years after the accident to bone, lung and liver were 8.6, 2 and 1.6 Gy, respectively [H2].

3. Accidents with releases to the environment and potentially significant population exposures

33. Of the seven accidents at nuclear facilities that resulted in potentially significant exposures of the general public or the environment, four were associated with nuclear weapons programmes and are listed in table 2a. Three of these are described briefly below.

34. *Former Soviet Union, Mayak Complex, 1957.* In 1957, at the Mayak Complex, overheating of a storage tank containing radioactive nitrate–acetate salts led to an explosion and the release of some 740 PBq of radioactive products off-site to an area of some 20,000 km^2 of the Chelyabinsk and Sverdlovsk regions. The contaminated zone had a population of 272,000. There were 1,154 individuals inhabiting areas with a ^{90}Sr deposition density of greater than 40 MBq/m^2 [U6].

35. *United Kingdom, Windscale, 1957.* In 1957, a fire in the Windscale graphite reactor burned for three days, resulting in major releases of radioiodine and other nuclides into the environment in and around Cumbria. The release of ^{131}I was estimated at some 740 TBq. It was accompanied by 22 TBq of ^{137}Cs, 3 TBq of ^{106}Ru, 16 PBq of ^{133}Xe and 8.8 TBq of ^{210}Po. The maximum doses to local individuals were estimated to be 0.01 Gy to the thyroids of adults and 0.1 Gy to the thyroids of children. Measurements in Leeds and London indicated thyroid doses of 0.001 and 0.0004 Gy [C2, G4, U6, U9].

36. *Russian Federation, Siberian Chemical Enterprises, 1993.* In April 1993, a serious accident occurred at the Siberian Chemical Enterprises facility at Tomsk-7. The accident caused damage to both the reprocessing line and the building, resulting in the release of about 30 TBq of beta- and gamma-emitting radionuclides and about 6 GBq of ^{239}Pu. Radiological monitoring of plant personnel demonstrated that only six individuals received doses of above the 0.2 mGy detection thresholds of the dosimeters used. Dosimetry on 14 of the 20 firefighters indicated individual doses of 1–7 mGy [I19].

B. Accidents not related to nuclear weapons programmes

1. Criticality accidents

37. Of the 23 criticality accidents in total that have been reported, 6 occurred at facilities not related to nuclear weapons programmes; they are listed in table 2b and briefly described below. One of these, the 1999 accident at Tokai-mura, is also listed under accidents with releases to the environment and potentially significant population exposures.

38. *Former Yugoslavia, Boris Kidrich Institute, 1958.* In October 1958, a criticality accident occurred during an experiment at a zero power reactor facility at the Boris Kidrich Institute in Vinca. The accident exposed six individuals to relatively uniform doses of 4.36, 4.26, 4.19, 4.14, 3.23 and 2.07 Gy. One individual died as a result of the accident [L1, M4].

39. *Belgium, Venus Assembly, 1965.* In December 1965, an accident occurred at the Venus Assembly in Mol, involving a tank type water moderated (70% H_2O and 30% D^2O) critical assembly operating with 7% enriched UO_2 rods. Although there was a written rule in the reactor safety report that no manipulation of a manual rod should be performed without first emptying the vessel, a written order was given to a technician prescribing the loading of a manual control rod followed by the unloading of another one. The technician inadvertently extracted the manual rod instead of first inserting the other rod, and a criticality resulted. The technician received approximately 3–4 Gy to the head and approximately 3–10 Gy to the trunk. The dose to his feet was estimated to be 40 Gy. Medical treatment was successful, but amputation of his left foot was necessary [J3, L1, P2].

40. *Former Soviet Union, Kurchatov Institute, 1971.* In February 1971, an accident occurred at Kurchatov Institute in Moscow during a series of experiments designed to evaluate

the relative effectiveness of iron and metallic beryllium as a reflector on a power reactor core. The supervisor determined that the substitution of iron for beryllium would not result in any considerable increase in reactivity. He supervised the addition of water prior to the arrival of the console operator and supervising physicist. The control rods had not been actuated, and a criticality occurred, evidenced by a flash of blue light. The supervisor and two visiting scientists were exposed; each received a whole-body dose of about 3 Gy; the supervisor and one of the visitors received doses to the legs of between 15 and 20 Gy [L1, V4].

41. *Former Soviet Union, Kurchatov Institute, 1971.* In May 1971, a second accident occurred at Kurchatov Institute during an experimental programme to measure critical masses formed by a certain type of highly enriched (about 90%) ^{235}U fuel rod. Following the insertion of control rods and removal of the neutron source from the core, the supervisor ordered the water to be removed through a fast dump valve. Because the gap size was smaller than the size of the fast dump outlet, an internal plate sagged and fuel rods fell out of the lattice into an unsafe geometry, resulting in a criticality excursion. The yield was estimated to be 5×10^{18} fissions. Four individuals were in the facility at the time of the criticality. A technician received about 60 Gy and died five days after the accident. The supervisor received about 20 Gy and died after 15 days. The other two individuals survived doses estimated at 7–8 Gy, but suffered long-term health effects [L1, S2].

42. *Argentina, Constituyentes Atomic Centre, 1983.* In September 1983, at the Constituyentes Atomic Centre, a prompt criticality accident occurred at the RA-2 zero power critical facility light water cooled test and training reactor near Buenos Aires. RA-2 utilized 90% enriched uranium MTR-type fuel. Facility procedures required that fuel and control rod alterations be performed without the moderator present. The operator attempted to make changes to the core configuration without draining the moderator water. The core went prompt critical, resulting in the moderator expanding rapidly and shutting down the reactor. It is estimated that the operator received an initial average whole-body dose of 17 Gy due to fast neutrons and about 20 Gy due to gamma photons. He experienced symptoms of ARS, including neurological disorders, and died two days after the accident [B15, G6, L1, N1, P3, W4, W5].

43. *Japan, Tokai-mura fuel conversion plant, 1999.* In September 1999, a criticality accident occurred in a fuel conversion plant in Tokai-mura during the processing of highly enriched fuel for an experimental fast reactor. Using unauthorized procedures, the workers poured 16.6 kg of 18.8% enriched uranium into a precipitation tank, resulting in a criticality excursion. Two individuals working near the precipitation tank received whole-body doses of 10–20 Gy Eq (individual A) and 6–10 Gy Eq (individual B) from gamma rays and neutrons, using a value for the relative biological effectiveness (RBE) of 1.7. A third individual, several metres distant from the precipitation tank, received a dose estimated to be 1.2–5.5 Gy Eq. Early administration of granulocyte colony-stimulating factor (G-CSF) was used in the medical management of these individuals. Individual A died 83 days after exposure and individual B 211 days after exposure. In the course of treatment, individual A received peripheral blood stem cell transplantation from his HLA-identical sister, and individual B received a transplant of umbilical cord blood.

44. The accident resulted in off-site doses from direct neutron and gamma irradiation to nearby populations, although no significant long-term effects are expected. Approximately 200 residents living within a 350 m radius were evacuated. Ninety per cent of them received doses of less than 5 mSv. Ten per cent received doses of between 5 mSv and 25 mSv. While there were measurable levels of airborne fission products on local plant life, maximum readings were less than 0.01 mGy/h, and the activity was short-lived [A2, I6].

2. Other accidents with only on-site consequences

45. Of the eight accidents (other than criticality accidents) in total that occurred during the operation of nuclear facilities and that led to early health effects among operators, plant staff or emergency response personnel, but had no off-site consequences for public health or the environment, three occurred at facilities not associated with nuclear weapons programmes and are listed in table 2b.

3. Accidents with releases to the environment and potentially significant population exposures

46. Of the seven accidents at nuclear facilities that resulted in significant exposures of the general public or the environment, three were not associated with nuclear weapons programmes; they are listed in table 2b. Two of these are described briefly below. One other, the 1999 accident at Tokai-mura, has been listed also under "criticality accidents" and has been described briefly in subsection 1 above.

47. *United States, Three Mile Island, 1979.* In March 1979, an accident occurred at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania. The sequence of events leading to the accident began with the closure of a valve that fed water to the boiler. A series of events thereafter led to core melt and the release of fission products through a relief valve in the primary water make-up system. Most fission products were retained in the water, but about 370 PBq of noble gases, mainly ^{133}Xe, and some 550 GBq of ^{131}I were released into the atmosphere. While the accident released large amounts of activity from the failed reactor core, the resulting exposures of the public were negligible [U6, U9].

48. *Former Soviet Union, Chernobyl nuclear power plant, 1986*. The 1986 accident at the Chernobyl nuclear power plant was the most severe accident ever to have occurred in the civilian nuclear power industry. Two workers died in the immediate aftermath, and high doses of radiation to 134 plant staff and a number of emergency personnel resulted in ARS, which proved fatal for 28 of them. The accident caused the largest uncontrolled radioactive release into the environment ever recorded for any civilian operation, including 1,760 PBq ^{131}I and 86 PBq ^{137}Cs. It deposited radioactive material over large areas of the former Soviet Union and some other countries in Europe, contaminating land, water and biota, and causing serious social and economic disruption for large populations in Belarus, the Russian Federation and Ukraine. The consumption of fresh milk contaminated with ^{131}I in the first weeks after the accident led to thyroid doses that have been estimated to range between 0.05 and 5 Gy to populations of Belarus, the Russian Federation and Ukraine. More details are provided in annex D, "Health effects due to radiation from the Chernobyl accident".

C. Summary

49. Tables 2a and 2b list 35 reported accidents at nuclear facilities that resulted in acute health effects or caused significant population exposures, of which 24 were at facilities associated with nuclear weapons programmes. In general, criticality accidents have occurred during experiments or operations in research reactors, or during work with fissile material in solution or slurries. One accident occurred in the processing of metal ingots. Only one criticality resulted in the release of radioactive material off-site, albeit a very small quantity. Of the 23 criticality accidents, 17 were at facilities associated with nuclear weapons programmes. Of the accidents at nuclear power plants, the 1986 Chernobyl accident was by far the most serious. Causes identified in these accidents were: inadequate facility design, process equipment that resulted in poor geometry, personnel errors and violation of operational procedures. Because of the regulatory regimes in place, the Committee considers it likely that most of the fatal radiation accidents at nuclear facilities have been reported.

II. ACCIDENTS AT INDUSTRIAL FACILITIES

50. Table 3 summarizes information on 80 accidents that have been reported at industrial facilities. Of these, 17 are described briefly below to illustrate the characteristics of these events. Section A presents accidents with sealed radioactive sources and section B accidents involving machine-generated radiation (i.e. from accelerators or X-ray devices).

A. Sealed radioactive sources

51. Table 3 summarizes information on 59 accidents that have been reported involving sealed radioactive sources at industrial facilities; 13 of these accidents are described briefly here.

52. *USSR, 1973*. Disregarding rules, an operator entered the main room of an industrial gamma–facility in the Moscow area, where the 4.2 PBq ^{60}Co source was unshielded. The operator walked around the source and as soon as he saw that it was in the "on" mode he immediately left the room. The estimated distance from the source to the victim ranged from 0.75 to 1 m. The whole-body dose appeared to be about 4 Gy and he survived a moderate ARS [B11].

53. *United States*, *1974*. In June 1974, at a medical product sterilization facility in New Jersey, a 61-year-old man was exposed for 5–10 seconds to gamma radiation from a 4.4 PBq ^{60}Co industrial source. The individual had failed to use a survey meter upon entering the facility and received a non-uniform exposure owing to partial shielding from Teflon-filled fibre drums. Nausea and vomiting were evident one hour after exposure, and the haematological nadir was reached about one month after exposure. The estimated dose, using cytogenetic dosimetry, was 4.1 Gy, and the patient was treated with standard antibiotic therapy and platelet/leucocyte transfusions. The individual returned to work in October 1974 [B2].

54. *United States, 1977*. In September 1977. at a facility in New Jersey, a 32-year-old man was exposed for about ten seconds to gamma radiation from an 18.5 PBq ^{60}Co source used to sterilize medical and chemical products. The accident was caused by construction work that had led to alterations in the hot cell entry area, failure to see the interlock warning and interlock failure. The individual experienced nausea and vomiting two hours after exposure. The estimated dose, using cytogenetic dosimetry, was 2.0 Gy. The patient reached the haematological nadir about 30 days after exposure and was treated with standard antibiotic therapy. Peripheral blood counts returned to normal in August 1978 [B2].

55. *United States, 1978*. In June 1978, an industrial radiographer working on a barge off the coast of Louisiana in the Gulf of Mexico sustained a radiation injury to the hand from a 3.7 TBq ^{192}Ir source. A dosimeter malfunction was thought to be the cause of the accident. About three weeks after the suspected date of exposure, the individual experienced a burning sensation, swelling, erythema and dryness of the thumb, index finger and middle finger of the left hand. The formation of bullae occurred one week later, and healing was apparent within 5–8 weeks, although the palmar surfaces demonstrated thin epithelium. Amputation of the digital two thirds of the index finger was performed at six months [S1].

56. *USSR, 1980.* An accident occurred in a gamma irradiation facility in Leningrad with a 22.2 PBq ^{60}Co source. The operator entered the irradiation room thinking the source was “down”. Within less than a minute and as soon as he realized he was wrong, he left the room. However the whole-body dose appeared to be more than 12 Gy, and he died on day 10 [S2].

57. *China, 1980.* In 1980, a 25-year-old man was accidentally exposed to a ^{60}Co source in Shanghai. The estimated source activity was 1.96 PBq, and the exposure time was about 40 seconds. The individual experienced early profuse vomiting and a rapid fall in lymphocytes and other haematological parameters. The estimated dose based on the survival of haemopoietic stem cells was 5.22 Gy. Following treatment, the patient was discharged from the hospital five months after exposure. Radiation-induced cataracts were observed three years after exposure [U3, Y1].

58. *Norway, 1982.* In 1982, an accident occurred in a gamma irradiation plant at the Institute of Energy Technology at Kjeller near Oslo. The plant was used for sterilization of medical equipment. A 2.43 PBq ^{60}Co source could be raised to various positions above the shielded position on the concrete floor. Owing to technical failure and human error, the operator entered the irradiation room although the source was not in the shielded position. He stayed in the irradiation room for several minutes and shortly afterwards was found sitting outside the plant and obviously ill. Shortly after the event he was admitted to a local hospital suffering from nausea, vomiting and facial erythema. During the next four days he had persistent nausea and increasing mucositis in the mouth. After a week his haematological values were markedly reduced. On the basis of dose reconstruction using electron spin resonance (ESR) spectroscopy of nitroglycerine tablets in his pocket, the mean whole-body dose was considered to have been slightly above 20 Gy. The patient died 13 days after exposure [R1, S3].

59. *China, 1986.* In May 1986, in Kaifun, Honan Province, a young man and a young woman were accidentally exposed to a 255 TBq ^{60}Co source for about 1.5–2 minutes at a local irradiation facility. The man received a whole-body dose estimated at 3.5 Gy and the woman a dose estimated at 2.6 Gy. Both individuals experienced radiation-induced vomiting and haematological depression [W2, Y1].

60. *China, 1987.* In March 1987, in Zhengzhou, Honan Province, a young man was exposed for 10–15 seconds to photons from a ^{60}Co source of 3.29 PBq. The estimated exposure was 1.35–1.45 Gy. He experienced lassitude, thirst and dryness of the eyes immediately after exposure. Four hours later he experienced nausea and anorexia but no vomiting. The nadir values of leucocytes and platelets occurred on the 35th and 31st days, respectively. Restoration of his leucocyte count was rather slow, and the count remained subnormal until the 120th day after exposure [Y1].

61. *El Salvador, 1989.* An accident occurred in February 1989 at an industrial irradiation facility near San Salvador. The facility had 0.66 PBq of ^{60}Co in a movable source rack, badly degraded safety systems and poor maintenance at the time of the accident. After the unshielded source rack became stuck, three individuals entered the radiation room and received non-uniform doses to the whole body. Subsequently they all developed ARS. Cytogenetic studies indicated doses of 8 Gy to patient A, 3.6 Gy to patient B and 3 Gy to patient C. Two of these individuals experienced serious radiation-induced injuries of the lower extremities, with doses estimated at 100 Gy. They were transferred to a specialized hospital in Mexico City. The leg of the most seriously irradiated individual was amputated approximately four months after exposure. Following transfer back to El Salvador, this patient died as a result of a surgical procedure and complications due to radiation-induced lung damage. Another individual required amputation of both legs. A third individual experienced minor injuries to one foot. Before the accident was fully understood, a fourth individual, a maintenance manager, entered the facility and received a whole-body dose that was medically insignificant [I1].

62. *Israel, 1990.* In June 1990, at a commercial irradiation facility in Soreq, an operator bypassed safety systems to enter the irradiation room in order to free cartons stuck on the conveyor system. He was not aware that the movable ^{60}Co source rack was obstructed in the irradiation position. At the time of the accident the total activity was 12.6 PBq. He promptly developed symptoms and left the area. It was determined that his whole-body dose was between 10 and 20 Gy. He was hospitalized with severe haematopoietic and gastrointestinal syndromes, and skin injury was soon evident. Despite aggressive medical efforts, including use of haematopoietic growth factors and a bone marrow transplant, he died 36 days after exposure [I2].

63. *China, 1990.* In June 1990, seven workers were exposed to radiation from a ^{60}Co source at an industrial facility in Shanghai. The accident was caused by improper maintenance of safety features. None of the workers was wearing a personal dosimeter at the time of the accident. One individual, with a dose estimated at 12 Gy, died 25 days after exposure. A second individual, whose dose was estimated at 11 Gy, died 90 days after exposure. The other five workers received doses estimated to range from 2 to 5.2 Gy and recovered after medical treatment [L2, P1].

64. *Belarus, 1991.* In October 1991, an accident occurred at a ^{60}Co irradiation facility used to sterilize agricultural and medical products in the town of Nesvizh. The source activity was 28.1 PBq at the time of the accident. Owing to a malfunction of the product transport system and human error, the operator entered the irradiation area and remained inside for 1–2 minutes with the source array in the full “out” position. He received prompt medical attention in Belarus and then in Moscow. He experienced ARS and skin injuries resulting from an estimated whole-body dose of 11–18 Gy. His intensive medical treatment included administration of

granulocyte–macrophage colony-stimulating factor (GM-CSF). He died 113 days after exposure of pulmonary and multiorgan failure [I3].

B. Accelerators and X-ray devices

65. Table 3 summarizes 21 accidents involving machine-generated radiation (i.e. from accelerators or X-ray devices), four of which are described briefly here.

66. *United States, 1960.* In March 1960 nine civilian employees at a military installation in Lockport, New York, were exposed to X-radiation from an unshielded klystron tube. Two of the individuals were seriously injured, five other individuals demonstrated less severe injuries and two individuals remained asymptomatic. The highest dose received was estimated to be 12–15 Gy (non-uniform). Seven exposed individuals demonstrated varying degrees of nausea, vomiting, headache, erythema, fatigue, epilation and conjunctival reddening. The individual with the highest estimated dose demonstrated signs and symptoms of ARS [H5].

67. *United States, 1967.* In October 1967 three technicians in Pittsburgh, Pennsylvania, simultaneously incurred accidental non-uniform whole-body exposures to radiation from a water-cooled Van de Graaff linear accelerator. The water cooling system had failed, and the technicians were attempting to repair the system. They followed all safety procedures and entered the accelerator area unaware that the safety interlock system had failed. The workers experienced early signs and symptoms of radiation injury, and dosimetric tests indicated whole-body exposures of 1, 3 and 6 Gy. The most seriously irradiated worker also had localized doses of 59 Gy to the hands and 27 Gy to the feet. He had a more complicated clinical course, and demonstrated pancytopenia and complete bone marrow depletion. His situation was unique because he had an identical twin brother who donated bone marrow for transplant on the eighth day after exposure. The patient developed extensive local skin injury to the hands and feet, and four months after exposure, amputation of portions of the hands and feet was performed. The amputation sites manifested lack of healing, and further necrosis led to 11 additional operative procedures over a 22 month period. The patient was eventually fitted with prostheses on all extremities. He required psychological support for many years [G2, G3].

68. *France, 1991.* In July and August 1991, three individuals working at an accelerator facility in Forbach received high doses of radiation from a Van de Graaff device. The accident was reportedly due to negligence and non-compliance with regulatory requirements. The workers' exposure was associated with "dark current" after the accelerator had been turned off, although the voltage was maintained to save time. The residual dose rate was a few grays per second. The most severely exposed individual suffered skin lesions following a dose estimated at 40 Gy, while the other two were less seriously affected [C1, U3, Z3].

69. *United States, 1991.* In 1991, an accelerator operator at a facility near Baltimore, Maryland, was exposed to electron dark current during routine maintenance. The filament voltage was off, but the high voltage was on, resulting in dose rates of 0.4–13 Gy/s. The operator placed his hands, head and feet in the beam. Three months later, most of the digits on both of the operator's hands had to be amputated. Using electron paramagnetic resonance (EPR) on bone samples from the fingers, the dose was estimated to be 55 Gy [D3].

C. Summary

70. Table 3 lists 80 accidents at industrial facilities. Nine deaths were reported in these accidents. They all occurred at industrial irradiation facilities using high-activity sealed sources, primarily because of improper entry into the hot cell, and a lack or failure of safety mechanisms. At least 84 other people were excessively overexposed in these facilities. In other industries, 36 workers were injured during the use of radiography sources, X-ray devices and accelerators, and during manufacturing procedures. The Committee considers it probable that some accidents at industrial facilities involving deaths and injuries have not been reported.

III. ACCIDENTS INVOLVING ORPHAN SOURCES

71. Orphan sources are radioactive sources that were never under regulatory control or were under regulatory control but then abandoned, lost, misplaced, stolen or otherwise transferred without authorization [G1]. Orphan sources have been the cause of serious accidents involving members of the general public, who were entirely unaware that they were being exposed to radiation. Table 4 summarizes key information about 34 accidents involving orphan sources (sometimes multiple sources). Of these, 20 are described briefly below to illustrate some of the characteristics of these events.

72. *Mexico, 1962.* Between March and September 1962, an engineer left a 200 GBq ^{60}Co source unprotected in the yard of a house in Mexico City. The source was found by a 10-year-old boy and subsequently taken to his home, where it remained for approximately four months. The boy and his sister died following estimated protracted whole-body doses of 47 and 28.7 Gy, respectively. The children's mother and grandmother also died following doses estimated at 35 and 30 Gy, respectively. The children's father survived, although he became permanently sterile, following an estimated protracted dose of 120 Gy [M6].

73. *China, 1963.* In 1963, a ^{60}Co source with an estimated activity of 0.43 TBq was found in a lead cask by a farmer fishing near the Anhui Agricultural Institute, located in Hefei City in Anhui Province. He took the source and returned to his home. Nine days later, authorities located the source. The six individuals living in the home were sent to a hospital for medical assistance. Two individuals in the home received estimated whole-body doses of 80 Gy and 40 Gy, and died within the following two weeks. The other four individuals received doses estimated at 8, 6, 4 and 2 Gy, and survived after medical treatment. No significant long-term effects were noted 17 years after exposure [P1].

74. *Mexico, 1973.* On 24 May 1973, during the construction of the refinery at Tula, in Hidalgo state, a truck was transporting a container holding a ^{137}Cs source. The container had a "plug" made of a piece of wood. Owing to the motion of the truck, the plug failed and allowed the source to emerge from the container. The box that held the container had a crack, and the source fell out on to the road. A 38-year-old bricklayer found it and took it home, carrying the source in his trouser pocket for several hours. The dose to the thigh was reported to be 1,386 Gy. He subsequently suffered radiodermatitis of the left thigh median third and the buttock. His left leg was amputated from the hip down; the middle finger of the right hand was also amputated. His family, who were exposed to the source over three days, showed no symptoms of radiation injury [N5].

75. *Algeria, 1978.* In May 1978, a 925 GBq ^{192}Ir source used for industrial radiography fell from a truck travelling on the road from Algiers to Setif. Two young boys found the source a few days later. Both boys handled the source, and it was eventually placed in their home. It remained there for 5–6 weeks, exposing the family to radiation under various conditions depending on their location and time spent in the kitchen. The two boys developed serious skin lesions; their 47-year-old grandmother and four females aged 14, 17, 19 and 20 years, who spent most of their time in the house, were exposed to varying doses. The actual doses to these five females were difficult to resolve, owing to many uncertainties, including those in the total time of exposure per day, geometry, shielding and distance from the source over a period of 38 days. Thus their treatment was based primarily on haematological presentations. The grandmother died in late June 1978. The foetus of the pregnant 20-year-old woman also died during the haematological recovery period of the mother, and both boys required surgery for their skin injuries [J2].

76. *United States, 1979.* In June 1979 a worker at an industrial site in Los Angeles (Riverside), California, found a lost ^{192}Ir radiography source with an estimated activity of 1.04–1.22 TBq. The worker placed the source in his right hip pocket and left it there for approximately 45 minutes. He subsequently developed a severe ulcerated radiation burn. The estimated skin surface dose was 800–4,000 Gy, and the 1 cm tissue depth dose was 520 Gy to an area measuring 11 × 9 × 2 cm. At 36 days after exposure a full-thickness myocutaneous flap, with vascular pedicle intact, was mobilized from the right thigh and sutured to the bed of the excised ulcer. Additional surgeries were required since the lesion did not completely heal. Five other workers handled the source before it was returned to the radiographer. Four of these workers developed moderate injuries to the fingertips. An additional five workers did not have medically significant exposures [H8, R2].

77. *Mexico, 1983.* In early December 1983, a ^{60}Co therapy machine was dismantled and loaded into a pick-up truck. The machine had been acquired in November 1977 by the Centro Medico Hospital in Ciudad Juarez and had been in storage since its acquisition. The source activity was about 16.6 TBq contained in some 6,000 small pellets, each with an average activity of 2.77 GBq. During the dismantling, the source container was punctured and a number of pellets (800–1,000), with an estimated activity of 1.85 TBq, were spilled into the truck's cargo area. The truck was later parked on a city street and was not discovered for about seven weeks. The machine was sold at a local scrapyard and then to foundries in Chihuahua and Durango, Mexico, with subsequent contamination of metal. During movement of the machine, some cobalt pellets were lost on the streets of Ciudad Juarez, in the scrapyard, along highways and in the foundries.

78. The accident was not discovered until January 1984 when a truck loaded with contaminated rebar stopped at an entrance to the Los Alamos National Laboratory in New Mexico, United States, and tripped radiation alarms. An investigation led to the discovery of the pick-up truck. No acute effects were noted in the general population; doses were protracted over a period of about 60 days. Cytogenetic dosimetry was performed on two scrapyard employees and eight individuals living near where the truck had been parked. Owing to uncertainties regarding exposures of the individuals, two mathematical models were used to estimate doses. The mathematical model used to extrapolate dose assuming acute exposure at a high dose rate resulted in estimates of 0.09–1.91 Gy. The estimate assuming chronic exposure at a low dose rate ranged from 0.13 to 15.16 Gy. There were no fatalities reported following the accident [B3].

79. *Morocco, 1984.* In March 1984, a worker at a facility in Casablanca took home an industrial radiography source (603 GBq of ^{192}Ir) and placed it on a shelf near his bed. The worker died 44 days after exposure. Over the next several weeks, the worker's pregnant wife and their four children also died as a result of their exposures. After the father's death, a cousin and his mother stayed in the house, using the room where the source was located. These two individuals also died as a result of their exposures. Three other persons living in the house experienced bone marrow suppression but survived their overexposures. Authorities recovered the source 80 days after it was removed from the facility [M2, M5].

80. *China, 1985.* In April 1985, an accident occurred in Mudanjiang when a lost source (370 GBq of ^{137}Cs) was brought into a dwelling where a 21-year-old man and his

parents (the mother was 68 years old and the father 66 years old) were exposed over a period of 150 days with estimated cumulative whole-body doses of 8–10 Gy to each individual. The father also experienced a radiation-induced burn on his right thigh. The clinical findings upon hospital admission were general malaise, bleeding and pancytopenia. The therapeutic measures were bed rest, adequate nutrition and strict control of infection. The father died from myelodysplastic syndrome complicated by pulmonary fungal infection 22 months after exposure. The other two individuals remained apparently well [Y1].

81. *Brazil, 1987.* In 1987, an abandoned 50.9 TBq ^{137}Cs teletherapy device located in Goiânia was stolen and dismantled, and the source capsule ruptured. Over the next two weeks, ^{137}Cs chloride powder was spread throughout a scrapyard, surrounding homes and the vicinity. The problem of radiation exposure was noted after numerous individuals developed illness and skin lesions. Subsequently a monitoring station was set up at a soccer stadium and 110,000 persons were monitored for contamination with radioactive material. Of these individuals, 249 were found to have ^{137}Cs deposits on their skin or clothing, and 129 of these persons were found to be internally contaminated with ^{137}Cs. Outpatient care was provided to 79 individuals, while 50 required close medical surveillance. Of these latter patients, 14 required intensive medical care for ARS, internal contamination and local lesions. Four persons died, including one child. There are 150 persons currently in a follow-up cohort. A group of 755 professionals participated in extensive environmental decontamination. Eighty-five residences required decontamination, and seven residences had to be demolished. The total volume of waste generated for temporary storage amounted to 3,134.5 m^3 and since 1987 has been disposed in a repository [I11, I12, N8].

82. *USSR, Ukraine, 1988–1991.* This accident occurred when a family consisting of a man, a woman and two children moved to an apartment in a new complex built 200 km south-east of Kiev. After several months the older son became ill and was found to have bone marrow depression. The cause was not identified, and the boy recovered and returned home. Over the next year the same scenario was repeated several times, and the boy developed osteosarcoma of the foot and died of metastatic disease. His younger brother was then allowed to move into his bedroom, and within several months developed severe bone marrow depression. The younger boy also developed a necrotic lesion on his foot. Thinking the problem was associated with the Chernobyl accident, the boys' mother requested authorities to survey the apartment for radiation. Finally a 2.6 TBq ^{137}Cs industrial source was found embedded in the wall of the boys' bedroom, located near the foot of the bed. How the source came to be there was never clear. Several months later the younger boy developed additional haematological problems and subsequently died [M2, S2].

83. *China, 1992.* In November 1992, in Xinzhou, Shanxi Province, a farmer was demolishing a closed irradiation facility when he found a 100 GBq ^{60}Co source contained in a cylindrical steel bar. The individual placed the bar in his jacket. Later that afternoon he was sent to a local hospital after complaining of nausea followed by vomiting. The jacket containing the source remained with the individual during his hospitalization. He died in early December. His father and elder brother, who had taken care of him at the hospital, died from exposure the following week. The farmer's wife also assisted in his care, and in mid-December she requested medical assistance. The doctors suspected that she, too, was suffering from radiation exposure. Through dose reconstruction, the farmer, his father and his brother were estimated to have received doses of greater than 8 Gy, and the dose to his wife was estimated to be about 2.3 Gy [P1].

84. *Turkey, 1993–1998.* Unauthorized long-term storage (1993–1998) and subsequent transport and transfer to a new owner resulted in a loss of control over two ^{60}Co therapy sources in Istanbul. The packages containing the sources were sold as scrap. Later the shielding of one container was opened at the scrapyard. In December 1998 ten persons fell ill, and six experienced nausea and vomiting. The cause of their illness was not diagnosed until four weeks later. Once the cause had been diagnosed, media reports caused alarm, and 404 persons applied for medical examinations. Eighteen persons (including seven children) were admitted to hospital. Ten of the hospitalized adults exhibited signs and symptoms of ARS. Five of these persons were hospitalized for 45 days. One person had local injury to a finger [I7].

85. *Estonia, 1994.* In October 1994 in Tammiku, three brothers entered a waste repository without authorization and removed a metal container holding a 1.6 TBq ^{137}Cs source. During removal the source was dislodged and fell to the ground. One of the men picked it up and placed it in his pocket. Before leaving the repository, he began to feel ill. A few hours later he began to vomit. He took the source to his home in the nearby village of Kiisa. Subsequently he was admitted to a hospital with severe injuries to his leg and hip, and he died on 2 November 1994.

86. The injury and subsequent death were not initially attributed to radiation exposure, and the source remained in the man's house with his wife, his stepson and the boy's great-grandmother. The boy was hospitalized on 17 November with severe burns on his hands, and a doctor identified the burns as being induced by radiation. The authorities were alerted, and the Estonia Rescue Board recovered the source from the house. The occupants of the house and one of the man's two brothers were hospitalized and diagnosed as suffering from radiation-induced injuries of varying severity. All were subsequently released from the hospital and continued to receive outpatient treatment for at least four years. Studies conducted on other people living in the area where the source was discovered revealed no symptoms of radiation sickness [I13].

87. *Russian Federation, 1995.* In 1995, a 48 GBq ^{137}Cs source was discovered in the cabin door pocket on the

driver's side of a truck near Moscow. The driver of the truck was apparently overexposed over a period of about five months. The dose rate at the left side of the driver's seat was estimated to be about 50 mGy/h. An estimate of the average whole-body dose of 7.9 ± 1.3 Gy was made on the basis of cytogenetic studies of chromosomal aberrations in the driver's blood lymphocytes. The driver was hospitalized in Moscow in July 1995 with complaints of fatigue and shortness of breath. Epilation was evident on the lateral surfaces of the left thigh and buttock. Pancytopenia, myelodysplasia and anaemia progressed over the next several months, eventually leading to myelomonocytic leukaemia. The individual died 22 months after the source was discovered [B7, S7].

88. *Islamic Republic of Iran, 1996.* In July 1996, industrial radiography was under way at the Gilan combined cycle fossil fuel power plant located 600 km north of Tehran. After making a series of radiographs, the radiography team failed to notice that the 185 GBq ^{192}Ir source was missing from the container. A 33-year-old plant employee found the source, handled it and then placed it in his shirt pocket, where it remained for about 90 minutes. Over the next few weeks the irradiated individual demonstrated haematological depression and was treated with antibiotics, platelet transfusions, and the haematological growth factor granulocyte-colony-stimulating factor (G-CSF). He also developed lesions to the right thorax, right elbow, right thigh and left palmar surface. He was treated in Tehran and subsequently transferred to Paris for treatment of his skin lesions. His chest and thigh lesions were successfully treated with a free graft from the undamaged thigh. About 16 months after exposure, the skin lesions healed, although there was thickening of the skin on the hand, slight retraction on the right side due to the fibrotic chest graft and contracture of the right elbow. The estimated whole-body dose was 2–4 Gy, while the maximum skin doses did not exceed about 40 Gy [I21].

89. *Georgia, 1996–1997.* Numerous sources were abandoned when Soviet troops turned over the Lilo Training Centre to the Georgian army in 1992. From April to August 1997, several Georgian soldiers sought medical care because of skin lesions. After radiation injury was diagnosed, high-activity sources were found 30 cm below the surface of a soccer field, 10 cm below ground in an area used for smoking, stored in lead containers and in the pocket of a soldier's winter jacket. In addition, 200 discarded sighting devices containing ^{226}Ra and a ^{60}Co source were found. In total, 12 ^{137}Cs sources were located. Eleven persons suffered local and systemic effects as a result of their exposures. The estimated doses for protracted exposures ranged from 4.2 to 0.6 Gy. Seven patients remained under treatment in 1999 [I20].

90. *Peru, 1999.* In February 1999, an ^{192}Ir industrial radiography source with an estimated activity of 1.37 TBq was lost at the Yanango hydroelectric power plant in the San Ramon district 300 km east of Lima. A few hours later a welder found the source and placed it in the right back pocket of his trousers. Over the next several hours the welder worked in a pipe and then took a minibus home. He changed clothing, placing his trousers (with the source still in the pocket) on the floor, and sought local medical assistance because of pain in his right thigh. He was diagnosed with an insect bite. Meanwhile his wife sat on the trousers while breastfeeding her 18-month-old child. Authorities recovered the source at 1 a.m. the following morning, and the welder was transferred to Lima for medical care. The estimated 1 cm depth dose to his thigh was 9,966 Gy, and over the next three months he developed an extensive severe lesion on the right thigh. He was then transferred to Paris for skin grafts using porcine xenografts. The grafts failed, and the right leg was disarticulated at the hip. Additional surgeries were required after the welder's return to Peru. His wife developed moist desquamation and ulcerative and fibrotic lesions of her lower back [I8].

91. *Thailand, 2000.* In 1999, unauthorized teletherapy sources were relocated to an unsecured site in Samut Prakarn. In January 2000, four scrap collectors gained access to the facility, partially disassembled a teletherapy head and took the device home for further disassembly. On 1 February two of the individuals sold the components to a junk dealer. During further disassembly of the device at the junkyard, the source fell out of its housing but was not noticed. By mid-February several individuals had sought medical attention, and suspicion of radiation injury was reported to the authorities. The 15.7 TBq ^{60}Co source was recovered on 20 February. Ten people were hospitalized. Three junkyard employees died of ARS-associated infections in March. Four other individuals suffered local injuries; one required hand amputation. G-CSF and GM-CSF were used in the medical management of these patients [I9].

92. *Egypt, 2000.* In May 2000, a farmer from Meet Halfa village found a 1.17 TBq ^{192}Ir industrial gamma radiography source that had been lost by a worker testing pipe welds. The farmer took the source to his home, where he lived with his wife, a sister and four children. In the following weeks the source was handled by family members and moved to various locations within the family home. The 9-year-old son died in June, and death was reported to be due to bone marrow failure and inflammation caused by a viral or bacterial infection. Other family members were also found to be sick with skin lesions, bone marrow failure and gastrointestinal symptoms, but the diagnosis again was incorrect. On 16 June the farmer died. On 25 June, a fact-finding mission detected high radiation levels at the family home, and the source was recovered. Family members were hospitalized with skin lesions and bone marrow depression. G-CSF was used in their treatment. Dose estimates were: father, 7.5–8 Gy; 9-year-old son, 5–6 Gy; five other family members, 3.5–4 Gy. Between 200 and 300 neighbours and relatives were monitored, and the affected family received continuing treatment and surveillance [E1, I10].

93. *Georgia, 2001.* In December 2001, three woodsmen found two heat-emanating ceramic objects near their

campsite in the remote Inguri River Valley of Georgia. Two of the woodsmen carried the containers on their backs, and experienced nausea, vomiting and dizziness within hours of exposure. The third carried the source attached to a wire. At a hospital in Tbilisi, the woodsmen were diagnosed with radiation sickness and severe radiation burns, and at least two of the three men were in serious condition. A Georgian team recovered the sources in early 2002 with the assistance of the International Atomic Energy Agency (IAEA). They were unshielded ceramic sources from two Soviet-era radioisotope thermoelectric generators (RTGs), each containing about 30,000 Ci (1 PBq) of ^{90}Sr. Two of the patients were treated in hospitals in Paris and Moscow for many months before recovering from their severe radiation burns [I23].

A. Summary

94. Table 4 presents information on 34 accidents involving orphan sources. These accidents resulted in 42 early deaths and in disfiguring injuries to both children and adults. Significant environmental contamination and the internal contamination of 129 persons occurred in one of these accidents. The Committee considers it probable that some radiation accidents involving orphan sources and that resulted in deaths or injuries have not been reported.

IV. ACCIDENTS AT ACADEMIC AND RESEARCH FACILITIES

95. Table 5 summarizes information about 22 radiation accidents at academic and research facilities, seven involving sealed radioactive sources and 15 involving machine-generated radiation (i.e. from accelerators and X-ray devices). Some examples of these accidents are described briefly below to illustrate the nature of these events.

A. Sealed radioactive sources

96. *USSR, 1962*. A ^{60}Co source of about 1.9 PBq was used at a research institute in Moscow for irradiating metal samples. A researcher opened the locked door and entered the irradiation room, believing the time to change the sample would be so short as to be not dangerous. However, she received a whole-body dose (non-uniform) of about 2.5–3.0 Gy, and 12 Gy to her right hand. She survived a moderate ARS with mild local skin injury [G5].

97. *United States, 1971.* In February 1971, a 32-year-old technician was performing seed irradiation experiments at the Variable Dose Rate Irradiation Facility at the University of Tennessee Comparative Animal Research Facility in Oak Ridge. Because of an interlock failure, the technician was able to enter the facility with a 285 TBq ^{60}Co source unshielded. He was within 50 cm in front of an unshielded source for about 40 seconds. When the technician left the facility, the operator noticed that the source was unshielded and notified the authorities. The technician was hospitalized within two hours, and experienced episodes of nausea and vomiting starting 2.25 hours after exposure and lasting for about 24 hours. Maximum haematological depression lasted from day 24 to day 34 after exposure. The estimated whole-body and bone marrow doses were 1.27 Gy and 1.18 Gy. The patient was treated with standard antibiotic and haematological support, and returned to work 11 weeks after exposure [V2].

B. Accelerators and X-ray devices

98. *USSR, 1977.* In March 1977, a 40 MeV proton accelerator in the Institute of Nuclear Physics, Kiev, was activated for the first time. A physicist—who had fostered its construction—decided to demonstrate the presence of the beam. He inserted a luminescent lamp by hand “into the beam”, and it illuminated. However the physicist received an absorbed dose within the hands’ tissues ranging from 12 Gy on the surface to more than 30 Gy at the depth of 0.5 cm at some points. This led to a complicated clinical course of local radiation injury to both hands, and several surgical interventions were performed in order to save some of the hands’ functionalities [A5, B12].

99. *United States, 1977.* In April 1977, a graduate student at the Donner Laboratory of Lawrence Berkeley Laboratory, University of California at Berkeley, was conducting a research experiment involving the effects of X-rays (about 30 kVp) on yeast cultures. On the day of the accident the student was to expose 60 Petri dishes of yeast cultures. An interlock failure resulted in the student’s hands receiving about 70 Gy. There was noticeable erythema within 12 hours, followed by blistering and desquamation over a period of several months. Two fingers on the left hand and one finger on the right hand were amputated [T2, U3].

100. *USSR, 1978.* A powerful 70 GeV proton accelerator was used at the Institute of High Energy Physics, Protvino, for a broad spectrum of scientific experiments. In June 1978, after a long chain of procedure violations and errors, a researcher was accidentally exposed to a needle-thin beam of protons, which pierced his head from left occipital lobe of the brain to the left nostril. His middle ear was destroyed, and facial nerve injured. He survived, and the function of the facial nerve was restored. However, deafness in his left ear and a scar on the left nostril remained; and brain damage caused mild epilepsy six years later [B13].

101. *USSR, 1978.* An accident occurred in an electron linear accelerator in Leningrad, involving a 12.7 MeV electron beam. A worker entered the experimental room after irradiation was complete and a timer had cut the voltage to the controlling electrode. She stood with her back to the exit window and then turned 180°. It appeared that she was exposed twice owing to so-called "dark current", because the high voltage to the accelerating tube was still on. The localized doses to her back and chest were estimated as more than 20 Gy and 8 Gy respectively. Skin reactions corresponded to these doses; however, signs of severe radiation damage to the spinal cord appeared six months later [A5].

102. *Vietnam, 1992.* In November 1992, an accident involving a research X-ray accelerator occurred at the Hanoi Institute of Health Physics. One individual entered the irradiation room without supervision and subsequently exposed his hands to the X-ray beam. The dose to the individual's left hand was estimated to be 10–25 Gy, and the whole-body dose was estimated to be 1–2 Gy. The individual's hands were seriously injured, and one hand had to be amputated [I4].

103. *United States, 1994.* In June 1994 two graduate students at the University of California at Davis were analysing samples using a water-cooled Enraf-Nonius X-ray diffraction unit operating at 45 kVp, 25 mA, with the timer mode set in the "continuous" position. On previous occasions, the students and a faculty member had dismantled the unit to clean corrosion that had built up between the X-ray tube column and the primary shutter. Procedures called for the unit's electrical power to be in the "off" position. The students had, however, adopted the practice of expediting sample changing by bypassing the cabinet door safety interlock rather than turning the power to the "off" position. This led to significant exposure to areas of both hands of one of the students. The skin entrance dose rate was 960 Gy/min. The clinical course over one year after exposure included tightness and paraesthesiae in the student's fingers, swelling, erythema, bullae, hyperkeratosis and significant pain [B4].

C. Summary

104. Table 5 lists accidents in academic and research facilities. Twenty-two accidents have been reported in the use of accelerators, research reactors, radiochemistry laboratories, small irradiation facilities, and with the use of X-ray diffraction, spectroscopy, crystallography and fluorescence units. The hands were commonly the area injured. The Committee considers it probable that some radiation accidents in academic and research work have not been reported.

V. ACCIDENTS ASSOCIATED WITH THE MEDICAL USE OF RADIATION

105. A summary of nearly 100 radiotherapy accidents has been presented by the IAEA [I25], and a similar number have been reported by the International Commission on Radiological Protection (ICRP) [I24]. Table 6 summarizes information on 32 serious radiation accidents associated with the medical use of radiation. Some examples of accidents associated with the diagnostic and therapeutic uses of radioactive materials and machine-generated ionizing radiation are described briefly below. More discussion on accidents in radiotherapy is provided in annex A, "Medical radiation exposures".

A. Nuclear medicine

106. *United States, 1968.* In August 1968 a 73-year-old woman was scheduled for a diagnostic nuclear medicine liver/spleen scan at a hospital in Wisconsin. The radiopharmaceutical being used was colloidal ^{198}Au, administered intravenously. The intended activity was 7.4 MBq, but because of an error, the patient received 1,000 times more of the radionuclide, or 7.4 GBq. The estimated bone marrow dose was 4–5 Gy, and the dose to the liver was 70–90 Gy. The patient died 69 days after exposure [M3].

B. Sealed radioactive sources

107. *United States, 1974–1976.* This accident involved 426 patients being treated with a ^{60}Co teletherapy unit over a 16-month period (1974–1976) at the Riverside Hospital in Columbus, Ohio. Dose rates had been underestimated by 10–45% owing to an error in calculating the source decay and to a lack of routine periodic calibration. Of the 183 who survived beyond one year, 34% had severe complications, some of which led to death. Fifteen years after the accident, 18 individuals remained alive, with 50% experiencing severe complications [M1].

108. *France, 1981.* During the initial loading of a radiation therapy device in a new radiotherapy department in Saintes, the 137 TBq ^{60}Co source had become jammed in the loading channel instead of being in its retracted, shielded position. Unaware of this, an assistant operator placed his hands in contact with the device in an area where the source was jammed. On removal of the source transport apparatus that contained a dummy source, both the dummy source and the ^{60}Co source fell on to the floor. Despite 25 years of experience, the main operator picked up the source with his bare hands and put it in a safe position. Doses to the hands

of both the operator and his assistant exceeded 25 Gy at the wrists. The amputations of both hands of both victims were unavoidable. A third operator received an unexplained high-level exposure of one hand, leading to amputation of a large portion of the hand [N7].

109. *United States, 1992.* An accident occurred in November 1992 in Indiana, Pennsylvania, involving a female patient scheduled for a high-dose-rate brachytherapy procedure using a 159 GBq ^{192}Ir source. The treatment was to be given in three fractions of 6 Gy each. During the first procedure the source broke off the guide wire and remained inside one of the catheters surgically implanted into the patient's tumour. A radiological survey of the patient was not performed, and she was returned to a local nursing home. The source became dislodged from the catheter on day 4 and was discarded in the biohazard waste. It was discovered some days later when a waste truck passed through a radiation detector installed at an incinerator facility.

110. The estimated dose at 1 cm in tissue was 16,000 Gy. Death occurred four days after the procedure, but was thought to be associated with the patient's disease and age. The patient's remains were later exhumed and an autopsy was performed, resulting in the death certificate being changed to reflect death from ARS. Ninety-four additional individuals, including staff, visitors, family members and other nursing home residents, were exposed, although the doses were not medically significant [N4].

111. *Costa Rica, 1996.* In August 1996, a ^{60}Co radiotherapy source was replaced at a hospital in San José. Following the replacement, a calibration error was made. Over the next 37 days, radiation doses 50–60% greater than those prescribed were delivered to 115 patients under treatment for neoplasms. These overexposures were confirmed by recalibration of the source and review of individual patient charts. In July 1997, an IAEA investigation team evaluated 70 of the 73 patients who were still living. The team concluded that 20 patients were suffering from major adverse effects due to their overexposures, with 26 other patients experiencing less severe effects. Twenty-two had no discernible effects, because of incomplete therapy. Two patients were underexposed and three were not examined. Seventeen deaths associated with the radiation exposures were reported [I14, I24].

112. *Panama, 2000.* At the Instituto Oncológico Nacional in Panama, a computerized treatment planning system was used to calculate the dose distribution and determine treatment times. In August 2000, medical physicists changed the method for entering data on shielding blocks in the computer program in order to overcome limitations for treatments that required more than four blocks. Soon thereafter, the radiation oncologists started to observe prolonged diarrhoea in some patients. In March 2001, physicists identified a problem with the calculation of exposure times, and the treatment of patients with abnormal symptoms was suspended. Further studies revealed that 28 patients had received a proportionately higher dose than prescribed. Further investigations were undertaken, although eight patients had already died. At least five of these deaths were probably radiation related. The 20 surviving patients were examined, and a number were found to be suffering from bloody diarrhoea, necrosis, ulceration and anaemia [B10, I15].

C. Accelerators and X-ray devices

113. *United States and Canada, 1985–1987.* In 1985, 1986 and 1987, several serious overexposures occurred when patients were being treated for carcinoma using a Therac-25 electron linear accelerator. The device was first manufactured in 1982, and 12 units were in use within the United States and Canada. Accidents occurred in United States hospitals located in Marietta, Georgia; Tyler, Texas; and Yakima, Washington; as well as at a hospital in Hamilton, Ontario, Canada. Control of the device was achieved using a small digital computer. Unfortunately, the computer had a software problem such that when the technician made an error in the treatment procedure, the computer screen displayed a "malfunction 54", which was the code for "dose input error". This resulted in the patient receiving a direct electron beam at 25 MeV.

114. Six patients were irradiated during machine malfunction and received severe burns. Two of the patients died as a result of their injuries following therapy in Texas. In March 1986, a 33-year-old man with a liposarcoma on his left upper back was treated; owing to the machine malfunction, the patient experienced severe damage to the cervical cord, resulting in death five months after exposure. In April 1986, a 66-year-old man with a multifocal skin cancer on the left side of the face was treated during machine malfunction. He died three weeks later from damage to the right temporal lobe of the brain and the brain stem [N2].

115. *Spain, 1990.* In Zaragoza, 27 patients received higher radiotherapy doses than those prescribed, because of a malfunction in a linear accelerator. During a repair procedure, the electron energy of the accelerator was modified, and this change was not noted by the therapists, who thought that the meter on the control panel was faulty. The increased energy resulted in greater penetration of energy and effects on deeper tissues. In addition, the electrons were focused in a smaller cross-section of the beam. This resulted in doses three to seven times higher than intended. Patients developed injuries in the lungs, pharynx and spinal cord, complicated by vascular and skin injuries. As the victims of this malfunction were suffering severe tumours for which they were being treated with radiation, it is difficult to accurately assess the contribution of the accident to the number of deceased. It was estimated that 15 patients died with radiation as the primary or major cause of death, while others had severe disabilities [I24, S5].

116. *Poland, 2001.* In February 2001, at the Bialystok Oncology Centre, a serious accidental overexposure injured five female patients undergoing post-operative radiotherapy for breast cancer. The accident involved a NEPTUN 10P linear accelerator. A transitory electrical power loss occurred, and following restart of the device, the patients received considerably higher doses than planned. Prescribed doses were 2–2.5 Gy per fraction from an 8 MeV electron beam. EPR assessment of rib samples resulted in dose estimates of 60–80 Gy. Medical examination revealed local injuries in the five patients, which worsened over time. Surgical intervention was necessary in all cases. The condition of four patients improved with the use of hyperbaric oxygen therapy [I22].

117. *United Kingdom, 2006.* In January 2006, a 15-year-old female patient was receiving radiotherapy for a brain tumour at an oncology centre in Glasgow. Twenty planned fractions of 1.75 Gy (35 Gy total) were to be delivered using a linac system, but owing to a dose planning error undiscovered until the 19th fraction, the estimated delivered dose was 55.5 Gy [J5].

D. Summary

118. Those at risk in the medical use of radiation include patients, physicians and staff, as well as those involved in changing sources, repairing devices, and so on. Human error has been a common cause of these accidents in the medical field. Examples of errors include delivering the radiation dose to the wrong patient or to the wrong location, giving the wrong dose because of errors in treatment planning and failure to use survey equipment/monitors as intended. The IAEA [I25] and ICRP [I24] have catalogued over 100 radiotherapy accidents, and table 6 lists 32 examples of serious radiation accidents in the medical field. It is noteworthy that such accidents were sometimes not recognized, because injuries were not always evident until some time after a procedure, or symptoms were masked by the severity of the underlying disease process. Both underexposure and overexposure to radiation have had serious consequences. Only overexposures have been included in this annex. The Committee considers it likely that some deaths and many injuries in the medical use of radiation have not been reported.

VI. OTHER ACCIDENTS

A. Transport accidents

119. Millions of packages of radioactive material are safely transported throughout the world each year. Most of these materials are for medical or general industrial use. Many packages are manually handled and are transported by road, or sometimes by air, sea or rail. Some packages require remote handling because of their weight. Road and rail traffic is often through urban areas, and members of the public may be in close proximity to the packages. In the event of an accident, there could be a local release with some atmospheric or aquatic dispersion [H1, I16].

120. Accidents do occur during transport, although any consequences are normally limited by built-in safety features of the packages/containers and by adherence to regulatory controls, including emergency response procedures. (See reference [I17] for detailed information regarding accident frequency, types and consequences.) A recent United Kingdom study of accidents and incidents over the period 1958–2004 concluded that the most serious radiological consequences occurred as a result of transporting improperly packaged industrial radiography sources [H10].

121. Less commonly, accidents have occurred during military and civilian movement of radiological or nuclear materials by aircraft, ship, submarine or spacecraft (see table 7). These accidents have involved small nuclear reactors, RTGs, nuclear weapons, nuclear waste and other radioactive shipments [B1, I16, I18, T1]. A number of these accidents have resulted in loss of life due to causes other than radiation. Again, consequences have been limited by the substantial built-in safety features, by adherence to the controls required for transport, and by the emergency response and recovery procedures utilized.

122. Table 7 summarizes 24 accidents involving sea, air and space vehicles. With the exception of the submarine accidents in the former Soviet Union (see table 1), these accidents did not lead to early acute effects of radiation exposure. Some of them, however, did lead to widespread dispersion of radioactive material in the environment. Military activities have involved at least two documented serious transport accidents that led to environmental contamination: the accidents at Palomares, Spain, and Thule, Greenland. These accidents were described in the UNSCEAR 1993 Report [U6]. More detailed information on accidents and losses in the marine environment can be found in reference [I18].

B. Suspected malicious act

123. While malicious acts are clearly not accidental, they are in principle of interest for the Committee's assessments if they lead to early acute health effects of radiation or to widespread significant population exposures. The Committee has not reviewed such events comprehensively in the context of this report. Nevertheless, it considered it appropriate to note a recent suspected malicious act that received much media attention.

124. On or about 1 November 2006, a Russian living in the United Kingdom was allegedly poisoned with ^{210}Po [H9]. He died on 23 November 2006 [H6]. The death caused widespread public interest. An extensive public monitoring programme revealed no public health consequences for open public spaces. More than 700 persons in the United Kingdom were tested for ^{210}Po contamination. Of these, more than 100 showed ^{210}Po concentrations in urine indicating some contamination from the incident, but fewer than 20 had results indicating committed effective doses of greater than 6 mSv [H7, U17].

VII. SUMMARY

125. Early acute (deterministic) health effects of radiation exposure have occurred as a result of accidents or malicious acts. Some serious accidents have additionally led to significant population exposures (at levels below that for deterministic effects) owing to widespread dispersion of radioactive material in the environment.

126. This annex categorizes and summarizes radiation accidents that have resulted in early acute health effects, deaths and/or major environmental contamination during the past 60 years (tables 2–6). Selected examples of each accident type have been briefly described in the text to provide insight into the nature of the reported accidents, their medical consequences and the associated radiation doses that resulted in injuries and deaths.

127. Table 8 presents an overall summary of the number of accidents reported in each category over time. Table 9 presents published estimates of the collective doses for a spectrum of accidents that have led to significant population exposures owing to environmental contamination. Table 10 presents a summary of the numbers of deaths and early health effects that have been reported owing to radiation accidents over the last 60 years. These summaries cannot be deemed complete. For example, it was not possible to use fully the summary information in table 1.

128. In more than 60 years (1945–2007) of work at nuclear facilities there have been 35 serious radiation accidents reported. Seven of these caused off-site releases of radioactive materials, with potential for significant population exposures. Of the 35 reported accidents, 24 were in facilities related to nuclear weapons research, development and production, and to the reprocessing of nuclear fuel for weapons programmes. Other accidents occurred in power reactor research, development and operation, and in the reprocessing of nuclear fuel. Excluding the 1986 accident at Chernobyl, 32 deaths are known to have occurred as a result of radiation exposure in accidents at nuclear facilities, and 61 workers suffered radiation injuries requiring medical care. The incidence of accidents in these facilities has fallen; most of the deaths and injuries occurred in the early years of research and development in the context of nuclear weapons programmes. Only one criticality accident, with the death of two workers, has occurred in the past 20 years.

129. Eighty accidents were reported at other industrial facilities utilizing radiation sources, accelerators and X-ray devices. Nine deaths were reported in these accidents, and 120 workers were injured, with the hands being a common site of injury. Serious injuries frequently led to amputations. Acute radiation syndrome developed in some injured workers, and multiple amputations were necessary in some cases.

130. Thirty-four accidents have been attributed to lost, stolen or abandoned sources (orphan sources) since 1960. These accidents are known to have resulted in the deaths of 42 members of the public, including children. In addition, ARS, serious local injuries, internal contamination or psychological problems necessitated medical care for hundreds of persons. The number of reported accidents involving orphan sources has increased in the past 20 years (see table 8). It is noteworthy that six accidents were associated with abandoned medical therapy units.

131. Reports of accidents in academic and research facilities have been rare, with 22 accidents since 1960 and only four within the past 20 years. Most of these accidents resulted in injuries to the hands.

132. The Committee considers that accidents associated with the medical use of radiation in diagnosis and treatment may have been under-reported. There have been relatively few reports of serious accidents, considering the extremely large number of procedures performed annually throughout the world (annex A). Since 1967, 32 accidents with 46 deaths have been considered here. However, there have been a large number (623) of persons who developed early acute (deterministic) health effects as a result of these accidents. Delays in recognizing errors led to greater numbers of persons being injured. The 32 accidents considered here involved serious overexposures to radiation, but underexposures can also have serious consequences for patients.

133. The extensive worldwide civilian transport of radioactive materials has not resulted in any human injuries related to radiation exposure. Accidents have occurred during military transport of radioactive materials. Some resulted in, or had the potential for causing, environmental contamination, and some have resulted in the loss of lives (although not necessarily because of the radioactivity). A limited number of spacecraft carrying radioactive material have burned up on re-entry into the earth's atmosphere or have crashed, resulting in significant releases of radioactive material to the environment. However, there is no documented evidence of anyone sustaining injury from these events.

134. This annex does not explicitly address observable late effects due to ionizing radiation exposure. However, for comparative purposes, table 9 presents estimates for collective doses sustained by local and regional populations from a spectrum of accidents that led to dispersion of radioactive material in the environment. One accident dominates the collective dose, namely the 1986 Chernobyl accident, on which the Committee has prepared a dedicated annex, annex D, "Health effects due to radiation from the Chernobyl accident".

135. Serious radiation accidents have been rare occurrences. Much information has been published about these accidents, but information about some less serious accidents remains unreported in the literature. Human error, carelessness, failure to follow procedures and safety guidelines, defective equipment or defective repair, inadequate training, loss of control and source abandonment, and other conditions have led to accidents in the past 60 years, and will probably lead to accidents in the future.

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Table 1. Major types of radiation accident on the territory of the former USSR and the nature of their early effects
As recorded up to 30 June 2003 [I27]

Type	*Number of radiation accidents*	*Number of people with significant clinical symptoms*					
		Total (ARS + LRI)[a]	*ARS severity grade*[b]				*Died*
			I	*II*	*III*	*IV*	
Radioisotope units and their sources (total)	92	170	49	27	11	6	16
^{60}Co	17	28	15	9	6	3	3
^{137}Cs	19	59	13	7	1	—	9
^{192}Ir	37	54	10	3	—	—	1
Other gamma emitters	8	10	2	1	—	—	—
beta/gamma emitters	2	2	—	—	—	—	—
beta emitters	9	17	9	7	4	3	3
X-ray units and accelerators (total)	39	43	—	—	—	—	—
X-ray units	27	30	—	—	—	—	—
Electron accelerators	9	10	—	—	—	—	—
Proton accelerators	3	3	—	—	—	—	—
Reactors and critical fissile materials (total excluding Chernobyl accident)	33	82	73	39	25	13	13
Criticality	16	42	42	30	20	10	10
Reactors (other than criticality)	17	40	31	9	5	3	3
Mayak Production Association (1949–1956) with LRI	168[c]	168	—	—	—	—	—
Nuclear submarine	4	133	85	29	19	12	12
Others	12	17	7	3	2	2	2
Total excluding Chernobyl accident	348[c]	613	214	98	57	33	43
Chernobyl accident	1	134	134	93	43	21	28
Total	349[c]	747	348	191	100	54	71

[a] Acute radiation syndrome (ARS) and local radiation injuries (LRI).
[b] ARS severity grades: I – mild, II – moderate, III – severe, IV – extremely severe.
[c] Each LRI case at Mayak Production Association (1949–1956) is considered as a separate accident.

Table 2A. Accidents at nuclear facilities: Related to nuclear weapons programmes

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
Criticality accidents							
1945	United States: Los Alamos, New Mexico	Nuclear research facility	Unsafe procedure; during a critical assembly experiment, a scientist's hand slipped, allowing a tungsten carbide brick to fall into the assembly	1	1	Experimenter received 5.1 Gy whole-body dose and died 28 days after exposure; a guard received 0.5 Gy	[L1]
1946	United States: Los Alamos, New Mexico	Nuclear research facility	Unsafe procedure; a critical assembly reflected by beryllium was being demonstrated; the reflector slipped, allowing a criticality excursion	1	6	Man performing demonstration died nine days after exposure of 21 Gy; seven others had doses of between 0.37 and 3.6 Gy	[L1]
1952	United States: Argonne, Illinois	Nuclear research facility	Failure to follow operating procedure during replacement of control rod		3	Radiation doses to four workers were 1.36, 1.27, 0.6 and 0.09 Gy	[L1]
1953	USSR: Chelyabinsk	Nuclear research and reprocessing facility	Poor design; unfavourable geometry used for mixing, dilution, storage, etc. of plutonium nitrate products		2	Chief operator received 10 Gy non-uniform whole-body exposure with maximum dose of 30 Gy to legs; survived moderate ARS, and both legs were amputated; another worker survived moderate ARS (1.5–2.0 Gy)	[G5, L1, V1]
1957	USSR: Chelyabinsk[a]	Nuclear research and reprocessing facility	Poor design; accumulation of uranyl oxalate in unsafe geometry	1	5	Operator exposed for approximately 10 minutes, dose estimate was more than 10 Gy, died 12 days after exposure; five others had ARS (2.0–6.0 Gy) but recovered	[G5, L1, V1]
1958	USSR: Chelyabinsk	Nuclear research and reprocessing facility	Unsafe geometry during draining of uranium solution; neutron reflector contributed to criticality	3	1	Three workers died in 5–6 days; doses estimated at 40–50 Gy; a fourth person was approximately 3 m away and survived, with continuing health problems and loss of eyesight	[B11, G5, K2, L1, V1]
1958	United States: Oak Ridge, Tennessee	Nuclear processing facility	Valve leakage led to an unplanned transfer of enriched uranium solution to a 55-gallon (208 L) drum. Unsafe geometry resulted in a criticality		8	Doses of the eight injured ranged from 0.7 to 3.65 Gy; all survived	[A1]
1958	United States: Los Alamos, New Mexico	Nuclear research facility	Unsafe geometry occurred when plutonium solids were washed from two vessels into one	1		Operator died 36 hours after the accident; dose to upper torso was estimated to be 120 Gy; two others had whole-body doses of 1.34 and 0.53 Gy but no ill effects	[L1]
1961	United States: Idaho Falls, Idaho	Reactor research facility	Evidence suggests control rod was manually pulled out too fast, causing power rise	3 (trauma)		Two men were killed instantly from a steam explosion; a third man died two hours later as a result of head injury	[L1]
1961	USSR: Seversk, Siberia	Chemical processing facility	Criticality controls were not in place during condensing and evaporation of uranium hexafluoride		1	Process operator received a dose of about 2 Gy, with mild radiation sickness symptoms	[L1, V1]
1962	United States: Hanford, Washington	Processing facility	Improper control of solutions led to unfavourable geometry		1	One person received 1.1 Gy	[L1]
1963	USSR: Arzamas, Sarov	Nuclear weapons research facility	Violation of operating procedures		2	Two operators received doses of 3.7 and 5.5 Gy; both developed radiation sickness but survived; four others working in adjacent areas received low doses (0.07–0.0002 Gy)	[L1]

1964	United States: Wood River Junction, Rhode Island	Chemical processing facility	Human factors; labelled bottle indicated high concentration of U; contents were transferred to vessel and unsafe geometry resulted	1	2	Radiation dose to the operator was estimated to be 100 Gy; he died 49 hours after the accident; two individuals who entered the room received doses of 1 and 0.6 Gy	[K1, L1]
1968	USSR: Chelyabinsk-70	Reactor	Violation of procedures; failure to reposition a reflector	2		One technician received 20–40 Gy from gamma and neutron exposures and died three days later; a second technician received 5–10 Gy and died 54 days after the excursion	[L1]
1968	USSR: Chelyabinsk-40	Plutonium extraction facility	Inadequate design leading to unfavourable geometry of plutonium solution	1	1	Shift supervisor died on day 34 after receiving whole-body dose of more than 7 Gy and 50 Gy to the legs; the operator survived moderate ARS and subsequently had both legs and one arm amputated	[V1, V4]
1978	USSR: Siberia	Plutonium processing facility	Unfavourable geometry of plutonium ingots during packaging; deficient box design		1	Operator received approximately 2.5 Gy whole-body dose and 70 Gy to the hands, he survived moderate ARS, but with amputation of both hands; seven others received doses of between 0.05 and 0.6 Gy	[B11, L1, V1]
1997	Russian Federation: Sarov	Nuclear weapons research facility	Criticality; experimenter violated safety requirements	1		45 Gy neutrons and 3.5 Gy gamma whole-body dose; death in 66.5 hours	[I5, L1]
Other accidents with only on-site consequences							
1951	USSR: Chelyabinsk-40	Nuclear research and reprocessing facility	Unknown	1	4	External gamma and beta exposure causing local and/or ARS injury	[S2]
1952	USSR: Chelyabinsk-40	Nuclear research and reprocessing facility	Unknown	2		Internal contamination with tritiated water	[S2]
1954	USSR: Arzamas, Sarov	Nuclear weapons facility	Unknown	1		^{210}Po internal exposure; ARS	[S2]
1976	United States: Hanford, Washington	Research processing facility	Chemical explosion in glovebox		1	Worker injured by glass, nitric acid and intake of ^{241}Am; 8.6 Gy dose to bone marrow; death 11 years later of cardiovascular disease	[H2]
1986	United States: Gore, Oklahoma[b]	Uranium processing facility	Accidental rupture of a 14 ton (1 270 kg) cylinder of UF_6	1 (trauma)	7	Internal contamination of workers as well as low-level internal contamination of seven members of the public	[N3]

Accidents with releases to the environment and potential public health consequences

Year	*Location*	*Operation/ installation*	*Main cause and nature of accident*	*Ref.*
1957	USSR: Mayak Complex, Kyshtym[a]	Radiochemical plant	Overheating and resulting explosion of a storage tank led to release of 740 PBq of radioactive products	[U6]
1957	United Kingdom: Windscale, Cumbria	Graphite reactor	Overheating and fire resulted in release of 740 TBq ^{131}I; other radionuclides also released	[C2, G4, U6, U9]
1986	United States: Gore, Oklahoma[b]	Uranium processing facility	Accidental rupture of a 14-ton (1 270 kg) UF_6 cylinder resulting in a trauma death as well as low-level contamination of seven members of the public and of the environment	[N3]
1993	Russian Federation: Tomsk, Siberia	Reprocessing facility	Largest occupational group exposed were 1 920 persons involved in clean-up; build-up of gases in vessel followed by explosive rupture and explosion of flammable cloud	[I19]

[a] This accident is listed twice in this table under two categories: Criticality accidents and Accidents with releases to the environment and potentially significant population exposures.

[b] This accident is listed twice in this table under two categories: Other accidents with only on-site consequences, and Accidents with releases to the environment and potentially significant population exposures.

Table 2B. Accidents at nuclear facilities: Not related to nuclear weapons programmes

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
			Criticality accidents				
1958	Yugoslavia: Vinca	Zero power reactor	Equipment failure (controls) caused nuclear excursion	1	5	Five individuals recovered from severe cases of radiation sickness; radiation doses ranged from 2.07 to 4.36 Gy	[L1, M4]
1965	Belgium: Mol	Experimental reactor	Failure to follow safety procedures, resulting in criticality excursion		1	Technician received non-uniform exposure of 3–40 Gy, with highest exposure to left foot; medical therapy was successful but left foot required amputation	[J3, L1, P2]
1971	USSR: Moscow	Power reactor research facility	Violation of operating procedures; control rods not actuated when water was added to tank containing fuel rods		3	Three persons received whole-body doses of about 3 Gy; two of them also received doses of about 20 Gy to the legs	[L1, V4]
1971	USSR: Moscow	Power reactor research facility	Faulty construction of the fuel assembly in the reactor; fuel rods fell into highly supercritical geometry	2	2	Technician received approximately 60 Gy and died in five days; supervisor received 20 Gy and died within 15 days; two others received 7–8 Gy and survived with long-term health effects	[L1, S2]
1983	Argentina: Buenos Aires	Critical facility	Failure to follow procedures in removing water from tank containing fissile material	1		Acute whole-body dose (17 Gy neutron and 20 Gy gamma); death two days after the accident from ARS (neurological) with radiopneumonitis in right lung	[L1, N1]
1999	Japan: Tokai-mura[a]	Fuel conversion plant	Workers unknowingly added higher enriched uranium into a tank bypassing criticality controls	2	1	Two fatalities (uneven exposures of 10–20 Gy Eq and 6–10 Gy Eq) and one person with whole-body dose of 1.2 to 5.5 Gy Eq	[A2, I6]
			Other accidents with only on-site consequences				
1977	Argentina: Atucha	Nuclear power plant	Worker not wearing lead gloves		1	Wound contaminated with 3 800 Bq; mean beta dose of 364 Gy in period 1977–1985 and annual gamma dose of 0.04 Gy in 1 cm^3 of soft tissue	[U3]
1985	Czechoslovakia: Petrvald		Carelessness and inadequate equipment for work with transuranics		1	Intake through wound of 600 Bq of ^{241}Am; surgical excision of wound and administration of DTPA	[U3]
1989	Hungary: Paks	Nuclear power plant	Careless handling of detectors from reactor vessel		1	Whole-body dose of 29 mGy; 1 Gy to fingers of left hand; slight increase in chromosomal aberrations	[U3]

Accidents with releases to the environment and potentially significant population exposures

Year	*Location*	*Operation/ installation*	*Early*		*Main cause and nature of accident*	*Ref.*
			Deaths	*Effects*		
1979	United States: Three Mile Island, Pennsylvania	Nuclear power plant			Low water levels in reactor led to severe damage to fuel elements; 550 GBq ^{131}I released to the atmosphere. Limited evacuation of local population	[U6, U9]

1986	USSR: Chernobyl	Nuclear power plant	28 radiation induced, 2 trauma	106	Breach of operating rules and violation of safety procedures, combined with a flawed design resulted in a steam explosion, fire and destruction of the reactor. Whole-body doses of 1–16 Gy and localized doses to skin among plant staff and emergency personnel; 30 deaths; 106 others with ARS; medical treatment, including bone marrow transplants (101 others initially examined for ARS). Significant release of radionuclides into the environment (including 1 760 PBq of ^{131}I and 86 PBq of ^{137}Cs). Major evacuation and relocation of populations in the area. See annex D, "Health effects due to radiation from the Chernobyl accident" for more details	[U7]
1999	Japan: Tokai-mura[a]	Fuel conversion plant	2	1	Overfilling of tank led to criticality, neutron and gamma irradiation of people in the vicinity of the facility, and a very small release of fission products into the air. Limited evacuation of local population	[A2, I6]

[a] This accident is listed twice in this table under two categories: Criticality accidents and Accidents with releases to the environment and potentially significant population exposures.

Table 3. Accidents at industrial facilities

Year	*Location*	*Industrial source/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
Sealed radioactive sources							
1968	Argentina	^{60}Co source	Worker carried a 0.5 TBq source in pocket for 18 hours		1	Whole-body dose of 0.5 Gy; maximum dose to thigh of 17 000 Gy; both legs amputated	[B6, B16]
1968	India	^{192}Ir source	Worker picked up a source that had fallen off a camera and kept it in his pocket for two hours		1	Skin dose of 130 Gy; ulcer took one year to heal	[A3]
1968	Germany	^{192}Ir source	Worker carried source in jacket pocket		1	Whole-body dose of 1 Gy; maximum dose to pelvis and thigh of 40–60 Gy	[S4]
1969	United Kingdom: Scotland	^{192}Ir source	Radiographer travelled with unshielded source		1	Whole-body dose of 0.6 Gy; dose to chest of 20–200 Gy; skin graft to chest required	[H4]
1972	China: Sichuan	^{60}Co irradiation facility	Accidental entry into the irradiation room		Unknown	0.5–1.47 Gy whole-body exposure to workers	[P1]
1973	USSR, Moscow area	4.2 PBq ^{60}Co industrial source	Operator entered room while source was in “on” mode		1	Operator survived whole-body dose of about 4 Gy	[B11]
1974	United States: New Jersey	4.4 PBq ^{60}Co industrial source	Failure to use survey meter prior to entering irradiation room		1	Non-uniform exposure estimated to be 4.1 Gy	[B2]
1975	Italy: Brescia	^{60}Co industrial irradiation facility	Lack of safety systems on conveyer entry point	1		Non-uniform exposure with mean whole-body dose of 12 Gy; haematopoietic syndrome; death 12 days after exposure	[J3, U3]
1975	USSR: Kazan	^{60}Co irradiation facility	Deterioration of safety system and improper actions to regain control		2	Whole-body doses of 3 and 5 Gy; dose to hands of 30 Gy and more than 50 Gy	[N10, U3]
1975	Iraq	^{192}Ir radiography source	Unknown		1	Whole-body dose of 0.3 Gy plus localized exposure of hand	[U3]
1976	United States: Pittsburgh, Pennsylvania	^{192}Ir radiography source	Unknown		1	Dose of 10 Gy to hand	[U3]
1976	USSR: Moscow region	^{60}Co irradiation facility	Technical failure of the equipment and improper entry		1	Whole-body dose of 4 Gy; moderate ARS	[U3]
1977	Czechoslovakia: Pardubice	^{192}Ir industrial irradiation source	Technical failure of the equipment and improper actions to bring source back under control		1	Whole-body dose of about 5 mGy; data insufficient for estimating local doses; bullous dermatitis of the thumb of the right hand; plastic surgery two years later	[U3]
1977	United States: Rockaway, New Jersey	^{60}Co industrial irradiation source of 18.5 PBq	Construction in the facility, lack of safety precautions and interlock failure		1	Whole-body dose of 2 Gy	[B2]

1977	United Kingdom	^{192}Ir radiography source	Operator working in a confined area held source for 90 seconds while conducting radiography on a weld		1	Equivalent whole-body dose of <0.1 Gy estimated on the basis of cytogenetic dosimetry; radiation burns on three fingers	[U3]
1977	Hungary: Györ	Industrial defectoscope	Failure of equipment to withdraw source into its container		1	Whole-body dose of 1.2 Gy; slight nausea, changes in blood and increased frequency of chromosomal aberrations	[U3]
1977	United Kingdom	Filling gaseous tritium light source	Broken inlet manifold led to the release and escape of 11–15 TBq of tritium		2	Whole-body doses of 0.62 and 0.64 Gy	[U3]
1977	South Africa: Sasolburg, Transvaal	^{192}Ir source	Faulty operation of pneumatically operated container and monitor; carelessness of operator		1	Whole-body dose of 1.16 Gy; amputation of two fingers, rib removal and skin grafts	[U3]
1977	Peru: Ona del Oleoducto	^{192}Ir source	Untrained personnel and lack of supervision; equipment neither registered nor authorized		3	Maximum doses of 164 Gy to hands; 0.9 Gy to lens of the eye; 2 Gy to the whole body; amputation of fingers of two people and effects on the left hand of another person	[U3]
1978	Argentina: Buenos Aires	^{192}Ir industrial source	Manual handling of source		1	Dose of 12–16 Gy, causing radiation burns on two fingers of left hand	[U3]
1978	United States: Monroe, Louisiana	^{192}Ir radiography source	Radiography of pipe welds on barge (off-shore drilling)		1	Localized exposure of hand; amputation of finger	[S1]
1979	Czechoslovakia: Sokolov	^{192}Ir industrial radiography	Technical failure of the equipment and inadequate monitoring during and after work		1	Whole-body dose of about 5 mGy; data insufficient for estimating local doses; bullous dermatitis of the third finger of the left hand and adjacent areas; plastic surgery two years later	[U3]
1979	France: Montpelier	^{192}Ir radiography source	Unknown		1	Whole-body and localized exposure; amputation of left arm	[U3]
1980	USSR: Leningrad	^{60}Co irradiation facility	Failure of safety device and improper entry	1		Whole-body dose of more than 12 Gy	[S2]
1980	China: Shanghai	^{60}Co irradiation facility	Entry into the irradiation chamber during power failure and with defective interlocks		1	Whole-body dose of 5.22 Gy and localized exposure	[U3, Y1]
1980	USSR	^{60}Co irradiation facility	Unknown		1	Dose of 50 Gy to lens of eye	[U3]
1981	Argentina: Buenos Aires	^{192}Ir industrial source	Source became detached and lodged in the delivery tube		2	Doses were not specified; radiation burns on fingertips	[U3]
1982	Norway: Kjeller	^{60}Co irradiation facility	Failure of safety device and failure to follow procedures	1		Mean whole-body dose estimated to be slightly higher than 20 Gy; death 13 days after exposure	[R1, S3]
1983	United Kingdom	Gamma radiography source	Inadvertent exposure to radiographer		1	Whole-body dose of 0.56 Gy	[U3]
1983	German Democratic Republic: Schwarze Pumpe	^{192}Ir industrial source	Technical defect and inappropriate handling		1	Dose to the right hand of about 5 Gy; acute and chronic radiodermatitis (1st degree)	[U3]

Year	*Location*	*Industrial source/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
1983	India: Muland, Bombay	^{192}Ir radiography projector	Operation by untrained personnel		1	Dose to the skin of 20 Gy and whole-body dose of 0.6 Gy; severe damage to fingers; four were amputated	[U3]
1984	Hungary: Tiszafured	^{192}Ir industrial defectoscope	Failure of equipment and careless handling of source		1	Whole-body dose of 46 mGy; 20–30 Gy estimated to fingers of left hand; irreversible necrosis at tip of one finger, surgically removed; slight increase in chromosomal aberrations	[U3]
1984	Argentina: Mendoza	^{192}Ir radiography source	Operator pushed source into camera using a finger		1	Dose of 18 Gy to finger (radiation burn on finger) and whole-body dose of 0.11 Gy	[U3]
1985	India: Yamunanager	^{192}Ir radiography projector	Violation of safe working practices associated with power failure in the workplace		2	Doses of 8–20 Gy to hands of both operators; damage to fingers; two fingers amputated from each individual	[U3]
1985	India: Visakhapatnam	^{60}Co radiography projector	Violation of safe working practices and lack of maintenance		2	Skin dose of 10–20 Gy to operator and 0.18 Gy to an assistant; damage to fingers; one finger amputated	[U3]
1986	China: Harran	^{60}Co irradiation facility	Power loss occurred and source was manually raised; workers entered room with source unshielded		2	Doses to workers of 3.5 and 2.6 Gy	[U3]
1986	China: Beijing	^{60}Co irradiation facility	Workers entered irradiation room when source was unshielded; failed drive system; door open		2	Doses to workers of 0.7 and 0.8 Gy	[U3]
1986	China: Kaifun City	^{60}Co source	Accidental exposure for about 1.5–2 minutes		2	Whole-body doses of 2.6–3.5 Gy; haemopoietic type of ARS	[W2, Y1]
1987	China: Zhengzhou City	^{60}Co irradiation facility	Accidental entry into irradiation room, 10–15 seconds		1	Estimated whole-body dose of 1.35–1.45 Gy; anorexia and nausea four hours later; severe damage to haemopoietic system with relatively slow restoration of white blood cells	[Y1]
1988	China: Liaoning	Radiography source	Workers handled source with hands		6	Local exposure of 0.1–12.6 Gy	[Z2]
1988	Czechoslovakia: Prague	Manufacturing of foils containing ^{241}Am for use in fire alarms	New rolling methods untested; poor radiation protection practice		1	Inhalation of 50 kBq of dispersed ^{241}Am; hospitalization and administration of DTPA; no clinical manifestations	[U3]
1988	China: Zhao Xian	^{60}Co irradiation facility	Accidental entry into irradiation room, about 40 seconds		1	Estimated whole-body dose of 5.2 Gy; ARS (bone marrow syndrome); after three years of follow-up, condition good	[U3]
1989	India: Hazira Gujarat	^{192}Ir radiography projector	Failure of safety management and improper maintenance		1	Dose of 10 Gy to fingers and whole-body dose of 0.65 Gy; radiation burns on fingers of both hands; fingers amputated	[U3]
1989	South Africa: Witbank, Transvaal	^{192}Ir industrial radiography source	Detached source; negligence of radiographer (source improperly attached) and failure of portable monitor to register detached source		3	Whole-body doses to three workers were 0.78, 0.1 and 0.09 Gy; computed effective dose to the most exposed worker was 2.25 Gy; this worker had amputation of right leg at the hip six months after exposure and amputation of three fingers one year after exposure	[U3]
1989	China	^{192}Ir radiography source	Unknown		1	Localized dose of 18.37 Gy	[U3]
1989	Bangladesh	^{192}Ir source	Unknown		1	Whole-body dose of 2.3 Gy	[U3]

1989	China: Beijing	^{60}Co source	Accidental exposure to source for about four minutes		2	Whole-body doses of 0.87 and 0.61 Gy; two workers suffered mild haemopoietic radiation sickness; recovered	[U3]
1989	El Salvador: San Salvador	^{60}Co irradiation facility	Deterioration of safety system and lack of understanding of radiation hazards	1	2	Three workers developed ARS after whole-body doses of 3–8 Gy; all three had local radiation injuries; one patient had both legs amputated; the most seriously irradiated patient had one leg amputated and died 197 days after exposure	[I1]
1990	South Africa: Sasolburg, Transvaal	^{60}Co industrial radiography source	Source left behind after radiography work; loss undetected because of inadequate monitoring; source handled by six people		6	One individual had right hand amputated above the wrist; three others had local radiation injuries; whole-body doses were less than 0.55 Gy	[U3]
1990	Israel: Soreq	^{60}Co irradiation facility	Improper entry and maintenance	1		10–20 Gy whole-body dose; death 36 days after exposure; bone marrow transplant and growth factors administered	[I2]
1990	China: Shanghai	^{60}Co irradiation facility	Entry into the irradiation chamber during power failure and with defective interlocks	2	5	Workers received doses of 2–12 Gy; the two who received 11 and 12 Gy died	[L2, P1]
1991	Belarus: Nesvizh	^{60}Co irradiation facility	Improper entry with source exposed	1		11–18 Gy whole-body dose; death in 113 days; haematopoietic growth factor administered	[I3]
1991	United Kingdom	Industrial radiography	Chronic incidents over 14 years	1	1	30 Gy to fingers, parts of two fingers amputated; estimated whole-body dose (chronic) of <10 Gy; death from acute myeloid leukaemia	[U3]
1992	China	Irradiation facility	Power loss and safety interlocks out of order		4	One worker with ARS	[P1]
1992	Switzerland	^{192}Ir radiography source	Jammed 700 GBq source; released by hand		1	Erythema of fingers: 3.5–10 Gy	[U3]
1993	United Kingdom	Gamma radiography unit	Improper procedures		1	Overexposure caused erythema and subsequent necrotic ulceration; hand dose of 30 Gy	[U3]
1998	China: Harbin	Unknown	Safety equipment failure		1	One worker with ARS	[P1]
2000	Brazil: Rio de Janeiro	^{60}Co industrial gamma radiography	Exposure during a routine service		1	Serious injuries to left hand	[D1]
2006	Belgium: Fleurus	^{60}Co irradiation facility	Malfunction of a command/control hydraulic system and failure of safety system		1	Worker entered an irradiation area and stayed approximately 20 seconds; he developed nausea and vomiting but did not seek medical attention until he developed massive hair loss; estimated whole-body dose of 4.4–4.8 Gy	[S9]
			Accelerators and X-ray devices				
1960	United States: Lockport, New York	Klystron tube X-irradiation	Shielding not in place during maintenance/repair		7	Non-uniform exposures; two individuals seriously injured, five others with less severe injuries	[H5]
1965	United States: Rockford, Illinois	Accelerator (10 MeV electrons)	Unknown		1	Man received 290 Gy to right ankle, 420 Gy to right hand and 0.05 Gy whole-body dose; amputations necessary	[G2, L3]
1967	United States: Pittsburgh, Pennsylvania	Linear accelerator	Failure of safety interlock system		3	One individual with severe radiation syndrome and multiple amputations; two other individuals had exposures of 3 and 1 Gy	[G2, G3]

Year	*Location*	*Industrial source/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
1975	Germany	X-ray fluorescence unit	Carelessness and technical faults during repair		1	Estimated dose of 30 Gy to the fingers; reddening of two fingers ten days after exposure	[U3]
1975	Germany	X-ray equipment	Carelessness and technical defects		1	Welding seam test; estimated dose of 2 Gy to the stomach region	[U3]
1976	Germany	X-ray equipment	Inexpert handling of equipment		1	Estimated whole-body dose of 1 Gy; reddening of skin after 24 hours and radiation after-effects	[U3]
1977	Argentina: La Plata	X-ray crystallography	Shutter removed from crystallography set		3	Dose of 10 Gy to hands of one operator (radiation burns); doses to two workers not specified	[U3]
1978	France: Nancy	X-ray equipment	Unknown		1	Localized exposure of hand; amputation of finger	[U3]
1979	German Democratic Republic: Freiberg	X-ray fluorescence unit	Violation of safe working practice		1	Dose of 10–30 Gy to right hand and whole-body dose of 0.2–0.5 Gy; acute and chronic radiodermatitis (2nd and 3rd degree)	[U3]
1980	German Democratic Republic: Bohlen	Analytical X-ray unit	Violation of safe working practice		1	Dose of 15–30 Gy to left hand; acute and chronic radiodermatitis (2nd and 3rd degree)	[U3]
1980	Germany	Radiography	Defective equipment		2	Estimated dose of 23 Gy to the hand and an effective dose of 0.2 Gy	[U3]
1981	Germany	X-ray fluorescence device	Violation of safe working practice		1	Partial-body exposure with 20–30 Gy dose to the right thumb; extensive tissue damage developing over several months	[U3]
1983	Germany	X-ray equipment	Defective equipment		1	Partial-body exposure of approximately 6–12 Gy to regions of the body; localized physical changes	[U3]
1985	China: Shanghai	Accelerator	Entry into irradiation area while main motor was running		1	Worker incurred local radiation injury with dose of 25–210 Gy	[Z1]
1991	France: Forbach	Irradiation accelerator	Exposure to dark current		3	Severe skin lesions to one worker; less serious injury to two others	[C1, U3, Z3]
1991	United States: Baltimore, Maryland	Accelerator	Exposure to dark current during maintenance		1	55 Gy to fingers; most required amputation	[D3]
1992	Italy	X-ray spectrometer	Improper procedure during maintenance		1	Acute radiodermatitis of fingers of both hands	[S6]
1993	United Kingdom	~160 kV radiography unit	Improper procedures		1	Erythema of hands leading to necrotic ulceration	[I26]
1994	Mexico: Lazarus Cardenas	X-ray spectrometer	Failure to de-energize device prior to repair		1	Amputation of portion of finger necessitated	[B8]
1995	Brazil	X-ray diffraction unit	Poor maintenance of device allowing open back window		3	Acute radiodermatitis of hands caused by low-energy X-rays	[V3]
1999	United States	Electron beam device	Residual beam exposed operator's hand during manufacture testing		1	Skin dose to hand estimated to be 50 Gy	[M1]

Table 4. Accidents involving orphan sources

Year	Location	Operation/ installation	Main cause of accident	Early		Nature of exposure/health consequences	Ref.
				Deaths	Effects		
1960	USSR: Moscow	^{137}Cs source	Person deliberately placed source in belt of trousers and around body for suicide	1		Whole-body dose of 14.8 Gy; maximum dose to several points of skin of 1 650 Gy; death on day 18	[D2]
1962	Mexico: Mexico City	^{60}Co source (0.2 TBq)	Unsecured source removed from site	4	1	Family died as a result of exposure. The 10-year-old boy had a protracted (four months) exposure of 47 Gy; the 3-year-old child received a dose of 28.7 Gy, the 27-year-old pregnant mother 35 Gy and the 57-year-old grandmother 30 Gy; the father's exposure over approximately seven months was 120 Gy and he survived	[M6]
1963	China: Hefei City, Sanli'an	^{60}Co source (0.43 TBq)	Abandoned source taken to farmer's home	2	4	Farmer's dose was 80 Gy; source was in his pocket for approximately 52 hours; his 7-year-old brother had the source in his pocket for 18 hours, receiving a dose of 40 Gy; both failed to respond to medical treatment; the other four people exposed had doses of 8, 6, 4 and 2 Gy and survived	[P1, W2]
1971	Japan: Chiba	^{192}Ir source	Lost source picked up by worker		6	Three patients had minimal blood changes and were hospitalized for two months; three others had ARS and local radiation injuries	[H3]
1973	Mexico: Tula, Hidalgo	^{137}Cs source	Source fell out of its container in truck and was picked up and put in pocket		1	One person suffered injury to hand, thigh and buttock, leading to amputation of left leg and one finger; estimated local dose to thigh of 1 386 Gy	[N5]
1975	USSR: Sverdlovsk	^{60}Co medical source (17 TBq)	Source fell unnoticed during transport for burial	1	2	Driver died from very severe ARS (7 Gy) on day 33; two others (about 3 Gy) survived moderate ARS	[B11, S2]
1977	South Africa	^{192}Ir source	Source picked up from factory floor and taken home		1	Burns of hands and chest; skin graft on chest required; whole-body dose of 1.1 Gy; maximum skin dose of 50–100 Gy; three individuals with low-level symptoms	[L5]
1978	China: Herran	^{137}Cs source	Unused source was taken to worker's home		29	Doses of 0.01–0.53 Gy to bone marrow of individuals	[U3]
1978	Algeria	^{192}Ir radiography source	Source fell out of truck and was picked up	1	6	One fatality (member of public); source found by boys aged 3 and 7 years; one foetus also aborted	[J2]
1979	United States: Los Angeles, California	Lost ^{192}Ir radiography source	Failure of radiographer to check source storage		5	Individual who carried source in hip pocket developed severe lesion to the right buttock from a dose at the skin surface of 800–4 000 Gy; whole-body dose was 0.75–1 Gy; four individuals had minor skin injuries; 11 persons were involved	[R2]
1980	USSR: Yuzhno-Sakhalinsk	^{192}Ir radiography source	Taken from improper storage by 2 children for play; one put it in jacket pocket	1	1	First boy received more than 15 Gy to the hands, and two spots on abdomen received more than 20 Gy; he died after 3 months from poor liver function; second boy received 8 Gy to the hand, and developed not severe local radiation injury	[N11]
1982	China: Hanzhong	^{60}Co source	Source was stolen	Not specified		Doses ranged from 0.42 to 3 Gy	[W1]

Year	Location	Operation/ installation	Main cause of accident	Early		Nature of exposure/health consequences	Ref.
				Deaths	Effects		
1982	USSR: Azerbaijan	^{137}Cs military source	Two abandoned sources circulated among soldiers	5	17	Five of the most exposed had very severe radiation injury to one or both thighs and lower abdomen (doses from 500 to 900 Gy); one died on day 26, three others in spite of treatment within 3-4 months; the fifth died after a year. Seventeen people developed local radiation injuries	[N11]
1982	USSR: Turkmenistan	^{60}Co medical source	Abandoned device containing the source was dismantled by hospital patients; a man found the source and took it home; on the next day, 11 other people touched it		13	A patient who dismantled the device and the man discovering the source received whole-body doses of 2 Gy and 6 Gy, and doses to the hands of 30 Gy and 700 Gy respectively. Both hands of the latter person were amputated. Eleven other people developed local radiation injuries to the hands	[N11]
1982	USSR: Ukraine	^{137}Cs source		2	2	ARS and local injuries	[S2]
1983	Mexico: Ciudad Juarez	^{60}Co teletherapy source	Device disassembled and sold to a scrapyard; lack of control		10	Source contained ^{60}Co in tiny pellets of 2.77 GBq each; total activity was 16.6 TBq	[B3]
1984	Morocco	^{192}Ir radiography source (603 GBq)	Source was taken home, kept in family bedroom and discovered after 80 days	8	3	Protracted exposures resulted in deaths of four adults and four children (ages 4, 5, 7 and 8)	[M2, M5]
1985	China: Mudanjiang	^{137}Cs source	370 GBq source was found and taken home	1	2	Accumulated local doses were 8–10 Gy; one person died after 22 months	[Y1]
1987	Brazil: Goiânia	^{137}Cs radiotherapy device	Abandoned device containing caesium source, disassembled	4	129	21 persons had doses in excess of 1.0 Gy (up to 7 Gy); 50 persons were admitted to hospital or primary care units; 79 persons received dispensary care. ARS, skin injuries and internal contamination were problems. Local environmental contamination occurred	[I11, I12]
1988–1991	USSR: Ukraine	^{137}Cs source (2.6 TBq)	Source found embedded in bedroom wall	2	1	Chronic exposure. Young boy had radiation injury of foot skin with transformation into sarcoma, and died; his 9-year-old brother had radiation injury of the foot and bone marrow depression with transformation into leukaemia, and died; a third person incurred mild chronic skin radiation injury and survived	[M2, S2]
1992	China: Xinzhou	Former ^{60}Co irradiation facility	Farmer working on the site demolishing the facility picked up source; it went with him to the hospital	3	11	14 persons were exposed to doses of $>$0.25 Gy; three received doses of $>$8 Gy and died	[P1]
1993–1998	Turkey: Istanbul	Two ^{60}Co medical therapy sources	Poor source security		18	Five persons with ARS (up to 3 Gy), one with lesions on one hand	[I7]
1994	Estonia: Tammiku	1.6 TBq ^{137}Cs source from part of an irradiator	Theft of source and poor source security	1	5	Whole-body exposure of up to 4 Gy, variety of localized exposures of up to 1 800 Gy	[I13]
1995	Russian Federation	^{137}Cs source (48 GBq)	Unshielded source in truck for approximately five months	1		Source located in door pocket of truck; protracted dose of 7.9 Gy (whole-body); local dose of approximately 65 Gy; death at 22 months after discovery	[B7, S7]
1995	France	^{192}Ir gamma radiography source	Direct handling of 1 TBq source		1	Erythema of hands; estimated local dose of $>$30 Gy	[U3]

1995	France	^{137}Cs density gauge source	Unknown		1	Erythema of hands	[U3]
1996	Islamic Republic of Iran: Gilan	^{192}Ir radiography source	Poor procedures; failure of lock on radiography container		1	Labourer found source and put it in breast pocket; 2–4 Gy whole-body dose, 40 Gy to chest	[I21]
1996–1997	Georgia: Lilo	^{137}Cs training sources, ^{60}Co source and sighting devices	Abandoned sources at a military training centre		11	12 sources (^{137}Cs) were found; later 200 discarded sighting devices (^{226}Ra) were found; local injuries and some individuals with systemic effects	[I20]
1999	China: Henan	^{60}Co “ex-service” therapy source	Source found in residence of farmer		7	Seven persons received high doses (1.0–6.0 Gy)	[X1]
1999	Peru: Yanango	1.37 TBq ^{192}Ir source	Welder found industrial radiation source		2	Source found and placed in trouser pocket; severe exposure to right thigh, perineum and hip led to amputation, colostomy; welder’s wife received local injury while sitting on trousers containing source	[I8]
2000	Thailand: Samut Prakarn	^{60}Co radiotherapy sources	Poor source security leading to three old therapy units ending up in scrapyard	3	7	Ten persons were hospitalized; three died	[I9]
2000	Egypt: Meet Halfa	^{192}Ir radiography source	Source lost by worker testing pipe welds was found by farmer	2	5	Abandoned source was taken home by farmer; he died 40 days later; his son died after 30 days of exposure. Dose estimates were: father 7.5–8 Gy; son 5–6 Gy; and five others 3.5–4 Gy	[E1, I10]
2000	Russian Federation: Samara Oblast	^{192}Ir radiography source	Insufficient safety training of radiographers		3	Three radiographers received whole-body doses of 1–3 Gy; one of them had hand burns due to localized doses of 30–70 Gy	[S8]
2001	Georgia: Lia	^{90}Sr radioisotope thermoelectric generator	Two abandoned sources		3	Woodsmen found thermally hot objects and used them as heaters. They suffered systemic effects; two developed severe local injuries	[I23, J1]

Table 5. Accidents at academic and research facilities

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
			Sealed radioactive sources				
1960	United States	^{60}Co source	Source detached during irradiation of samples		1	Graduate student exposed to 7 TBq ^{60}Co whole-body dose of 2.5–3 Gy; maximum skin dose of 30 Gy	[R3]
1962	USSR: Moscow	^{60}Co source (1.9 PBq)	Violation of safe working practices, improper entry to irradiation room		1	Whole-body dose of 2.5-3.0 Gy and 12 Gy to the hand	[G5]
1971	United States: Tennessee	^{60}Co irradiation	Equipment malfunction and operational error		1	Technician was in front of unshielded source for approximately 40 seconds; whole-body dose of <2 Gy, dose to hand of 12 Gy	[V2]
1978	Sweden: Nykoping	Research reactor	Instructions for work not followed		1	Dose of 30 Gy to skin of hand; radiation burn to skin	[U3]
1979	Germany: Rossendorf	Research reactor	Neutron activation of a sample grossly underestimated		1	Dose of 20–30 Gy to right hand; acute and chronic radiodermatitis (2nd and 3rd degree) and oedema	[U3]
1980	Germany: Rossendorf	Radiochemical laboratory	Defect in protective glove led to contamination with ^{32}P		1	Dose of 100 Gy to skin of left hand; no clinical symptoms	[U3]
1983	German Democratic Republic: Leipzig	Radiochemical laboratory	Explosion of vial containing ^{241}Am solution		1	Committed effective dose of 0.076 Gy	[U3]
			Accelerators and X-ray devices				
1972	United Kingdom	X-ray crystallography	Shutter was removed prior to and during servicing		1	Dose to two fingers of 15–20 Gy, resulting in burns	[L4]
1974	United States: Davis, California	X-ray diffraction unit	Safety interlock bypassed; failure to note warning light		2	Localized exposure of hands; one person had serious injuries	[B4]
1975	Germany	X-ray fluorescence unit	Violation of safe working practice		1	Dose of 1.2–2 Gy to finger; acute radiodermatitis	[U3]
1977	USSR: Kiev	Proton accelerator (40 MeV)	Violation in beam testing examinations		1	Localized doses to hands of 12–30 Gy	[A5, B12]
1977	United States: Berkeley, California	X-ray	Safety interlock failure		1	Loss of two fingers on one hand and one finger on the other hand	[T2, U3]
1978	USSR: Protvino	Proton accelerator (70 GeV)	Improper entry to adjust sample in beam		1	Beam pierced man’s head; middle ear destroyed, facial nerve injured, abortive epilepsy developed	[B13]
1978	United States	Accelerator	Unknown		1	Localized exposure to abdomen, hands, thighs	[U3]

1978	USSR: Leningrad	Electron accelerator (12.7 MeV)	Improper entry		1	Localized doses to back and chest of more than 20 Gy and 8 Gy respectively. Local radiation injury of skin and spinal cord	[A5]
1981	Germany: Berlin	Analytical X-ray unit	Violation of safe working practice		1	Dose of 5 Gy to the left hand; acute radiodermatitis (1st degree)	[U3]
1982	Germany: Berlin	Analytical X-ray unit	Violation of safe working practice		1	Dose of 6–18 Gy to the right forefinger; acute radiodermatitis (2nd degree)	[U3]
1984	Peru: Lima	X-ray diffraction equipment	Fault of supervision, deliberate exposure from lack of knowledge of risk; equipment not registered with authorities		6	Localized doses of 5–40 Gy to fingers; skin burns and blistering leaving residual scar tissue	[U3]
1988	German Democratic Republic: Trustetal	Analytical X-ray unit	Technical defect		2	Maximum dose of 4 Gy to the hand of one person; acute radiodermatitis (1st degree) in one person	[U3]
1988	German Democratic Republic: Jena	Analytical X-ray unit	Violation of safe working practice		1	Dose of 3 Gy to left hand; acute radiodermatitis (1st degree)	[U3]
1992	Vietnam: Hanoi	Research accelerator	Improper entry to adjust sample in beam		1	Individual unknowingly exposed hands; dose to left hand of 10–25 Gy, to right hand 20–50 Gy; fingers and one hand amputated; whole-body dose estimated to be 1–2 Gy	[I4]
1994	United States: Davis, California	X-ray diffraction equipment	Bypass of safety interlock to effect repair		1	Exposure of both hands with formation of bullae	[B4]

Table 6. Accidents associated with the medical use of radiation

Year	*Location*	*Operation/ installation*	*Main cause of accident*	*Early*		*Nature of exposure/health consequences*	*Ref.*
				Deaths	*Effects*		
1966	USSR: Kaluga	X-ray equipment (50 kV)	Poor maintenance	1		Localized dose to face and head of more than 20 Gy. Local radiation injury developed into atrophy and scars of face, loss of left eye; bone necrosis; death in year 7 of late radiation encephalitis	[B14, G5]
1967	India	^{60}Co teletherapy	Source gain during transfer		1	Skin dose to hand of 80 Gy	[B5]
1968	United States: Wisconsin	Nuclear medicine, ^{198}Au	Higher than prescribed dose administered	1		Acute whole-body radiation exposure from internal source; patient died 69 days after the misadministration	[B9, M3]
1972	China: Wukan	^{60}Co radiotherapy	Source fell from holder and was unnoticed for 16 days; design of device did not meet international standards		28	20 patients and eight workers received doses in the range 0.5–2.45 Gy	[W1]
1974–1976	United States: Riverside, Ohio	^{60}Co teletherapy	Use of incorrect decay curve, lack of periodic calibration of output		426	Overexposure of 426 patients; dose rates had been underestimated by 10–45%	[M1]
1975	Germany	X-ray equipment	Probable violation of safe working practice in maintenance		1	Dose in excess of 1 Gy to head and upper torso	[U3]
1975	Argentina: Tucumán	^{60}Co teletherapy	Failure of source mechanical mechanism		2	Technician and physician both received high doses to fingers; radiation burns on fingers	[U3]
1977	Germany	^{192}Ir radiography	Defective equipment		1	Estimated dose to hand of about 5 Gy and effective dose of 0.01 mGy; temporary reddening of fingers	[U3]
1977	United Kingdom	Laboratory	Accidental contamination of laboratory workers		2	Thyroid dose of 1.7 Gy to one person from a ^{125}I intake of about 1 MBq; a low dose to another person	[U3]
1979	Argentina: Paraná	Diagnostic radiology	Faulty wiring led to emission of X-rays when the top of the fluoroscope was open		1	Nurse received a whole-body dose of 0.94 Gy; slight bone marrow depression	[U3]
1981	France: Saintes	^{60}Co radiotherapy source	Direct hand contact with 137 TBq ^{60}Co source during source loading		3	Two victims had both hands amputated owing to severe injury caused by exposures estimated at $>$25 Gy; a third victim had a large portion of his right hand amputated	[N7]
1982	Argentina: La Plata	X-ray therapy facility	Operator looked through window while changing tubes without recognizing system was energized		1	Whole-body dose of 0.12 Gy and dose of 5.8 Gy to lens of eye; cataracts in both eyes	[N2]
1985	United States: Marietta, Georgia	Therac-25 accelerator	Problem of integration of hardware and software of system		1	Loss of function of one arm and shoulder	[N2]
1985	Canada: Hamilton, Ontario	Therac-25 accelerator	Problem of integration of hardware and software of system		1	Severe burn on hip; patient died of cancer four months after the accident	[N2]
1985	United Kingdom	Laboratory	Technician cut finger; poor technique		1	Technician cut his finger while wearing a glove contaminated with ^{125}I; sucked cut finger, which resulted in an intake of about 740 MBq and a thyroid dose of 400 Gy	[U3]

1986	United Kingdom	^{60}Co radiotherapy	Exposure during source changing		1	Dose of 15 Gy to hand; erythema, blistering at two weeks	[U3]
1986	United States: Tyler, Texas	Therac-25 accelerator	Problem of integration of hardware and software of system	1		Loss of function of arm and both lower extremities; skin injuries; periodic nausea and vomiting; radiation-induced myelitis at C5, C6 level of cervical cord; death five months after the accident	[N2]
1986	United States: Tyler, Texas	Therac-25 accelerator	Problem of integration of hardware and software of system	1		Victim died three weeks after the accident; acute high dose radiation injury to the right temporal lobe of the brain and brain stem	[N2]
1987	United States: Yakima, Washington	Therac-25 accelerator	Problem of integration of hardware and software of system; operator error		1	90–100 Gy accidentally delivered to chest of patient; the patient subsequently died of oesophageal carcinoma	[N2]
1987–1988	United States: Maryland	^{60}Co therapy	Treatment planning; computer file was not updated after source change		33	33 patients received whole-brain doses 75% greater than prescribed; 20 patients died either during or after completion of therapy	[I24]
1988	Netherlands: Rotterdam	Sagittaire accelerator	Leakage of radiation during therapy		1	Severe skin reactions of thorax, head and upper arm; dose estimated at 10–20 Gy	[W3]
1990	Spain: Zaragoza	Linear accelerator	Assumption that meter on control panel was stuck, although electron energy had been modified by technician	15	12	27 patients received doses 3–7 times higher than intended; 15 died with radiation exposure as primary cause; others had major disabilities	[I24, S5]
1992	United States: Indiana, Pennsylvania	Brachytherapy source	Source dislodged; failure to check for source's return to shielded holder	1		Source remained in patient for four days; 94 other individuals were exposed at the clinic, nursing home and other areas	[I24, N4]
1994	United States	High-dose-rate brachytherapy	Treatment planning errors		1	Patient was given a dose of 12 Gy to the vaginal area instead of the prescribed dose	[N6]
1996	Costa Rica: San José	^{60}Co teletherapy	Error in calculating dose rate	17	46	Exposures were significantly higher (50–60%) than prescribed	[I14, I24]
1996	Russian Federation, Moscow	Accelerator accident	Accidental dose rate increase		1	Localized dose of more than 100 Gy. Acute, high dose radiation injury to left part of chest	[B11]
2000–2001	Panama: Panama City	^{60}Co teletherapy	Misuse of treatment planning system	5	23	Patient doses were doubled; five died of radiation injuries; two deaths were questionable; nine of 16 survivors had marked or catastrophic complications	[B10, I15]
2001	Russian Federation: Nizhny Novgorod	X-ray cosmetic therapy	Systematic errors in dose rate calculations		9	Local radiation injuries to facial skin – dry and moist desquamation	[B11]
2001	Poland: Bialystok	Linear accelerator	Power failure causing equipment damage		5	Local radiation injuries were present in five patients; severely injured patients required surgery and skin grafts	[I22]
2004	France: Épinal	Hospital/therapy	Errors in treatment planning; operator's instructions not in language understood	4	19	23 patients received overdoses (20% more than intended); one patient died of radiation exposure; three died of severe radiation-induced complications	[A4]
2006	United Kingdom: Glasgow, Scotland	Linear accelerator	Inexperienced treatment planner		1	Critical error made in data used during treatment delivery; 15-year-old female was given 58% higher dose than planned	[J5]
2007	United States: Detroit, Michigan	Gamma knife radiotherapy	Image reversal on MRI led to wrong side of brain being treated		1	Small area of normal brain tissue and 7% of lesion treated with 18 Gy exposure, rather than whole lesion volume being treated	[N9]

Table 7. Summaries of sea, air and space vehicle accidents

Year	*Country*	*Vehicle type*	*Accident location*	*Identifying name*	*Cause and result*	*Reference*
				Sea		
1961	USSR	Nuclear submarine	North-west Atlantic	K-19	Leakage in heat transfer circuit with fuel overheating; submarine towed to base	[B1, I18]
1963	United States	Nuclear submarine	Atlantic (unspecified)	Thresher	Unknown cause; lost at sea with entire crew	[I18]
1968	USSR	Diesel submarine	Pacific near Hawaii	K-129	Submarine sank carrying two nuclear warheads that were subsequently recovered	[B1, I18]
1968	United States	Nuclear submarine	Atlantic (unspecified)	Scorpion	Unknown cause; lost at sea with entire crew	[I18]
1970	USSR	Nuclear submarine	Bicay Bay	K-8	Fire; rubber seals in hull failed and seawater entered; sank north-west of Spain	[B1, I18]
1978	Unspecified	Surface vessel	South-east Barents Sea	Nikel	Lighter carrying encapsulated waste was lost at sea during storm	[I18]
1984	France	Surface vessel	North Sea	Mont Louis	Collision of vessel and ferry; ship carrying 30 containers of $<1\%$ enriched UF_6 sank off Zeebrugge; all containers recovered	[I18]
1985	USSR	Nuclear submarine	Chazma Bay	K-431	Explosive criticality occurred during refuelling; environmental contamination in Russia resulted	[B1, I18]
1986	USSR	Nuclear submarine	North-east Atlantic	K-219	Fire and explosion damaged hull; towed to 6 000 m depth and sunk (Bermuda)	[B1, I18]
1989	USSR	Nuclear submarine	Norwegian Sea	K-278	Fire in the stern compartment while submerged; submarine sank	[B1, I18]
1989	USSR	Nuclear submarine	Ara Bay	Unknown member of North Fleet	Unknown problem; largest reported release of radioactive material	[I18]
1997	Panama	Surface vessel	Atlantic, Azores	MSC Carla	Three Type B packages containing ^{137}Cs involved	[I18]
2000	Russian Federation	Nuclear submarine	Barents Sea	Kursk	Cause unknown; two seismic events occurred on the day of the accident; the submarine sank with 118 crew members on-board; subsequently, the reactors on-board were found to be intact	[I18]
				Air		
1965	United States	Aircraft	Near Okinawa, Japan	Skyhawk jet	Jet carrying nuclear weapon rolled off aircraft carrier	[I18]
1966	United States	Aircraft	Palomares, Spain	Bomber (B-52)	Aircraft collision during refuelling; four nuclear weapons involved; two recovered intact, two destroyed on impact with land; significant ongoing plutonium contamination of the environment resulted	[I18]
1968	United States	Aircraft	Thule, Greenland	Bomber (B-92)	Aircraft crashed; four nuclear weapons destroyed, spreading plutonium contamination over large area of marine environment	[I18]
1987	USSR	Aircraft	Sea of Okhotsk		Helicopter emergency resulted in drop of RTG equipped with ^{90}Sr source (12.95–25.3 PBq) at sea in 30 m of water; attempts to locate it have been unsuccessful	[I18]
1997	Russian Federation	Aircraft	Sea of Okhotsk		Helicopter emergency resulted in disposal of RTG containing 1.3 PBq ^{90}Sr	[I18]

Space vehicle						
1964	United States	Spacecraft	West Indies Ocean	SNAP-9A Transit-5BN3	Satellite containing 630 TBq of ^{238}Pu failed to achieve orbit and vaporized during re-entry in the Southern Hemisphere	[I18]
1968	United States	Spacecraft	Santa Barbara, California	Nimbus BI	Spacecraft failed to achieve orbit; two RTGs recovered intact	[I18]
1970	United States	Spacecraft	South Pacific	Apollo 13	Malfunction in oxygen supply led to emergency return to Earth in the lunar landing module; an RTG on-board re-entered intact and is at a depth of not less than 6 000 m in the Tonga Trench	[I18]
1978	USSR	Spacecraft	Northern Canada	Cosmos 954	Research satellite carrying small nuclear reactor re-entered atmosphere and spread radioactive fragments over wide area	[I18]
1983	USSR	Spacecraft	South Atlantic	Cosmos 1402	Satellite failed to boost nuclear reactor into higher orbit after completion of mission; reactor core and fission products re-entered atmosphere east of Brazil	[I18]
1996	United States	Spacecraft	Pacific Ocean	Mars 96	Unsuccessful burn of booster resulted in re-entry into Earth’s atmosphere west of Chile; 18 RTGs onboard with total ^{238}Pu activity of 174 TBq	[I18]

Table 8. Number of accidents resulting in early acute health effects or significant population exposures

Based on published information; excludes malicious acts and nuclear testing

Type of accident	*1945–1965*	*1966–1986*	*1987–2007*
Accidents at nuclear facilities	19	12	4
Industrial accidents	2	50	28
Orphan source accidents	3	15	16
Accidents in academic/research work	2	16	4
Accidents in medical use[a]	Unknown	18	14

[a] The IAEA [I25] and ICRP [I24] have reported more than 100 accidents in radiotherapy. This table considers only serious radiation accidents in medicine.

Table 9. Estimated collective doses for a spectrum of accidents increasing population exposure

Not comprehensive, an illustrative selection; excludes malicious acts and nuclear testing

Year	*Accident*	*Local and regional collective effective dose (man Sv)*
1986	USSR: Chernobyl (see annex D)	320 000[a]
1964	SNAP-9A [U6]	
1957	United Kingdom: Windscale, Cumbria [U6]	2 000
1957	USSR: Mayak Complex, Kyshtym [U6]	1 200
1983	Mexico: Ciudad Juarez [U6]	150
1987	Brazil: Goiânia [U6]	60
1979	United States: Three Mile Island, Pennsylvania [U6]	40
1966	Spain: Palomares [U6]	3
1999	Japan: Tokai-mura	<0.6[c]
1993	Russian Federation: Tomsk, Siberia [I19]	0.02[b]

[a] Sum of collective dose estimates for 1986–2005 for evacuees and inhabitants of Belarus, the Russian Federation and Ukraine, and of the rest of Europe (annex D) multiplied by 1.25 to take account of dose yet to be delivered. The 61 000 man Sv received by the recovery workers is not included here.

[b] Estimated collective dose to the recovery workers was 13.3 man Sv [I19].

[c] Based on reference [M7].

Table 10. Numbers of deaths and early acute health effects due to radiation accidents

Based on published information; excludes malicious acts and nuclear testing

Type of accident	*1945–1965*	*1966–1986*	*1987–2007*	*Total*
Accidents at nuclear facilities	42 early effects 13 deaths	123 early effects 34 deaths	2 early effects 3 deaths	167 early effects 50 deaths
Industrial accidents	8 early effects 0 deaths	61 early effects 3 deaths	51 early effects 6 deaths	119 early effects 9 deaths
Orphan source accidents	5 early effects 7 deaths	98 early effects 19 deaths	205 early effects 16 deaths	308 early effects 42 deaths
Accidents in academic/ research work	2 early effects 0 deaths	22 early effects 0 deaths	5 early effects 0 deaths	29 early effects 0 deaths
Accidents in medical use	Unknown Unknown	470 early effects 4 deaths	153 early effects 42 deaths	623 early effects 46 deaths

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Volume II

Annex D (Health effects due to radiation from the Chernobyl accident)

Corrigendum

1. **Page 55, figure V, heading**

For references in the heading of the figure, *for* [I14, K22, K25, L4, Z4] *read* [K8, L4, R6, Z4]

2. **Page 182, footnote 1**

For kBq/km^2 *read* kBq/m^2

3. **Page 183, paragraph D251**

The fourth and final sentence of the paragraph *should read*

This is the position formulated by UNSCEAR in annex G, “Biological effects of low radiation doses”, of the UNSCEAR 2000 Report [U3], which states “For most tumour types in experimental animals and in man a significant increase in risk is only detectable at doses above about 100 mGy.”

ANNEX D

HEALTH EFFECTS DUE TO RADIATION FROM THE CHERNOBYL ACCIDENT

CONTENTS

I. INTRODUCTION

1. The 1986 accident at the Soviet Union's Chernobyl nuclear power plant (ChNPP) was the most severe ever to have occurred in the civilian nuclear power industry.[1] It triggered an unprecedented international effort to improve understanding of the health effects due to radiation from the accident and has become the most extensively studied accident involving radiation exposure.

2. Two workers died in the immediate aftermath; and high doses of radiation[2] to 134 plant staff and emergency personnel[3] resulted in acute radiation syndrome (ARS), which proved fatal for 28 of them. Other than this group of emergency workers, several hundred thousand were involved in recovery operations;[4] they were exposed externally and, to a lesser degree, internally to radiation from the damaged reactor and from radionuclides released to the environment.

3. 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 air for about 10 days. The radioactive cloud dispersed over the entire northern hemisphere, and deposited substantial amounts of radioactive material over large areas of the former Soviet Union and some other countries in Europe, contaminating land, water and biota, and causing particularly serious social and economic disruption for large populations in Belarus, the Russian Federation and Ukraine[5] (the three republics). Two radionuclides, the short-lived iodine-131 (^{131}I with a half-life of 8 days) and the long-lived caesium-137 (^{137}Cs with a half-life of 30 years), were particularly significant for the radiation dose they delivered to members of the public.

4. In the former Soviet Union, the contamination of fresh milk with ^{131}I and the lack of prompt countermeasures led to high thyroid doses, particularly among children. In the longer term, mainly due to radiocaesium, the general population was also exposed to radiation externally from radioactive deposition and internally from consuming contaminated foodstuffs. However, in part because of the countermeasures taken, the resulting radiation doses were relatively low (the average additional dose in 1986–2005 in "contaminated areas"[6] of the three republics was about equivalent to that from a computed tomography (CT) scan in medicine), and should not lead to substantial health effects in the general population that could be attributed to radiation exposure from the accident. Even so, the severe disruption caused by the accident, confounded with the remarkable political changes that took place in the Soviet Union and the new republics, resulted in major social and economic impact, and great distress for the affected populations.

A. Past assessments

5. There has been an unprecedented effort by the international community to assess the magnitude and characteristics of the health effects due to the radiation exposure resulting from the accident. As early as August 1986, a widely attended international gathering, the "Post-Accident Review Meeting", was convened in Vienna. The resulting report of the International Nuclear Safety Advisory Group (INSAG) contained a limited but essentially correct early account of the accident and its expected radiological consequences [I31]. In May 1988, the International Scientific Conference on the Medical Aspects of the Accident at the Chernobyl Nuclear Power Plant [I32] held in Kiev summarized the available information at the time and confirmed that some children had received high doses to the thyroid. In May 1989, scientists obtained a more comprehensive insight into the scale of the consequences of the accident at an ad hoc meeting convened at the time of the 38th session

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[1] The accident site is located in present-day northern Ukraine, some 20 km south of the border with Belarus and 140 km west of the border with the Russian Federation. The accident occurred on the 26 April 1986 during a low-power engineering test of the Unit 4 reactor. Improper, unstable operation of the reactor, which had design flaws, allowed an uncontrollable power surge to occur, resulting in successive steam explosions, which severely damaged the reactor building and completely destroyed the reactor [I7, I31].

[2] The term dose is used in this scientific annex in a number of ways: in a general sense, to indicate an amount of radiation absorbed from a given exposure, and in two specific senses, to indicate either the physical quantity, absorbed dose, or the protection quantity, effective dose. Absorbed dose is given in the unit, gray (Gy) (or appropriate submultiples) and effective dose is given in the unit, sievert (Sv) (or appropriate submultiples). In general, absolute values of dose relate to absorbed dose, unless otherwise indicated. The concepts of collective absorbed dose and collective effective dose are also used.

[3] Approximately 600 workers responded on site within the first day to the immediate emergency, including staff of the plant, firemen, security guards and staff of the local medical facility.

[4] In 1986 and 1987 some 440,000 recovery operation workers worked at the Chernobyl site, and more such recovery workers were involved in various activities between 1988 and 1990. The work included, among other things, construction of the sarcophagus over the damaged reactor and decontamination of the site and roads. Special health registers currently hold records on more than 500,000 recovery operation workers in total.

[5] At the time of the accident, these were three constituent Soviet Socialist Republics of the Soviet Union.

[6] The "contaminated areas" were defined arbitrarily in the former Soviet Union as areas where the ^{137}Cs levels on soil were greater than 37 kBq/m^2.

of UNSCEAR [G15, K25]. In October 1989, the former Soviet Union formally requested “an international experts’ assessment” and, as a result, the International Chernobyl Project (ICP) [I5] was launched in early 1990; its conclusions and recommendations were presented at an International Conference held in Vienna, 21–24 May 1991 [I5]. Many national and international initiatives[7] followed aimed at developing a better understanding of the accident consequences and in assisting in their mitigation. The results of these initiatives were presented at the 1996 International Conference on One Decade After Chernobyl[8] [I29]. There was a broad agreement on the extent and character of the consequences.

6. The Committee considered the initial radiological consequences of the accident in its UNSCEAR 1988 Report [U7]. The short-term effects of radiation exposure and the treatment of the radiation injuries to workers and firefighters who were on the site at the time of the accident were reviewed in the appendix to annex G, “Early effects in man of high doses of radiation”, of the UNSCEAR 1988 Report. The estimated average individual and collective doses to the population of the northern hemisphere were given in annex D, “Exposures from the Chernobyl accident”.

7. Annex J, “Exposures and effects of the Chernobyl accident”, of the UNSCEAR 2000 Report [U3] provided a detailed account of the known radiological consequences of the accident up to 2000. It reviewed the information on the physical consequences of the accident, the radiation doses to the exposed population groups, the early health effects in the emergency workers, the registration and health monitoring programmes, and the late health effects of the accident.

8. In spite of the general consensus of the international scientific community on the extent and nature of the radiation health effects that is reflected in the UNSCEAR 2000 Report [U3], there was still considerable public controversy within the three republics. Thus, in 2003, eight bodies of the United Nations family[9] (including the Committee) and the three republics launched the “Chernobyl Forum” 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. Drawing heavily on the UNSCEAR 2000 Report [U3], the IAEA led the environmental assessment and the WHO led the health assessment. The Forum’s work was reviewed at the International Conference: Chernobyl—Looking Back to Go Forwards: Towards a United Nations Consensus on the Effects of the Accident and the Future, held in Vienna, 6–7 September, 2005. Three detailed reports were issued [C22, I21, W5] in early 2006. The Chernobyl Forum essentially reconfirmed all previous assessments of the scale and character of the radiation health consequences. The Forum reports have been used as appropriate in the preparation of this annex.

9. The objective of the present annex 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 to clarify the potential risk projections, taking into account the levels, trends and patterns of radiation dose to the exposed populations. The Committee has evaluated the relevant new information that has become available since the 2000 Report, in order to determine whether the assumptions used previously to assess the radiological consequences are still valid. In addition, it recognized that some issues merited further scrutiny and that its work to provide the scientific basis for a better understanding of the radiation-related health and environmental effects of the Chernobyl accident needed to continue. The information considered included the behaviour and trends of the long-lived radionuclides in foodstuff and the environment in order to improve the estimates of exposure of relevant population groups, and the results of the latest follow-up studies of the health of the exposed groups. The effects of radiation on plants and animals following the Chernobyl accident are discussed separately in annex E, “Effects of ionizing radiation on non-human biota”. Other effects of the accident, in particular, distress and anxiety, and socio-economic effects, were considered by the Chernobyl Forum [W5] but are outside the Committee’s remit.

10. The Committee, in general, bases its assessments on reports appearing in peer-reviewed scientific literature and on information submitted officially by Governments in response to its requests. However, the results of many of the studies related to the Chernobyl accident have been presented at scientific meetings without formal scientific peer review. The Committee decided that it would only make use of such information when it could judge that the results and the underlying work were scientifically and technically sound.

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[7] Some of the more significant multinational initiatives were the following: the WHO launched an International Programme on the Health Effects of the Chernobyl Accident (IPHECA), the results of which were discussed at the WHO International Conference on the Health Consequences of the Chernobyl and other Radiological Accidents, held in Geneva, 20–23 November 1995 [W6]; the EC supported many scientific research projects on the accident consequences and their results were summarized at the First International Conference of the European Union, Belarus, the Russian Federation and Ukraine on the Consequences of the Chernobyl Accident, held in Minsk, 18–22 March 1996 [E4]; and UNESCO supported several studies, mainly on psychological impact [U20].

[8] The International Conference on One Decade After Chernobyl: Summing up the Accident's Consequences, which took place in Vienna in April 1996, was cosponsored by IAEA, WHO and EC in cooperation with the UN, UNESCO, UNSCEAR, FAO and the Nuclear Energy Agency of OECD. The Conference was presided over by A. Merkel, Germany’s Federal Minister for the Environment, Nature Conservation and Nuclear Safety. It was attended by high-level officials of the three most affected States (including the President of Belarus, the Prime Minister of Ukraine, and the Russian Federation's Minister for Civil Defence, Emergencies and Elimination of Consequences of Natural Disasters) and by 845 scientists from 71 countries and 20 organizations.

[9] FAO, IAEA, OCHA, UNDP, UNEP, UNSCEAR, WHO and the World Bank.

B. Structure of the present scientific annex

11. The annex comprises a main text with four supporting appendices. The main text summarizes the physical and environmental context of the accident and updates the estimates of radiation dose to the various exposed population groups (appendices A and B, respectively, provide additional details). Before considering the results of the health studies, the annex discusses some of the difficulties involved in attributing health effects to radiation exposure. It then briefly recapitulates the early health effects that had been seen among the emergency workers (appendix C provides details). Section VI (with details in appendix D) discusses the theoretical projections of the late health effects and the actual observations of effects to date that can be attributed to radiation exposure from the accident.

II. PHYSICAL AND ENVIRONMENTAL CONTEXT

12. This section briefly reviews the physical and environmental context of the accident with a particular focus on those aspects for which knowledge has improved and that have implications for refining the radiological assessment. Appendix A provides more details.

A. Radionuclide release and deposition

13. The accident released a mixture of radionuclides into the air over a period of about 10 days. Most of the radionuclides that were released in large amounts (in terms of activity) were of short half-life; radionuclides of long half-life were generally released only in small amounts. The most up-to-date estimates of the amounts released (table 1) are similar to those of the UNSCEAR 2000 Report [U3], except for the refractory elements, which are now about 50% lower [K13]. However, these changes are academic and have no influence on the assessment of radiation doses, which are rather based on direct human and environmental measurements.

Table 1. Principal radionuclides released in the accident
Refined estimates of the activities released

Radionuclide	*Half-life*	*Activity released (PBq)*
Inert gases[a]		
^{85}Kr	10.72 a	33
^{133}Xe	5.25 d	6 500
Volatile elements[a]		
^{129m}Te	33.6 d	240
^{132}Te	3.26 d	~1 150
^{131}I	8.04 d	~1 760[d]
^{133}I	20.8 h	910
^{134}Cs	2.06 a	~47[b]
^{136}Cs	13.1 d	36
^{137}Cs	30.0 a	~85[e]
Elements with intermediate volatility[a]		
^{89}Sr	50.5 d	~115
^{90}Sr	29.12 a	~10
^{103}Ru	39.3 d	>168
^{106}Ru	368 d	>73
^{140}Ba	12.7 d	240
Refractory elements (including fuel particles)[c]		
^{95}Zr	64.0 d	84
^{99}Mo	2.75 d	>72
^{141}Ce	32.5 d	84
^{144}Ce	284 d	~50
^{239}Np	2.35 d	400
^{238}Pu	87.74 a	0.015
^{239}Pu	24 065 a	0.013
^{240}Pu	6 537 a	0.018
^{241}Pu	14.4 a	~2.6
^{242}Pu	376 000 a	0.00004
^{242}Cm	18.1 a	~0.4

[a] From references [D11, U3].
[b] Based on ^{134}Cs/^{137}Cs ratio 0.55 as of 26 April 1986 [M8].
[c] Based on fuel particle release of 1.5% [K13].
[d] For comparison, the global release of ^{131}I from atmospheric nuclear weapon testing was 675,000 PBq [U3].
[e] For comparison, the global release of ^{137}Cs from atmospheric nuclear weapon testing was 948 PBq [U3].

14. The radioactive gases and particles released were initially carried by the wind in westerly and northerly directions, but subsequently, the winds came from all directions (figure I) [B24, I21, U3]. There are essentially no new data, but research to improve understanding of the atmospheric dispersion patterns continues [T5, T6].

15. Material was deposited, mainly because of rainfall, in a complex pattern over large areas of the three republics and beyond. Owing to the emergency situation and the short half-life of ^{131}I, few reliable measurements of the pattern of radioiodine deposition were made. There are ongoing efforts to reconstruct the deposition pattern of ^{131}I, using measurements of the long-lived ^{129}I as an analogue. Three main areas of the former Soviet Union (in total, 150,000 km^2 with more than 5 million inhabitants) were classified as contaminated areas (figure II). Outside of the former Soviet Union, other large areas of Europe were also subjected to deposition of radioactive material (45,000 km^2 had ^{137}Cs deposition levels ranging from 37 kBq/m^2 to 200 kBq/m^2). It was possible to measure trace concentrations of the radionuclides in essentially all countries of the northern hemisphere. The area classified as contaminated is gradually shrinking as the ^{137}Cs decays, e.g. it is expected to fall from 23% of the Belarusian territory in 1986 to 16% in 2016 and 10% in 2046 [S23].

Figure I. Formation of plumes by meteorological conditions for instantaneous releases on the dates and at the times (UTC) indicated [B24]

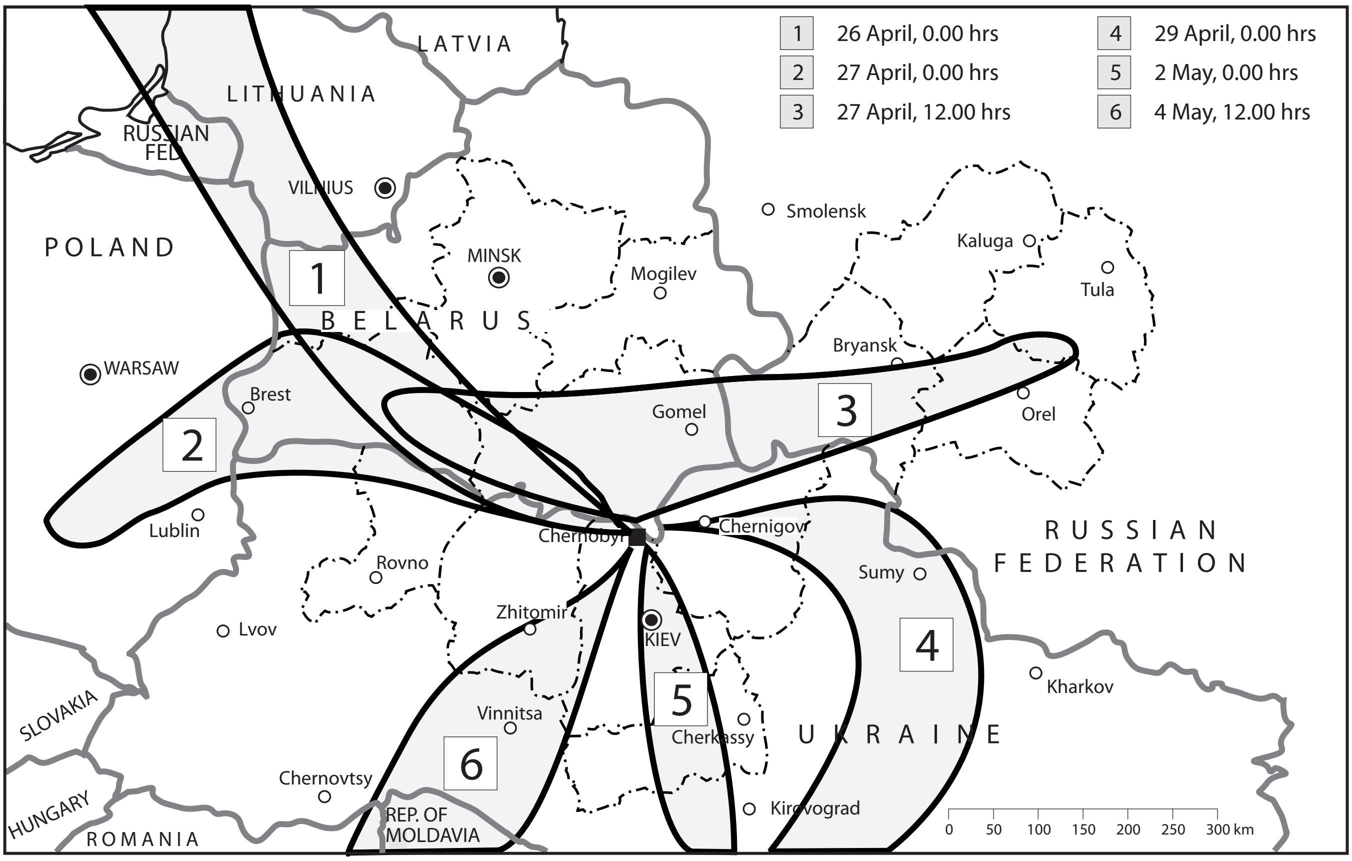
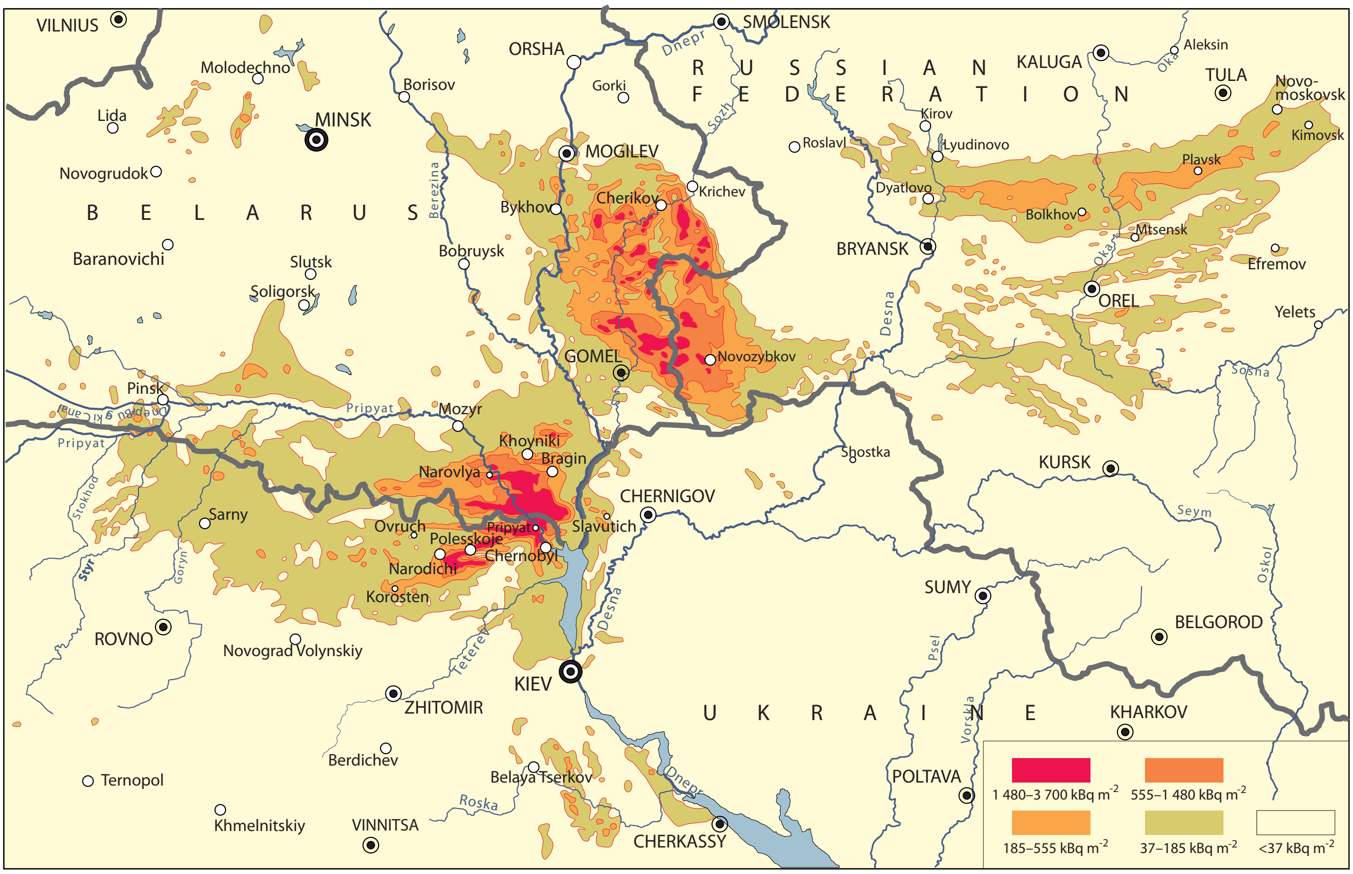


Figure II. Map of ^{137}Cs deposition levels in Belarus, the Russian Federation and Ukraine as of December 1989 [I28]

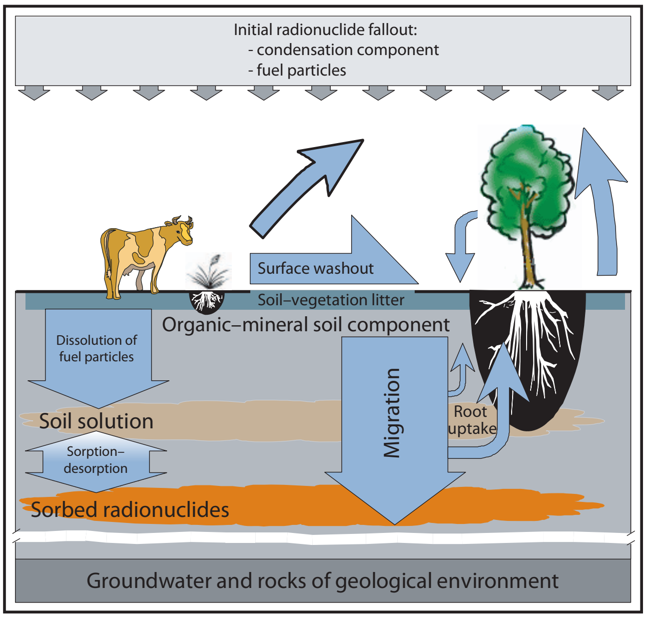


B. Environmental transfer

16. The main transfer pathways of radionuclides in the terrestrial environment are illustrated in figure III. For the short-lived ^{131}I, the main pathway of human exposure was via the transfer of deposited material on pasture grass to cow's milk. Within a few weeks, the very high initial concentrations became negligible because of radioactive decay and other physical and biological processes.

17. For the long-lived radionuclides such as ^{137}Cs, the long-term transfer processes through the environment needed to be considered. From mid-1986 onwards, internal exposure due to ^{134}Cs and ^{137}Cs in milk and meat were the most significant sources of exposure. The levels in food depended not only on the deposition pattern, but also on factors such as the soil type and agricultural practice. During the first few years, there was a substantial reduction in the levels of radiocaesium in most foodstuffs, with the levels in most of the contaminated areas falling below those recommended by the Codex Alimentarius Commission [C12]. However, since the mid-1990s, the levels have fallen more slowly. Further reductions in the levels in foodstuffs over the next decades are expected to be mainly due to radioactive decay. In parts of the contaminated areas, there are continuing difficulties for subsistence farmers with privately-owned dairy cows. The uptake and retention of ^{137}Cs has generally been much higher in semi-natural ecosystems than in agricultural ecosystems [H9], and the clearance rate from forest ecosystems is extremely slow. The highest levels in foodstuffs continue to be in mushrooms, berries, game and reindeer.

Figure III. The main transfer pathways of radionuclides in the terrestrial environment [S13]

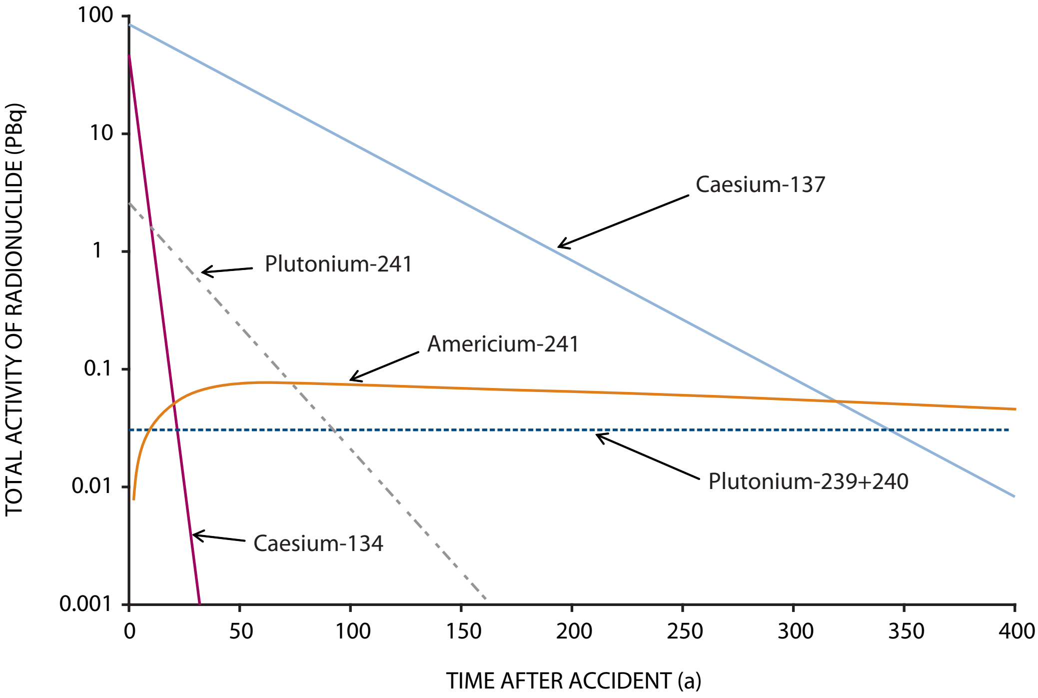


18. Levels of radionuclides in rivers and lakes directly after the accident fell rapidly and are now generally very low in water used for drinking and irrigation, although the radiocaesium levels in the water and fish of some closed lakes have fallen only slowly. Levels in seawater and marine fish were much lower than in freshwater systems.

19. Deposition of radioactive material in human settlements has also contributed to external exposure of inhabitants. The behaviour of the deposited material depended initially on the type of deposition (i.e. dry or wet) and on the characteristics of the settlement. The external dose rates have fallen with time, because of radioactive decay and weathering (e.g. radiocaesium levels on asphalt have fallen by over 90%). In most settlements, the dose rates have returned to pre-accident levels, although levels slightly above background can still be measured over undisturbed soil.

20. By 2008, most of the radionuclides released had long since decayed to negligible levels. Over the next few decades, ^{137}Cs will continue to be the most relevant radionuclide as far as exposure to radiation is concerned. Within about 20 km of the ChNPP, particles of the nuclear fuel (so-called “hot particles”) had been deposited with high concentrations of radionuclides including isotopes of strontium and plutonium. The particles are slowly dissolving with time and will release ^{90}Sr over the next 10-20 years [F4, K14]. Over the very long term, the only residual radioactivity from these particles will be trace levels of long-lived radionuclides such as isotopes of plutonium and ^{241}Am (figure IV).

Figure IV. Total amounts in the environment of various long-lived radionuclides as a function of time after the accident
Americium-241 is the only radionuclide whose levels are presently increasing with time owing to its ingrowth from the decay of ^{241}Pu. The total activity of ^{241}Am in the environment will reach a maximum in the year 2058, after which levels will slowly decline. This peak value is small compared to the initial levels of ^{241}Pu. Eventually ^{241}Am will be the most significant remaining radionuclide, albeit at trace levels



C. Environmental countermeasures

21. Owing to uncertainty about future releases and weather conditions, as well as to relatively high radiation dose rates, the authorities evacuated the nearest town of Pripyat within the first few days of the start of the accident and the surrounding settlements soon after (a total of 115,000 local people were evacuated in 1986). Subsequently, they resettled a further 220,000 people. They also decontaminated settlements in many regions of the former Soviet Union in order to reduce the long-term exposure of the public.

22. In the first few weeks, management of animal fodder and milk production (including prohibiting the consumption of fresh milk) would have helped significantly to reduce the doses to the thyroid due to radioiodine, particularly in the former Soviet Union where the levels were high. However, implementation of countermeasures in the former Soviet Union was flawed, because timely advice was lacking, particularly for private farmers. Many European countries changed their agricultural practices and/or withdrew food, especially fresh milk, from the supply chain, and, in Poland, iodine prophylaxis was promptly organized; these actions generally reduced thyroid doses in those countries to negligible levels.

23. Over the months and years after the accident, the authorities of the former Soviet Union introduced an extensive set of countermeasures, involving major human, economic and scientific resources. These helped to reduce the long-term exposures from the long-lived radionuclides, notably radiocaesium. During the first few years, substantial amounts of food were removed from human consumption because of concerns about the radiocaesium levels, especially in milk and meat. In addition, pasture was treated, and clean fodder and caesium binders were provided to livestock, resulting in considerable reductions in dose.

24. In addition, countermeasures were instigated to reduce exposures from living and working in forests and using forest products. They included: restrictions on access; restrictions on harvesting of forest foods, such as game, berries and mushrooms; restrictions on the gathering of firewood; and alteration of hunting practices.

25. Early restrictions on drinking water and changing to alternative supplies reduced internal doses from aquatic pathways in the initial period. Restrictions on the consumption of freshwater fish from some lakes also proved effective in Scandinavia and Germany. Other countermeasures to reduce the transfer of radionuclides from soil to water systems were generally ineffective.

III. RADIATION DOSES TO EXPOSED POPULATION GROUPS

26. The early assessments of dose to exposed populations based on the measurements available at the time tended to use cautious assumptions about the countermeasures applied and the environmental and dosimetric parameters involved. As a consequence, the doses were generally overestimated. Experience with the widespread application of countermeasures, and the extensive sets of measurements and records that were subsequently obtained have since been used to improve the models and dose assessments. Appendix B provides details of the latest dose assessments and the results, based on more than 20 years of experience and measurements.

27. Compared to the UNSCEAR 2000 Report [U3]: *(a)* dose estimates have been updated for a larger number of the Belarusian, Russian, and Ukrainian recovery operation workers (510,000 instead of 380,000), and new information is presented on the Estonian, Latvian, and Lithuanian recovery operation workers; *(b)* thyroid dose estimates have been updated for the Belarusian and Ukrainian evacuees, and new information is presented for the Russian evacuees; *(c)* the estimation of thyroid and effective doses has been expanded from 5 million to 100 million inhabitants of the three republics; and *(d)* thyroid and effective dose estimates have been updated for the inhabitants of other European countries.

28. Doses to the thyroid are expressed in terms of the quantity, absorbed dose, in units of gray (Gy); while doses to the whole body from external and internal irradiation combined are expressed in terms of the weighted quantity used in radiation protection, effective dose, in units of sievert (Sv). For comparison, the annual average effective dose from natural background radiation is 2.4 mSv, while the typical effective dose from a medical CT scan is of the order of 10 mSv.

29. The updated estimates of the average individual and collective doses received by the population groups exposed as a result of the Chernobyl accident are summarized in table 2. Because iodine concentrates in the thyroid gland, absorbed doses to the thyroid over the first few weeks after the accident for those members of the population drinking fresh milk containing ^{131}I were much higher than the dose to the thyroid due to natural sources of radiation; this was especially true for infants and children who consumed proportionally more milk than adults. In contrast, because caesium behaves chemically like its analogue potassium, and is therefore relatively evenly dispersed throughout the body, the effective dose due to the accident is comparable to or even much lower than the effective dose due to natural background radiation.

Table 2. Summary of updated dose estimates for the main population groups exposed

Population group	*Size (thousands)*	*Average thyroid dose in 1986 (mGy)*	*Average effective dose in 1986-2005 (mSv)*	*Collective thyroid dose in 1986 (man Gy)*	*Collective effective dose in 1986-2005 (man Sv)*
Recovery operation workers	530	—[a]	117[b]	—	61 200
Evacuees	115	490	31[c]	57 000	3 600
Inhabitants of contaminated areas[d] of Belarus, Russia and Ukraine	6 400	102	9[c,e]	650 000	58 900
Inhabitants of Belarus, the Russian Federation and Ukraine	98 000	16	1.3[c,e]	1 600 000	125 000[e]
Inhabitants of distant countries[f]	500 000	1.3	0.3[c,e]	660 000	130 000[e]

[a] Thyroid doses only exist for a very small number of workers; it is not possible to give a valid average value for the whole group.

[b] Effective dose estimates for the workers include only the doses from external irradiation, delivered essentially from 1986 to the end of 1990. It is assumed that the recorded dose in mGy is numerically equal to the effective dose in mSv.

[c] Effective dose estimates are the sum of the contributions from external and internal irradiation, excluding the thyroid dose.

[d] The contaminated areas were defined arbitrarily in the former Soviet Union as areas where the ^{137}Cs levels on soil were greater than 37 kBq/m^2.

[e] The total dose will continue to accumulate to be perhaps 25% higher for the whole lifetime.

[f] All the European countries except the three republics, Turkey, countries of the Caucasus, Andorra and San Marino.

A. Doses to workers involved in response and recovery

30. The average effective dose received by the recovery operation workers between 1986 and 1990, mainly due to external irradiation, is now estimated to have been about 120 mSv. The recorded worker doses varied from less than 10 mSv to more than 1,000 mSv, although about 85% of the recorded doses were in the range 20–500 mSv. Uncertainties in the individual dose estimates vary from less than 50% to up to a factor of 5, and the estimates for the military personnel are suspected to be biased towards high values.

31. The collective effective dose to the 530,000 recovery operation workers is estimated to have been about 60,000 man Sv. This may, however, be an overestimate, as conservative assumptions appear to have been used in calculating some of the recorded doses.

32. There is not enough information to estimate reliably the average thyroid dose to the recovery operation workers.

B. Doses to general population

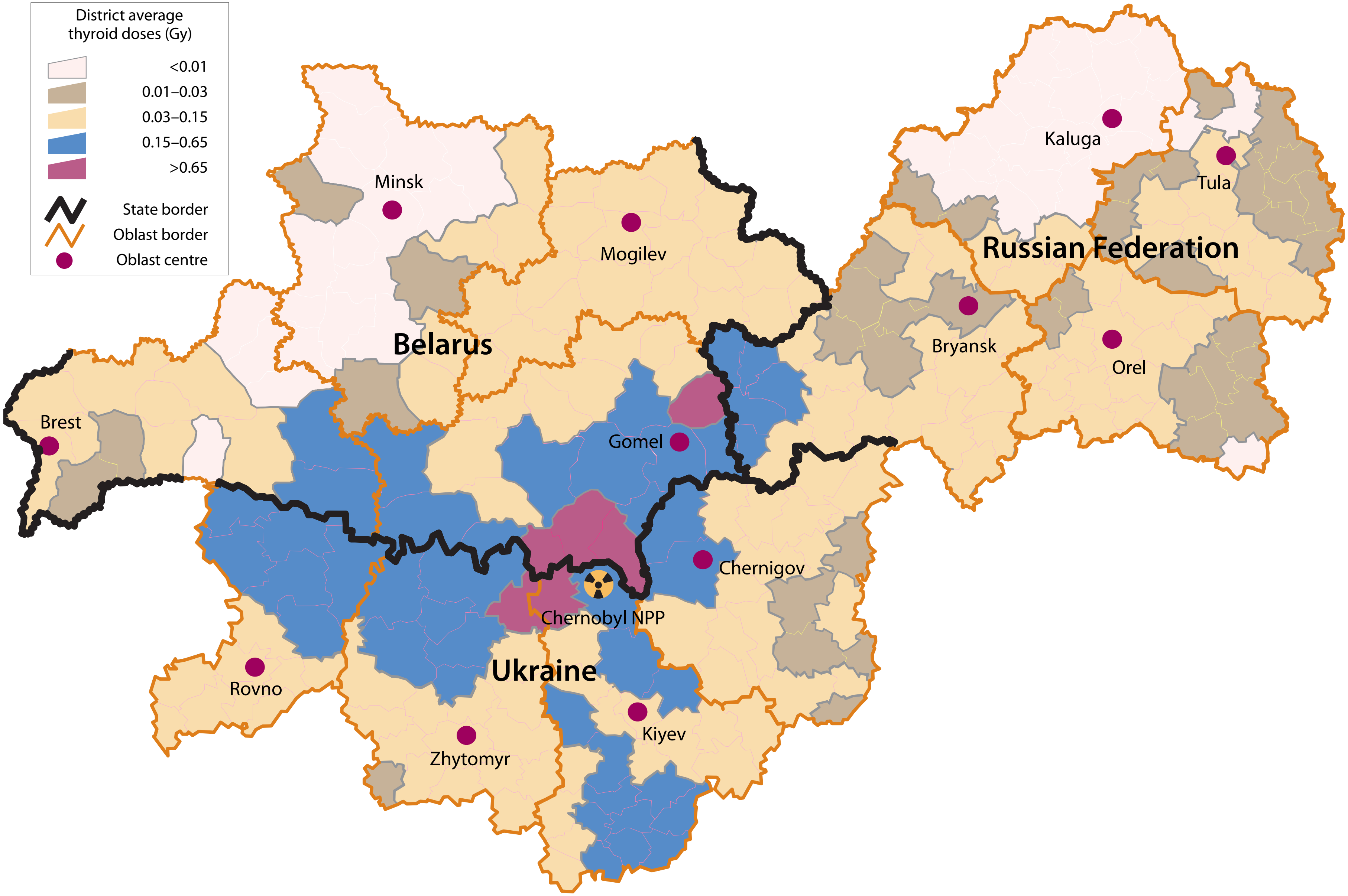
33. The high thyroid doses among the general population were due almost entirely to drinking fresh milk containing ^{131}I in the first few weeks following the accident. Figure V presents the estimated average thyroid dose to children and adolescents in 1986. The average thyroid dose to the evacuees is estimated to have been about 500 mGy (with individual values ranging from less than 50 mGy to more than 5,000 mGy). For the more than six million residents of the contaminated areas of the former Soviet Union (i.e. those with ^{137}Cs levels greater than 37 kBq/m^2) who were not evacuated, the average thyroid dose was about 100 mGy, while for about 0.7% of them, the thyroid doses were more than 1,000 mGy. The average thyroid dose to pre-school children was some 2 to 4 times greater than the population average. For the 98 million residents of the whole of Belarus and Ukraine and 19 oblasts of the Russian Federation, including the contaminated areas, the average thyroid dose was much lower, about 20 mGy; most (about 93%) received thyroid doses of less than 50 mGy. The average thyroid dose to residents of the other European countries was about 1.3 mGy.

34. The collective thyroid dose to the 98 million residents of the former Soviet Union was some 1,600,000 man Gy. At the country level, the collective thyroid dose was highest in Ukraine, with 960,000 man Gy distributed over a population of 51 million people, even though the average thyroid dose in Ukraine was about 3 times lower than in Belarus. At the regional level, the highest collective thyroid dose was to the population of the Gomel oblast, where a collective thyroid dose of about 320,000 man Gy was distributed over a population of 1.6 million people, corresponding to an average thyroid dose of about 200 mGy.

35. As far as whole body doses are concerned, the six million residents of the areas of the former Soviet Union deemed contaminated received average effective doses for the period 1986–2005 of about 9 mSv, whereas for the 98 million people considered in the three republics, the average effective dose was 1.3 mSv, a third of which was received in 1986. This represents an insignificant increase over the dose due to background radiation over the same period (~50 mSv). About three-quarters of the dose was due to external exposure, the rest being due to internal exposure.

36. About 80% of the lifetime effective doses had been delivered by 2005. Over this 20-year period, about 70% of the

Figure V. The estimated average thyroid doses to children and adolescents living at the time of the accident in the most affected regions of Belarus, the Russian Federation and Ukraine [K8, L4, R6, Z4]



population received effective doses below 1 mSv and about 20% received effective doses between 1 and 2 mSv. However, about 150,000 people living in the contaminated areas received an effective dose of more than 50 mSv over the 20-year period. For the population of about 500 million in other countries of Europe, the average effective dose is estimated to have been 0.3 mSv over this period. The collective effective dose is estimated at about 125,000 man Sv to the combined populations of Belarus, Ukraine and the relevant parts of the Russian Federation, and about 130,000 man Sv to the population in the rest of Europe.

IV. ATTRIBUTION OF HEALTH EFFECTS TO RADIATION EXPOSURE

A. General discussion

37. There has been widespread misunderstanding among the general public, media, authorities and even scientists regarding the scale and nature of the health impact of the Chernobyl accident. This is, in part, due to confusion regarding three aspects: *(a)* the nature of deterministic versus stochastic effects of radiation exposure; *(b)* the attribution of effects to radiation exposure for individuals and populations; and *(c)* theoretical projections of effects versus actual observations. This section aims to clarify the first two of these issues. Section VI.B discusses the third.

38. The effects of radiation exposure fall into two main classes: deterministic effects, where the effect is certain to occur under given conditions (e.g. individuals exposed to several grays over a short period of time will definitely suffer ARS); and stochastic effects, where the effect may or may not occur (e.g. an increase in radiation exposure may or may not induce a cancer in a particular individual but if a sufficiently large population receive a radiation exposure above a certain level, an increase in the incidence[10] of cancer may become detectable in that population).

39. Attribution is the process of ascribing an effect to a particular cause. If radiation exposure is not the only known cause of a particular effect, then it is only possible to ascribe a probability that that effect was caused by radiation exposure. In practice, attributing, either wholly or partly, a specific effect to radiation exposure involves considering whether the effect could have occurred by other means, and analysing factors such as the nature of the exposure, the surrounding circumstances, and the clinical evolution of the observed effect. Even though a vast scientific literature can be used to support attribution, each effect must be examined on its own merits; and varying degrees of confidence will be associated with any judgement.

B. Deterministic effects

40. Attribution of observed deterministic effects to radiation exposure requires at least a suspicion of an exposure above a threshold level, usually of a gray or more. It also requires observation of a specific set of clinical or laboratory findings in a particular time sequence. Acute radiation syndrome is a good example of a deterministic effect that is relatively easy to attribute to radiation exposure, because the observed signs and symptoms (e.g. depressed production of blood in the bone marrow with concurrent infection and haemorrhage, and high incidence of chromosome aberrations in the peripheral blood) are not easily produced by other causes. Although there are essential difficulties in determining the diagnosis, an experienced pathologist ought to be able to attribute the observed signs and symptoms to radiation exposure [I6].

41. There are deterministic effects, such as cataracts, for which radiation exposure is not the only known cause. If these effects occur, usually some time after high levels of exposure, and there is no specific marker for radiation exposure having caused them, it is not possible to attribute the effect with certainty to radiation exposure, but only to express a probability that radiation was wholly or partly the cause.

C. Stochastic effects

42. Cancer is the major stochastic effect of radiation exposure that has been demonstrated in human populations (inherited effects have only been observed in animal populations exposed to relatively high doses of radiation, although they are also presumed to occur in humans). Because there is currently no means of distinguishing tumours that are radiation-induced from those that are not, it is essentially impossible to attribute definitely a specific case of cancer to radiation exposure. On the other hand, if there is an increased incidence of cancer observed in an exposed population compared to that in an unexposed population that is matched for age, sex, genetic predisposition, lifestyle and other relevant factors, and if the observed increase is not inconsistent with the existing knowledge base derived from other exposed populations, then it is possible to attribute the increase to the radiation exposure, especially if there is an observed dependence of the incidence on the level of dose. Epidemiological studies need to have sufficient statistical power to attest to the occurrence of such stochastic effects and hence to their attributability to radiation exposure; the level of dose below which it is intrinsically impossible to detect such effects depends on the size of the population that is being studied.

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[10] The term incidence has two uses in this annex: in a general sense, often to contrast cancer incidence with cancer mortality, and in a specific sense, where the incidence of a disease is the number of cases of the disease that occur during a specified period of time (usually a year). The incidence rate is this number divided by a specified unit of population (see paragraph 4 of annex A of reference [U1]).

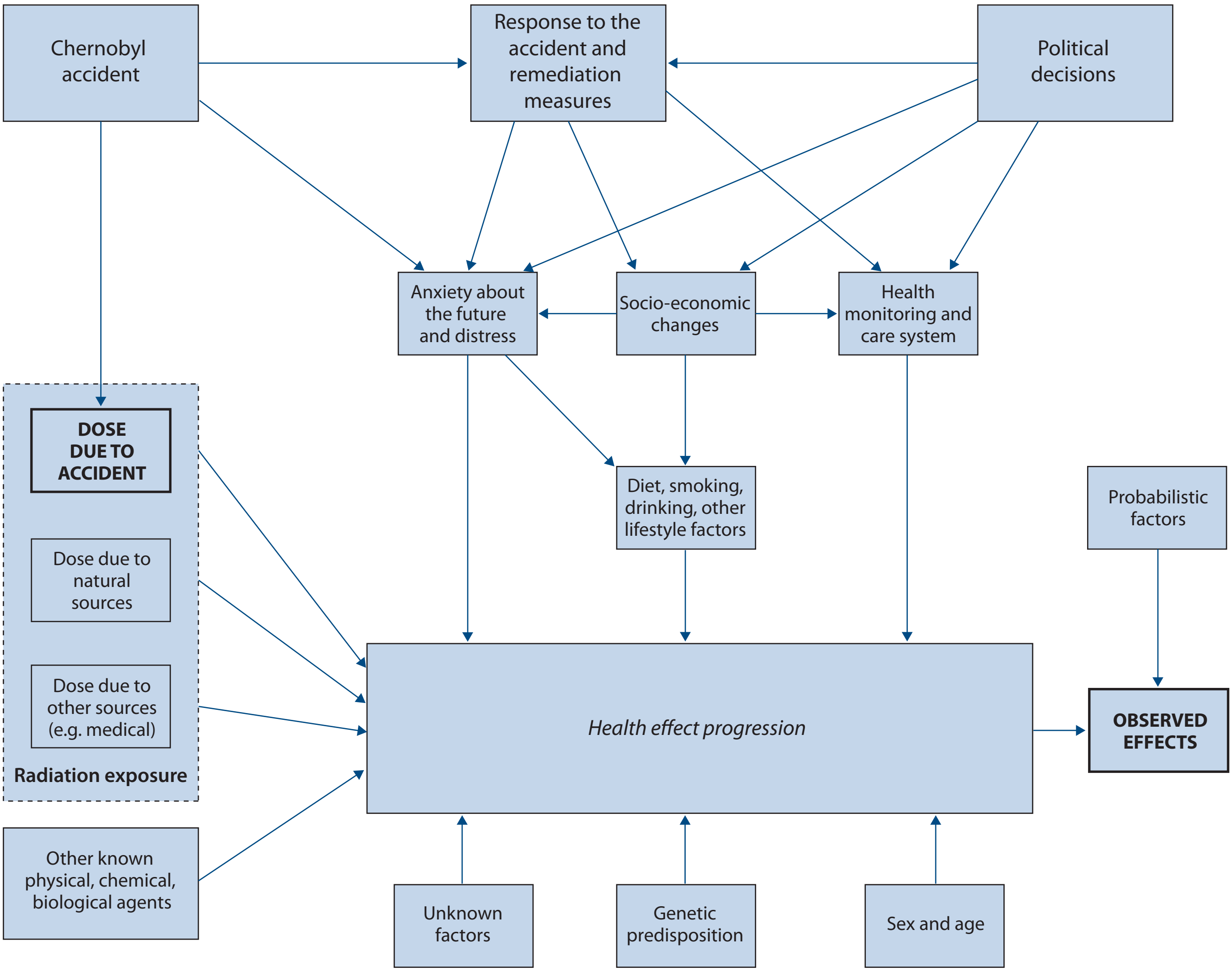
43. The factors that need to be considered for the purposes of consistency with the existing knowledge base on radiation-induced cancer include tumour type, time of onset, age of patient at exposure and radiation dose. Tumour type is important because some specific tumours are normally very rare in particular populations (e.g. thyroid cancer is normally very rare among children). Where this is the case, increases in the incidence of the tumour following radiation exposure may be much more apparent than when it is relatively common. Moreover, some tissues are more radiosensitive than others (again, for children who have particularly active thyroids, the thyroid is highly sensitive to radiation exposure).

44. Even for thyroid cancers occurring after the Chernobyl accident, the probability that radiation exposure caused the cancer may vary markedly from one individual to another. For a child who developed thyroid cancer several years after the accident and probably received a relatively high dose to the thyroid at the time, the probability that radiation exposure caused the cancer may also be relatively high. However, for an adult who developed thyroid cancer several months after the accident, the probability that radiation was the cause would be very low, because the adult thyroid appears to be very resistant to tumour induction by radiation, and the tumour occurred too soon relative to the known minimum latent period between exposure and cancer appearance.

D. Psychological trauma and other related effects

45. Deterministic and stochastic effects both have a biological basis traceable to radiation dose, i.e. to ionizing radiation depositing energy in tissue. However, the Chernobyl accident is known to have had major effects that are not related to the radiation dose. They include effects brought on by anxiety about the future and distress, and any resulting changes in diet, smoking habits, alcohol consumption and other lifestyle factors, and are essentially unrelated to any actual radiation exposure [U3]. Figure VI illustrates schematically some of the factors that might possibly influence the observation of health effects after the accident.

Figure VI. Schematic illustration of some of the factors possibly influencing the observed health effects



46. The Chernobyl Forum [W5] concluded that stress symptoms, increased levels of depression, anxiety (including post-traumatic stress symptoms), and medically unexplained physical symptoms, have been found in the exposed populations compared to control groups. Mostly, these conditions were subclinical and did not meet the criteria for classification as psychiatric disorders. Nevertheless, these subclinical symptoms had important consequences for behaviour, such as diet, smoking habits, drinking and other lifestyle factors. The Chernobyl Forum Expert Group "Health" concluded that they were unable to partition the attribution of these effects among radiation fears, issues with distrust of government, inadequate communications, the break-up of the Soviet Union, economic issues and other factors. Nevertheless, it is clear that a significant fraction of the effects is attributable to the Chernobyl accident, if not directly to radiation exposure.

47. In summary, the effects of the Chernobyl accident are many and varied. Early deterministic effects can be attributed to radiation with a high degree of certainty, while for other medical conditions, radiation almost certainly was not the cause. In between, there was a wide spectrum of conditions. It is necessary to evaluate carefully each specific condition and the surrounding circumstances before attributing a cause.

V. EARLY HEALTH EFFECTS

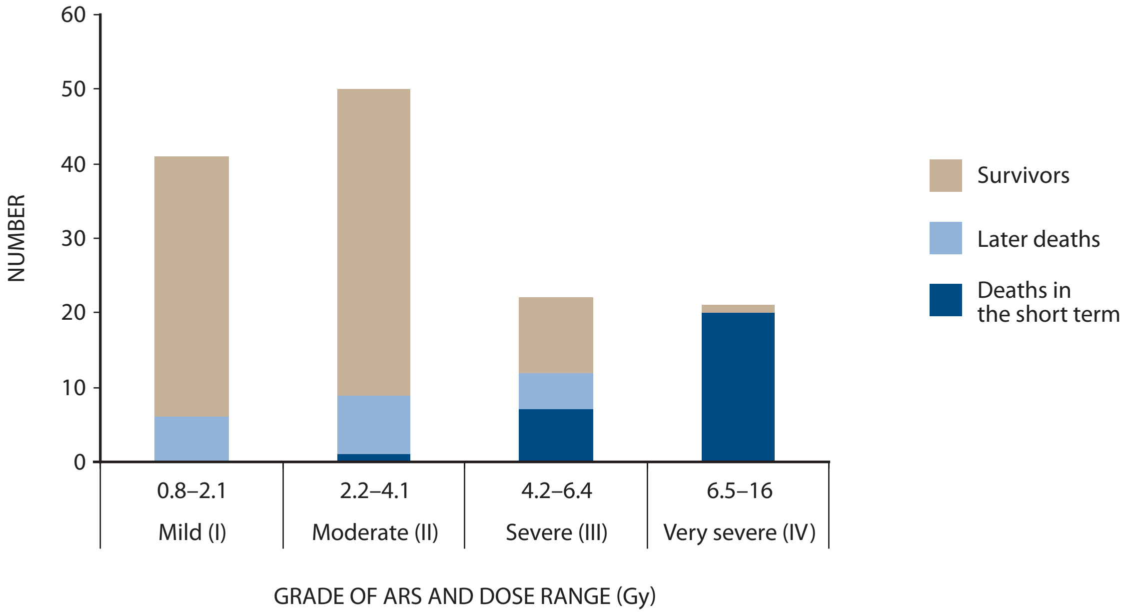
A. Acute radiation syndrome in emergency workers

48. The first information on the early severe health effects due to high acute levels of radiation exposure was presented to the international community in August 1986 [I31]. Analyses of clinical data were presented in the appendix to annex G, "Early effects in man of high doses of radiation", of the UNSCEAR 1988 Report [U7]. Updated information on the early health effects among emergency workers was provided in annex J, "Exposures and effects of the Chernobyl accident", of the UNSCEAR 2000 Report [U3]. There are no substantive new data regarding the early health effects, so only a short recapitulation is provided here (more detailed information is provided in appendix C).

49. A total of 237 emergency workers were initially examined for signs of ARS. Within several days, ARS was verified in 104 of these individuals, and in a further 30 at a later date. Of these 134 patients, 28 died within the first four months, their deaths being directly attributable to the high radiation doses (two other workers had died from injuries unrelated to radiation exposure in the immediate aftermath of the accident). Figure VII presents the outcome for the ARS patients.

Figure VII. Outcome for patients with ARS

While the figure indicates the numbers of later deaths for each category of ARS, most of the cases are not attributable to radiation exposure



50. The dominant exposures were external irradiation of the whole body at high dose rates and beta irradiation of the skin. Internal contamination was of relatively minor importance, while neutron exposure was insignificant.

51. Underlying bone marrow failure from the external whole body irradiation was the major contributor to all the deaths during the first two months. Bone-marrow transplantation was conducted on 13 patients, 12 of whom died, and 3

of whom were felt to have died partly because of inappropriate bone-marrow transplantation. Each patient with bone-marrow syndrome of grade III–IV usually also had serious radiation damage to the skin and required continuous intensive nursing by highly qualified personnel.

52. Skin doses exceeded bone marrow doses by a factor of 10–30, and many ARS patients received skin doses in the range of 400–500 Gy. Radiation damage to the skin aggravated other conditions. Radiation burns to the skin were felt to be a major contributor to at least 19 of the deaths and significantly increased the severity of the ARS, especially when skin burns exceeded 50% of the body surface area and led to major infections. After 50–60 days, if the skin was not healing, a number of patients received skin graft surgery. In addition, the leg of one patient was amputated more than 200 days after the accident, gastrointestinal syndrome was seen in 15 patients and radiation pneumonitis in 8 patients.

53. There is essentially no doubt that the initial 28 deaths and the clinical findings on the other 106 ARS patients were attributable to radiation exposure from the accident.

B. General public

54. There were no cases of ARS among the general public, either among those evacuated or those not evacuated. This is consistent with the assessment of the radiation exposures, which showed that the whole body radiation doses to members of the general public were much lower than the well-known dose thresholds for ARS.

VI. LATE HEALTH EFFECTS

A. Actual observations

55. The Committee decided in this annex to focus on the incidence of thyroid cancer, leukaemia, all solid cancers as a whole, cardiovascular mortality, cataract development and autoimmune thyroiditis. This decision was based on the potential sensitivity of these outcomes to radiation and because the Committee considered there were insufficient new data in other areas to potentially modify the conclusions of the UNSCEAR 2000 Report [U3]. A more detailed review of the various studies is provided in appendix D.

56. Even if an empirical epidemiological study provides evidence of an increased incidence of a potentially radiogenic disease, it still remains necessary to consider the issue of attributability of that effect to radiation. It is necessary to take detailed account of such possible confounding and bias factors as industrial pollution, environmental features (e.g. stable iodine levels in soil), lifestyle (e.g. smoking habits or alcohol consumption), reproductive history, improvement of diagnostic tools, and increased medical attention for affected populations.

57. Bias due both to screening and to diagnostic suspicion may operate in studies of the emergency and recovery operation workers, who are examined every year for various diseases and for whom there is consequently a greater likelihood of detection of small tumours. Trends of disease rates in groups of emergency and recovery operation workers are only scientifically informative if the same methods of detection in diagnosis are applied over the whole period of interest and are independent of the individual exposure level. Overall, interpretation of the results from studies on the populations exposed after the Chernobyl accident has to take into account the variation of detection methods with time, and the likelihood of different screening frequencies for different populations.

1. Late health effects in ARS survivors

58. The Committee in its 2000 Report [U3] summarized the observations made in the treatment of the workers who had developed ARS. Among those patients surviving ARS grades III and IV, haematopoietic recovery occurred within a matter of months. However, recovery of the immune system took at least half a year, and complete normalization several years. Cataracts, scarring and ulceration are important ongoing problems in the ARS survivors. Between 1990 and 1996, 15 ARS survivors with extensive skin injuries underwent surgery. Most ARS survivors had suffered functional sexual disorders up to 1996; however, 14 normal children were born to survivor families within the first five years of the accident.

59. Currently, only 10 patients are under clinical surveillance at the clinic of the Burnazyan Federal Medical Biophysical Center (former Russian State Research Center of the Institute of Biophysics) in Moscow, and 59 patients are being followed up by the Ukrainian Research Center of Radiation Medicine (URCRM) in Kiev. Unfortunately, it is very difficult to analyse and use the two sets of data from these clinics because they are presented in different formats, using different diagnostic criteria and time periods; furthermore, there are significant differences in the prevalence of diseases reported by the two clinics. For these reasons and also because of the small numbers of cases and the lack of analyses using formal epidemiological methods, it is generally not possible to infer trends in disease and mortality rates from these data.

60. The major health consequences from the radiation exposure of the ARS survivors remain the skin injuries and radiation-induced cataracts. The current nature and severity of the skin injuries depend on their severity during the early period. Patients who had suffered first-degree skin injuries

displayed various levels of skin degeneration, ranging from slight smoothing of the skin surface to more pronounced changes. However, over longer periods, the slight changes disappeared almost completely. With the second-degree skin injuries, degeneration was pronounced. With third- and fourth-degree injuries, there were areas of scarring, contractures, and radiation-induced ulcers. However, since the early 1990s, microsurgery techniques have significantly reduced the problems of radiation-induced ulcers.

61. Many of the patients who suffered moderate or severe ARS, developed radiation-induced cataracts in the first few years after the accident, with a strong correlation between the grade of ARS and cataract prevalence.

62. A high prevalence of nervous system diseases among the survivors had been registered during the first decade. Similarly, there have been reports of a high percentage of cardiovascular and gastrointestinal diseases. However, studies have shown no correlation with the grade of ARS, probably indicating a cause other than radiation exposure [B9, B39, B42].

63. Over the period 1987–2006, 19 ARS survivors died for various reasons [B9, B39, B41, B44, G9, U3], including seven deaths from non-cancer disease of internal organs (including two from pulmonary tuberculosis and two from cirrhosis of the liver), six from sudden cardiac arrest and five from malignancy; and, in one case, the cause of death was due to trauma (figure VII). As time progressed, the assignment of radiation as the cause of death has become less clear.

64. Among the ARS survivors under observation at the URCRM, there have been four confirmed cases of solid cancer, three cases of myelodysplastic syndrome, one case of acute myelomonoblastic leukaemia and one case of chronic myeloid leukaemia.

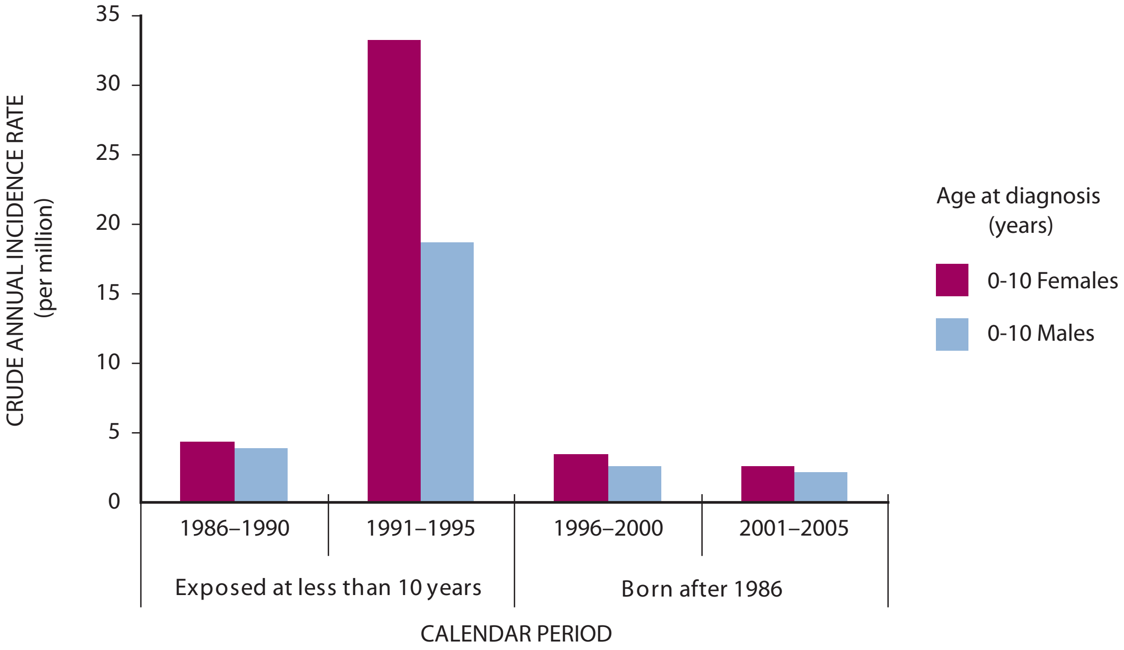
65. The follow-up of the ARS survivors indicates that: the initial haematological depression has recovered substantially in many patients; there remain significant local injuries; there has been an increase in haematological malignancies; and the increase in other diseases is probably largely due to ageing and other factors not related to radiation exposure.

2. Thyroid cancer

66. A substantial increase in thyroid cancer incidence has occurred in the three republics (the whole of Belarus and Ukraine, and the four most affected regions of the Russian Federation) since the Chernobyl accident among those exposed as children or adolescents. Amongst those under age 14 years in 1986, 5,127 cases (under age 18 years in 1986, 6,848 cases) of thyroid cancer were reported between 1991 and 2005 [I8].

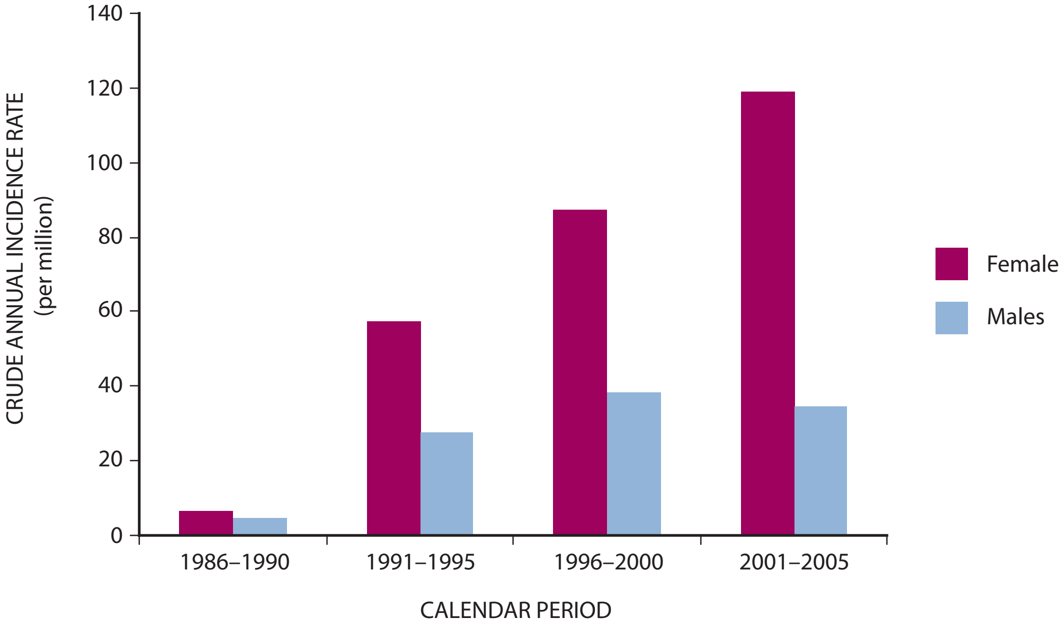
67. Figure VIII demonstrates that in Belarus, after the Chernobyl accident in 1986, thyroid cancer incidence rates among children under age 10 years increased dramatically and subsequently declined, specifically for those born after 1986 (see 1996–2005). This pattern suggests that the dramatic increase in incidence in 1991–1995 was associated with the accident. The increase was primarily among the children under age 10 years at the time of the accident [J4]. For those born after 1986, there was no evidence for an increase in the incidence of thyroid cancer. The increase in the incidence of thyroid cancer among children and adolescents began to appear about 5 years after the accident and persisted up until 2005 (see figure IX). The background rate of thyroid cancer among children under age 10 years is approximately 2 to 4 cases per million per year.

Figure VIII. Thyroid cancer incidence rate in Belarus for children under 10 years old at diagnosis



68. Figure IX shows the increase in thyroid cancer incidence rates with time among those exposed as children and adolescents in Belarus. There is no evidence for a decrease in the excess incidence of thyroid cancer up to 2005. Part of the increase is related to the normal age pattern of disease occurrence but the majority of the increase is attributed to the prior radiation exposure.

Figure IX. Thyroid cancer incidence rate among those exposed as children and adolescents (age under 18 years in 1986) in Belarus



69. This increase has been confirmed in several case-control and cohort studies that have related the excess incidence of thyroid cancer to the estimated individual doses due primarily to the radioiodine released during the accident. The estimates of radiation risk from these studies remain somewhat uncertain, however, and may have been influenced by variations in the use of ultrasonography and mass screening after the accident.

70. There is little suggestion of increased thyroid cancer incidence among those exposed as adults in the general population.

71. Among the recovery operation workers, elevated rates of thyroid cancer compared to the general population have been reported, but no clear association with external dose has been found. In addition, there are no current estimates of thyroid doses from inhaled radioiodine to those who worked on the Chernobyl site in April–June 1986. The influence of annual screenings and active follow-up of these cohorts make comparisons with the general population problematic.

72. Among the various radioactive isotopes of iodine released during the accident, ^{131}I is considered to be the most significant contributor to dose to the thyroid gland. The shorter-lived radioactive isotopes of iodine may also have contributed to the increased incidence of thyroid cancer. However, epidemiological studies to date have not been able to evaluate this possibility meaningfully.

73. Evidence has also emerged since the UNSCEAR 2000 Report [U3] indicating that iodine deficiency might have influenced the risk of thyroid cancer resulting from exposure to the radioactive isotopes of iodine released during the accident [C8, S6].

3. Leukaemia

74. The interest in leukaemia arises because of its known sensitivity to induction by ionizing radiation and also because of the short latent period expected between exposure and appearance of the condition. Amongst adults, the most promising studies are of the recovery operations workers. Although not conclusive, recent reports suggest an increase in the incidence of leukaemia among the recovery operation workers from Belarus, the Russian Federation, Ukraine and the Baltic Countries. The limitations of these studies include low statistical power, uncertainties in dose reconstruction, and internal inconsistencies that suggest potential biases or confounding factors that are difficult to address. Future studies may resolve these issues, although after about 5–15 years post exposure, the risk of radiation-induced leukaemia declines over time and most newly diagnosed leukaemia cases will be unlikely to have been due to radiation.

75. Among those exposed in utero and as children, no persuasive evidence has been found of a measurable increase in

the incidence of leukaemia attributable to radiation exposure. This is not unreasonable given that the doses involved were generally small, comparable with natural background doses, and therefore epidemiological studies lack the statistical power to confirm any radiation-related increases had they occurred.

76. Amongst adults, the most meaningful evidence comes from studies of the recovery operations workers. Although at this time, some evidence exists of an increase in the incidence of leukaemia among a group of recovery operation workers from the Russian Federation, this is far from conclusive. As yet, it would be premature to elevate the findings of these studies to the status of those, for example, from the survivors of the atomic bombings. Nevertheless, future results from such studies ought to provide important scientific information.

4. Other solid cancers

77. There appears, at present, to be no hard evidence of any measurable increased incidence of all solid cancers taken together among the populations of the Russian Federation and Ukraine. That conclusion takes account of the results from a few studies of breast cancer in women exposed as a result of the Chernobyl accident. The weaknesses of the studies of the incidence of breast cancer are numerous; in particular, they do not take into account some major confounding factors, such as the age at first pregnancy, other hormonal factors and nutrition. There appears to be no pattern of increased incidence of breast cancer among the inhabitants of the contaminated areas compared to that among those of the uncontaminated areas, and no difference in time trends in areas with different levels of radioactive deposition.

78. The evidence with respect to solid cancer incidence among the recovery operation workers is mixed. Although some groups show elevated incidence, significant relationships with increasing dose have not been quantified. In contrast, two Russian studies reported correlations between the solid cancer mortality rate and dose.

79. Some caution needs to be exercised in interpreting the results from these studies. First, for many cancers, a latent period of 10 years or more is expected, so if this applies to the incidence of all cancers taken together, one would not expect to see any effect manifest itself until the mid to late 1990s. Second, interpretation of comparisons of the results for the recovery operation workers with those for the general population is difficult owing to the regular annual medical examination offered to all recovery operation workers. Third, the risk values derived from some of the studies are substantially higher than those determined from other epidemiological studies that are reviewed in annex A [U1] and, therefore, need further analysis.

80. Assessments of statistical power, based on the follow-up to date and using findings from the study of the survivors of the atomic bombings, would suggest that the doses are too low—they are comparable with natural background radiation levels—to yield sufficient statistical power to detect any measurable increase in the incidence or mortality of all solid cancers combined in the populations exposed to radioactive material that was deposited after the Chernobyl accident.

5. Non-cancer effects

(a) Cataracts

81. Clinically significant cataracts developed in some of the ARS survivors exposed to high radiation doses. Several new studies have suggested that lens opacity may form after doses of less than 1 Gy. Although most of these refer to pre-clinical lesions, a recent study of the survivors of the atomic bombings suggests that there may be an increased incidence of clinical cataracts at these dose levels [N17].

82. The Ukrainian-American Chernobyl Ocular Study [C17, W7] indicates that lens opacity arising in the recovery operation workers, corrected for the most important confounding factors, is related to the dose received. For the most part, the doses were less than 0.5 Gy of low-LET radiation acquired in a somewhat protracted/fractionated manner. A key finding was that the data were not compatible with a dose–effect threshold of more than 0.7 Gy, and that the lower boundary of the estimated dose threshold was close to the current dose limit for the lens of the eye, i.e. 150 mSv, although this needs to be tempered by consideration of the uncertainties in the dosimetry.

83. While a specific type of cataract (i.e. posterior subcapsular cataract, PSC) is characteristic of radiation exposure, several sets of data suggest that broader categories (i.e. posterior cortical cataracts) may also be regarded as radiation-associated. PSC can also be caused by: drugs, systemic disorders, certain inflammatory or degenerative eye diseases and eye trauma. However, the studies of those exposed as a result of the Chernobyl accident [D3, W7] have largely addressed this issue of alternate causes by statistically evaluating and adjusting for various other risk factors.

84. A critical analysis of all existing information on radiation-induced cataracts, which, in particular, compares the new data with existing knowledge, is necessary in order to obtain a better understanding of any inconsistencies. Follow-up of the major cohorts is necessary in order to better evaluate latency and cataract progression, and to better characterize the risk to the lens of the eye from exposure to low-to-moderate radiation doses.

(b) Cardiovascular and cerebrovascular diseases

85. It has long been known that irradiation of the heart at the very high doses used in radiotherapy leads to increased risks of circulatory disease. However, little solid evidence

exists of any demonstrable effect of the lower radiation exposures due to the Chernobyl accident on cardiovascular and cerebrovascular disease incidence and mortality. One study of the recovery operation workers in the Russian Federation has provided evidence of a statistically significant association between radiation dose and both cardiovascular disease mortality rates and cerebrovascular disease incidence. The observed excess of cerebrovascular disease is linked to those having worked during less than six weeks and having cumulated doses of more than 150 mSv. However, the study was not adjusted for other factors, such as obesity, smoking habits and alcohol consumption. More evidence is needed to conclude whether or not radiation exposure due to the Chernobyl accident has increased the incidence of cardiovascular and cerebrovascular disease and associated mortality.

(c) Autoimmune thyroiditis

86. Autoimmune thyroiditis is a progressive disease of the thyroid gland characterized by the presence of antibodies directed against the thyroid. It almost certainly involves an interaction between genetic predisposition and environmental factors, such as the level of dietary iodine intake [D7]. However, its association with radiation exposure is controversial [E3]. In addition, the underlying incidence of autoimmune thyroiditis increases with age [D8]. Therefore, dissecting out the effect of radiation exposure due to the Chernobyl accident from the other elements that may or may not have a bearing on the incidence of autoimmune thyroid disease in the population requires extremely careful study.

87. There have been few studies of significant size that have addressed the relationship between autoimmune thyroiditis and exposure to radiation from the Chernobyl accident. The largest study [T7] could not demonstrate any conclusive evidence of a relationship between thyroid dose and autoimmune thyroid disease. This is consistent with the findings from studies on other exposed populations [D9, I27, N11].

B. Theoretical projections

88. In order to guide decision-making on public health resource management, and given that there is a latent period between exposure and the appearance of any increased incidence in stochastic effects, various groups have attempted to predict the health impact on populations exposed to radiation by applying radiation risk models to the estimates of population dose. These models are based partially on epidemiological data and partially on an understanding of biological processes [U3, U7, U17].

89. The major source of data for modelling increased incidence of stochastic effects due to radiation exposure remains the detailed study of long-term health effects among the survivors of the atomic bombings in Japan [P3]. However, applying those data to the populations exposed as a result of the Chernobyl accident requires various assumptions to be made. These include how to transfer the risk profile between populations with different demography, ethnic origins and background disease rates, and how to transfer the results from a population acutely exposed to high doses and dose rates to one that essentially received increased protracted radiation doses at levels comparable to natural background over several years and for which no increased incidence has actually been observed. Analysts have to make other assumptions regarding the future level of contributing factors (such as smoking), future levels of medical care and efficacy of treatment, and the average lifespan in future decades, among others.

1. Review of published projections

90. The first prognoses of the health consequences of the Chernobyl accident conducted in 1987 yielded four important conclusions for policymakers on the scale and nature of the effects [B47, I43, R4]:

- There would be no deterministic radiation effects among the general public;
- The increased incidence of cancers due to radiation exposure would not be significant from the point of view of organizing health care, although some effects on some population groups at specific periods of time might be detected using epidemiological methods;
- A considerable increase in the incidence of thyroid cancer due to radiation exposure should be expected, particularly among those exposed as children; and
- Psychological trauma caused by the accident would affect millions of people.

91. Subsequently, a large number of radiation risk projections have been made by various groups regarding the health consequences of the Chernobyl accident [A11, C1, C11, I43, T4, W5]; see appendix D for details. They predicted a potential increase in cancer mortality due to radiation-induced cancer in the range from 3% for the most affected parts of the former Soviet Union to 0.01% for the rest of Europe. All the projections were based on estimates of population doses made at the time; they usually assumed the linear non-threshold (LNT) model for the dependence of increased cancer incidence or mortality following an increase in dose, and used nominal parameters derived from reports of UNSCEAR [U9] and of the ICRP [I44, I45] and/or from some national publications, e.g. [N4]. As new dosimetric and epidemiological data became available, some groups updated their dose estimates, risk models and associated projections.

92. Although there is reasonable agreement between the projections subsequently made, it is very unlikely that monitoring national cancer statistics would be able to identify any

increase in cancer incidence due to radiation exposure. However, for particular population groups at specific periods of time after the accident, it was felt that some effects due to radiation exposure could be detected using scientific methods (e.g. an increased incidence of leukaemia among the recovery operation workers and of thyroid cancer in people who were children in 1986).

2. Scientific limitations

93. The interpretation and communication of radiation risk projections is fraught with difficulties, because it is not easy to communicate their intrinsic limitations adequately.

94. As discussed previously in the section on the attribution of effects to radiation exposure, because presently there are no biomarkers specific to radiation, it is not possible to state scientifically that radiation caused a particular cancer in an individual. This means that in terms of specific individuals, it is impossible to determine whether their cancers are due to the effects of radiation or to other causes or, moreover, whether they are due to the accident or background radiation. The situation with the ARS survivors of the accident is fundamentally different since each of them is known by name and ARS was diagnosed and attribution to radiation exposure was based on conclusive medical findings. However, projected numbers of stochastic effects in anonymous individuals could be misunderstood to be of a similar nature to actual identified cases.

95. An additional misunderstanding occurs regarding the nature of the evidence for stochastic effects from studies of exposed populations. For example, there is reasonable evidence that acute radiation exposure of a large population with doses above 0.1 Sv increases cancer incidence and mortality. So far, neither the most informative study of the survivors of the atomic bombings nor any other studies of adults have provided conclusive evidence for increased incidence of carcinogenic effects at much smaller doses [U3, annex A of U1].

96. Because of the absence of proper experimental evidence, the dependence of the frequency of adverse radiation effects on dose can be assessed only by means of biophysical models, among which, the LNT model has been used widely for radiation protection purposes [B48, U3]. However, others have been suggested, including superlinear and threshold ones, and even models assuming hormesis. It is important to understand the considerable statistical uncertainty associated with any projection based on modelling, which lends itself rather to estimations that are within an order of magnitude or even more.

97. The currently available epidemiological data do not provide any basis for assuming radiogenic morbidity and mortality with reasonable certainty in cohorts of the residents of the areas of the three republics and other countries in Europe who received total average doses of below 30 mSv over 20 years [A11, C1, C11, R4, T4]. Any increases would be below the limit of detection. At the same time, it cannot be ruled out that adequate data on the effects of low-dose human exposure will be obtained as further progress is made in understanding the radiobiology of man and other mammals, and using this knowledge to analyse the epidemiological data. This may provide in the future the scientific basis for evaluating the radiation health consequences of the Chernobyl accident among residents of areas with low radiation levels.

3. UNSCEAR statement

98. The Committee has decided not to use models to project absolute numbers of effects in populations exposed to low radiation doses from the Chernobyl accident, because of unacceptable uncertainties in the predictions. It should be stressed that the approach outlined in no way contradicts the application of the LNT model for the purposes of radiation protection, where a cautious approach is conventionally and consciously applied [F11, I37].

VII. GENERAL CONCLUSIONS

A. Health risks attributable to radiation

99. The observed health effects currently attributable to radiation exposure are as follows:

- 134 plant staff and emergency workers received high doses of radiation that resulted in acute radiation syndrome (ARS), many of whom also incurred skin injuries due to beta irradiation;
- The high radiation doses proved fatal for 28 of these people;
- While 19 ARS survivors have died up to 2006, their deaths have been for various reasons, and usually not associated with radiation exposure;
- Skin injuries and radiation-induced cataracts are major impacts for the ARS survivors;
- Other than this group of emergency workers, several hundred thousand people were involved in recovery operations, but to date, apart from indications of an increase in the incidence of leukaemia and cataracts among those who received higher doses, there is no evidence of health effects that can be attributed to radiation exposure;
- The contamination of milk with ^{131}I, for which prompt countermeasures were lacking, resulted in large doses to the thyroids of members of the general public; this led to a substantial fraction of the more

than 6,000 thyroid cancers observed to date among people who were children or adolescents at the time of the accident (by 2005, 15 cases had proved fatal);

– To date, there has been no persuasive evidence of any other health effect in the general population that can be attributed to radiation exposure.

100. From this annex based on 20 years of studies and from the previous UNSCEAR reports [U3, U7], it can be concluded that although those exposed to radioiodine as children or adolescents and the emergency and recovery operation workers who received high doses are at increased risk of radiation-induced effects, the vast majority of the population need not live in fear of serious health consequences from the Chernobyl accident. (This conclusion is consistent with that of the UNSCEAR 2000 Report [U3]). Most of the workers and members of the public were exposed to low level radiation comparable to or, at most, a few times higher than the annual natural background levels, and exposures will continue to decrease as the deposited radionuclides decay or are further dispersed in the environment. This is true for populations of the three countries most affected by the Chernobyl accident, Belarus, the Russian Federation and Ukraine, and all the more so, for populations of other European countries. Lives have been disrupted by the Chernobyl accident, but from the radiological point of view, generally positive prospects for the future health of most individuals involved should prevail.

B. Comparison of present annex with previous reports

101. This annex reviews the scientific information obtained since the UNSCEAR 2000 Report [U3] on the exposures and effects due to radiation from the Chernobyl accident. Although many more research data are now available, the major conclusions regarding the scale and nature of the health consequences are essentially consistent with the previous UNSCEAR reports [U3, U7].

102. The radioactive release has been re-evaluated, but the changes are academic and not relevant to the assessment of radiation dose, which is based on direct human and environmental measurements.

103. Dose estimates have been extended for an additional number of about 150,000 emergency and recovery operation workers. Based on direct human and environmental measurements made since 1988 and models that take into account the actual countermeasures, the estimates of the thyroid dose to the evacuees have been updated. The estimated thyroid and effective doses to the inhabitants of Belarus, the Russian Federation and Ukraine have been expanded from five million to about one hundred million people and the estimated thyroid and effective doses to about 500 million inhabitants of most other European countries have been updated.

104. With regard to the follow-up of the ARS survivors, there is significant new information in this annex. By 1998, 11 ARS survivors had died [U3]; since then another 8 have died up to 2006. The annex discusses the causes of death in the context of their radiation exposure.

105. For the larger number of emergency and recovery operation workers, there are indications of an increased incidence of leukaemia and cataracts among those who received higher doses, although further clarification of the epidemiological information is still needed. The information on cataracts indicates that the threshold for induction may be lower than previously thought. While there have been indications of an increase in the incidence of cardiovascular and cerebrovascular diseases among the recovery operation workers that correlate with the estimated doses, major concerns over the possible influence of confounding factors and potential study biases remain.

106. In the UNSCEAR 2000 Report [U3], fewer than 1,800 thyroid cancers had become evident among those aged under 18 at the time of the accident; this had increased to more than 6,000 by the year 2006. Several studies have now been conducted that provide rather consistent estimates of the radiation risk factors for thyroid cancer.

C. Comparison of observed late health effects with projections

107. Early assessments [B47, I43, R4] conducted in 1987 projected a considerable increase in thyroid cancer incidence due to radiation exposure in the three republics, particularly among children. To date, some 6,000 thyroid cancers have been seen among those in the three republics who were under 18 at the time of the accident, of which a substantial fraction is likely to have been due to radiation exposure.

108. Projections [C1] made in 1996 using dosimetric information on the emergency and recovery operation workers had indicated that there might be a detectable increase in the incidence of leukaemia among those who had received relatively high doses of radiation. There has been some evidence of a detectable increase among a group of Russian workers, although at present, it is far from conclusive.

109. Several groups [A11, B47, C1, C11, F10, I43, R4] have projected possible increases in solid cancer incidence for the general population. These assessments differ in the exact populations considered and the dosimetry and projection models used. However, for all the populations considered, the doses are relatively small, comparable with those from natural background radiation, and any increase was unlikely to be detected by epidemiological studies. Although it is now one decade after the minimum latent period for solid cancers, no increases in cancer incidence (other than of thyroid cancer) have been observed to date that can be attributed to irradiation from the accident.

110. The use of theoretical projections is fraught with difficulty. It is extremely difficult to communicate such

projections accurately and honestly to officials and the general public. Moreover, there is a limit to the epidemiological knowledge that can be used to attribute conclusively an increased incidence to radiation exposure. Therefore, any radiation risk projections in the low dose area should be considered as extremely uncertain, especially when the projection of numbers of cancer deaths is based on trivial individual exposures to large populations experienced over many years.

D. New knowledge from studies of the accident

111. Although there is general consensus on the scale and character of the health consequences due to radiation from the accident, studies of the world's worst nuclear accident have clearly produced a vast amount of useful scientific information. Most of this can be used to validate predictive capabilities and knowledge developed from research and experience before the accident. Other information is completely new and is helping to fill gaps in the current scientific knowledge base.

112. The accident has provided clear evidence that confirms pre-existing knowledge of the importance of ^{131}I in the pasture–cow–milk pathway, of the need to take prompt countermeasures, of the potential high doses to the thyroids, and of the anticipated increase in thyroid cancer incidence, particularly among those exposed during childhood or adolescence. Ongoing research is helping to refine this knowledge, particularly with respect to the patterns of thyroid cancer incidence for different doses, pathways, age groups, and levels of dietary iodine.

113. Similarly, for protracted irradiation due to the longer-lived radionuclides, the pre-existing understanding of the important pathways of exposure to humans has been validated by the experience obtained from the accident. Moreover, there has been a greater recognition of the importance of soil type in determining the transfer of radiocaesium to foodstuffs, a greater understanding of the radioecology in urban, semi-natural and forest environments, and considerable experience in the implementation of a whole range of countermeasures.

114. With regard to health effects, there have been dramatic improvements in the understanding of acute radiation effects and their treatment, and of the long-term sequelae of local radiation injuries due to irradiation of the skin and lens of the eye. With respect to the incidence of stochastic effects other than thyroid cancer, so far there have been few observations that have challenged pre-existing understanding derived from the studies of other exposed groups, such as the survivors of the atomic bombings in Japan and other studies of radiation exposed populations.

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APPENDIX A. PHYSICAL AND ENVIRONMENTAL CONTEXT

I. SUMMARY FROM THE UNSCEAR 2000 REPORT [U3]

A1. The accident on 26 April 1986 at the Chernobyl Nuclear Power Plant (ChNPP) occurred during a low-power engineering test of the Unit 4 reactor. Safety systems had been switched off and improper, unstable operation of the reactor allowed an uncontrollable power surge to occur that resulted in successive steam explosions; these steam explosions severely damaged the reactor building and completely destroyed the reactor.

A2. The radionuclide releases from the destroyed reactor occurred mainly over a 10-day period, but with varying release rates. An initial high release rate on the first day was caused by mechanical discharge as a result of the explosions in the reactor. There followed a 5-day period of declining releases associated with the hot air and fumes from the red-hot core material. During the next few days, the release rate of radionuclides increased until day 10, when the releases dropped abruptly, thus ending the period of intense release. The radionuclides released in the accident were deposited with greater density in the regions surrounding the reactor in the European part of the former Soviet Union.

A3. Two basic methods were used to estimate the release of radionuclides in the accident. The first method consisted in evaluating separately the inventory of radionuclides in the reactor core at the time of the accident and the fraction of the inventory of each radionuclide that was released into the atmosphere; the products of those two quantities are the amounts released. The second method consisted in measuring the density of radionuclide deposition on the ground all around the reactor; if it is assumed that all of the released amounts were deposited within the area where the measurements were made, the amounts deposited would be equal to the amounts released. In both methods, air samples taken above the reactor or at various distances from the reactor were analysed for radionuclide content to determine or to confirm the radionuclide distribution in the materials released. The analysis of air samples and of deposited material also led to information on the physical and chemical properties of the radioactive material that was released into the atmosphere.

A4. From the radiological point of view, ^{131}I and ^{137}Cs were the more important radionuclides released because they were responsible for most of the radiation dose incurred by the members of the general population. The releases of ^{131}I and ^{137}Cs were estimated to have been ~1,760 and ~85 PBq, respectively (1 PBq = 10^{15} Bq). It is worth noting, however, that doses in the following sections of this appendix are estimated on the basis of measurements of radionuclides in humans, foodstuffs and other environmental media, and of external gamma exposure rates. Thus, knowledge of the quantities of radionuclides released was not needed for the purpose of assessing doses.

A5. The deposited material consisted of hot particles in addition to more homogeneously distributed radioactive material. These hot particles have been classified into two broad categories: *(a)* fuel fragments with a mixture of fission products bound to a matrix of uranium oxide, similar in composition to that of the fuel in the core, but sometimes very much depleted in caesium, iodine and ruthenium, and *(b)* particles consisting of one dominant element (ruthenium or barium) but sometimes having traces of other elements. These monoelemental particles might have originated from embedments of these elements produced in the fuel during reactor operation and released during the fragmentation of the fuel. Typical activities were 0.1–1 kBq for a fuel fragment hot particle and 0.5–10 kBq for a ruthenium hot particle; a typical effective diameter was about 10 µm, to be compared with 0.4–0.7 µm for particles associated with ^{131}I and ^{137}Cs. Hot particles deposited in the pulmonary region have a long retention time and this can lead to considerable localized doses. Although it had been demonstrated in the 1970s that alpha-emitting hot particles are no more radiotoxic than the same activity uniformly distributed in the whole lung, it was not clear whether the same conclusion could be reached for beta-emitting hot particles.

A6. Radioactive deposition on the ground was found to some extent in practically every country of the northern hemisphere [U9]. In annex J, “Exposures and effects of the Chernobyl accident”, of the UNSCEAR 2000 Report [U3], “contaminated areas” were defined as areas where the average deposition density of ^{137}Cs exceeded 37 kBq/m^2 (1 Ci/km^2). Caesium-137 was chosen as a reference radionuclide for the ground contamination resulting from the Chernobyl accident for several reasons: its substantial contribution to the lifetime effective dose; its long radioactive half-life; and its ease of measurement. The areas deemed contaminated were found mainly in Belarus, the Russian Federation and Ukraine.

A7. The main radionuclide releases lasted 10 days, during which time, the wind often changed direction with the result that material was deposited in all areas surrounding the reactor site at one time or another. Details of the development of the plume over time had been given by Borzilov and Klepikova [B24] and are reproduced in figure A-I. The initial plumes of material moved towards the west. On 27 April, the winds shifted towards the northwest, then on 28 April, towards the east. Two extensive areas, Gomel–Mogilev–Bryansk and Orel–Tula–Kaluga, became contaminated as a result of the deposition of radioactive material from the plume that passed over at that time (figure A-I, trace 3). The deposition onto Ukrainian territory south of Chernobyl occurred after 28 April (figure A-I, traces 4, 5 and 6). Rainfall occurred in an inhomogeneous pattern, and this caused uneven areas of radionuclide deposition. The general pattern of ^{137}Cs deposition calculated based on simulations of the meteorological conditions had been shown to match the measured deposition pattern rather well.

A8. The principal physicochemical forms of the deposited radionuclides were: *(a)* dispersed fuel particles; *(b)* condensation-generated particles; and *(c)* mixed-type particles, including ones generated by adsorption. The radionuclide distribution in the nearby contaminated zone (less than 100 km from the damaged reactor), also called the "near zone", differed from that in the "far zone" (from 100 km to approximately 2,000 km). Deposition in the near zone reflected the radionuclide composition of the fuel. Larger particles, which were primarily fuel particles, and the refractory elements (zirconium, molybdenum, cerium and neptunium) were to a large extent deposited in the near zone. Elements with intermediate volatility (ruthenium, barium and strontium) and fuel elements (plutonium and uranium) were also deposited largely in the near zone. The volatile elements (iodine, tellurium and caesium), in the form of condensation-generated particles, were more widely dispersed into the far zone.

A9. The three main areas of radionuclide deposition were designated the Central, Gomel–Mogilev–Bryansk and Kaluga–Tula–Orel areas. The Central area is in the near zone, predominantly to the west and northwest of the reactor. Caesium-137 was deposited during the active period of release, and the deposition density of ^{137}Cs was greater than 37 kBq/m^2 (1 Ci/km^2) in large areas of Ukraine and in the southern parts of the Gomel and Brest oblasts of Belarus. The ^{137}Cs deposition was highest within the 30-km-radius area surrounding the reactor, known as the "30-km zone". Deposition densities exceeded 1,500 kBq/m^2 (40 Ci/km^2) in this zone and also in some areas of the near zone to the west and northwest of the reactor, in the Gomel, Kiev and Zhitomir oblasts.

A10. The Gomel–Mogilev–Bryansk area is centred 200 km to the north-northeast of the reactor at the boundary of the Gomel and Mogilev oblasts of Belarus and of the Bryansk oblast of the Russian Federation. In some areas, deposition was comparable to that in the Central area; deposition densities even reached 5 MBq/m^2 in some villages of the Mogilev and Bryansk oblasts.

A11. The Kaluga–Tula–Orel area is located 500 km to the northeast of the reactor. Radionuclide deposition here was a result of rainfall on 28–29 April during the passage of the same radioactive cloud that had deposited radionuclides in the Gomel–Mogilev–Bryansk area. The ^{137}Cs-deposition density was, however, lower in this area, generally less than 500 kBq/m^2.

A12. Outside these three main affected areas, there were many areas where the ^{137}Cs-deposition density was in the range of 37–200 kBq/m^2. Rather detailed surveys of the radionuclide deposition on the entire European part of the former Soviet Union had been completed. A map of measured ^{137}Cs deposition is presented in figure A-II. The total quantity of ^{137}Cs deposited in the former Soviet Union as a result of the accident, including in areas of lesser deposition, was estimated to be approximately 40 PBq. The total was apportioned as follows: 40% in Belarus; 35% in the Russian Federation; 24% in Ukraine; and less than 1% in other republics of the former Soviet Union. The amount of ^{137}Cs deposited in the contaminated areas (>37 kBq/m^2) of the former Soviet Union was estimated to be 29 PBq (for comparison, the residual activity resulting from atmospheric nuclear weapons testing was about 0.5 PBq with average soil-deposition density of about 2 kBq/m^2).

A13. The environmental behaviour of the deposited radionuclides depended on the physical and chemical characteristics of the radionuclide considered, on the type of deposition (i.e. dry or wet), and on the characteristics of the environment. Special attention was devoted to ^{131}I, ^{137}Cs and ^{90}Sr and their pathways of exposure of humans. Deposition occurred on the ground and on water surfaces.

A14. For most short-lived radionuclides such as ^{131}I, the main pathway of exposure of humans was the ingestion of milk, which was contaminated as a consequence of ^{131}I deposited on pasture grass grazed by cows or goats, or of contaminated leafy vegetables that were consumed within a few days. The amounts deposited on vegetation were retained with an ecological half-time of about two weeks before removal to the ground surface and to the soil.

A15. Radionuclides deposited on soil migrate downward into the soil column and are partially absorbed by plant roots, leading in turn to upward migration into vegetation. These processes did not need to be considered for short-lived radionuclides, such as ^{131}I (which has a physical half-life of only eight days); however, they needed to be considered for long-lived radionuclides, such as ^{137}Cs and ^{90}Sr. The rate and direction of radionuclide migration through the soil–plant pathway were determined by a number of natural phenomena, including relief features, the type of plant, the structure and composition of soil, and hydrological conditions and weather patterns, particularly at the time that deposition occurred. The vertical migration of ^{137}Cs and ^{90}Sr in soil of different types of natural meadows was rather slow, and the greater fraction of radionuclides was still contained in its upper layer (0–10 cm). On average, in the case of mineral soils, up to 90% of ^{137}Cs and ^{90}Sr was found in the 0–5 cm layer; in the case of peaty soils, in which radionuclide migration is faster, only 40–70% of ^{137}Cs and ^{90}Sr was found in that layer. The effective half-time of clearance from the root layer (0–10 cm) in meadows with mineral soils was estimated to range from 10 to 25 years for ^{137}Cs and to be 1.2–3 times faster for ^{90}Sr than for ^{137}Cs; therefore, the effective clearance half-time for ^{90}Sr was estimated to be 7–12 years.

A16. For a given initial deposition on soil, the transfer from soil to plant varies with time as the radionuclide is removed from the root layer and as its availability in exchangeable form decreases. The ^{137}Cs content in plants was at its maximum level in 1986, when the amount was due to direct deposition on aerial surfaces. In 1987, ^{137}Cs activities in plants were much lower than in 1986, as the amounts in plants were then mainly due to root uptake. Since 1987, the transfer coefficients from deposition to plants continued to decrease, although the rate of decrease slowed: from 1987 to 1995, the transfer coefficients of ^{137}Cs decreased by 1.5–7 times, on average. Compared with the ^{137}Cs deposited as fallout from nuclear weapons tests, ^{137}Cs resulting from the Chernobyl accident in the far zone was found to be more mobile during the first four years after the accident, as the water-soluble fractions of ^{137}Cs resulting from the Chernobyl accident and from weapons testing fallout were about 70% and 8%, respectively. Later on, ageing processes led to similar mobility values for ^{137}Cs resulting from the Chernobyl accident and from fallout from the testing of nuclear weapons.

A17. In contrast to ^{137}Cs, it seemed that the exchangeability of ^{90}Sr did not keep decreasing with time after the accident but might in fact have been increasing. In the Russian Federation, no statistically significant change had been found in the ^{90}Sr transfer coefficient from deposition to grass during the first 4–5 years following the accident. This was attributed to two competing processes: *(a)* conversion of ^{90}Sr from a poorly soluble form, which characterized the fuel particles, to a soluble form easily assimilated by plant roots; and *(b)* the vertical migration of ^{90}Sr into deeper layers of soil, which hindered its assimilation by vegetation.

A18. Milk, meat and potatoes usually accounted for the bulk of the dietary intake of ^{137}Cs. However, for residents of rural regions, mushrooms and berries from forests represented an important dietary component. The decrease with time of the ^{137}Cs concentrations in those foodstuffs was extremely slow, with variations from one year to another depending on weather conditions.

A19. Radioactive material had also been deposited onto water surfaces. Deposition on the surfaces of seas and oceans resulted in low doses because the radioactive material had been rapidly diluted in extremely large volumes of water.

A20. In rivers and small lakes, the levels of radionuclides resulted mainly from erosion of the surface layers of soil in the watershed, followed by run-off into the water bodies. In the 30-km zone, where relatively high levels of ^{90}Sr and ^{137}Cs had been deposited, the most important contaminant of surface water was found to be ^{90}Sr, as ^{137}Cs was strongly adsorbed by clay minerals in the soil. Much of the ^{90}Sr in water had been found to be in a soluble form; low levels of plutonium isotopes and of ^{241}Am had also been measured in the rivers of the 30-km zone.

A21. The contribution of aquatic pathways to the dietary intake of ^{137}Cs and ^{90}Sr was usually quite small. However, the ^{137}Cs concentration in the muscle of predator fish, such as perch or pike, might have been quite high in lakes with long water-retention times, as had been found in Scandinavia and in Russia. For example, the concentration of ^{137}Cs in the water of Lakes Kozhany and Svyatoe (located in the area of the Bryansk oblast of the Russian Federation deemed contaminated) was still high in 1996 because of special hydrological conditions: 10–20 Bq/L of ^{137}Cs and 0.6–1.5 Bq/L of ^{90}Sr. The concentration of ^{137}Cs in the muscles of the silver crucian (*Carassius auratus gibelio*) sampled in Lake Kozhany was in the range of 5–15 kBq/kg and of pike (*Esox lucius*) in the range 20–90 kBq/kg. In the summer of 1986, whole-body counters were used to measure the activity of ^{137}Cs in inhabitants of the village of Kozhany located along the coast of Lake Kozhany. The mean body content was 7.4 ± 1.2 kBq for 38 adults who did not consume lake fish (according to interviews performed before the measurements), but was 49 ± 8 kBq for 30 people who often consumed lake fish. The average annual internal doses were estimated to be 0.3 mSv and 1.8 mSv to persons in these two groups, respectively. In addition, the relative importance of the aquatic pathways, in comparison to terrestrial pathways, might have been high in areas downstream of the reactor site where ground deposition had been small.

II. UPDATE

A22. The Chernobyl Forum issued a report in 2006 [I21] on the environmental consequences of the accident, including the assessment of individual and collective doses to members of the general public. The report was prepared by a group of 35 scientists, collectively referred to as the “Expert Group Environment”. These experts were from the three most affected countries—Belarus, the Russian Federation and Ukraine—and also from the international community of scientists who had worked either with colleagues from these three countries or who had performed scientific work related to the environment and to deposition of radionuclides resulting from the Chernobyl accident in their own countries. The work of this expert group was managed by the International Atomic Energy Agency. Unless specified otherwise, the materials in section (A.II) are taken from [I21].

A. Radionuclide release and deposition

1. Radionuclide source term

A23. Over the years, the understanding of the amount of material released during the course of the accident has improved considerably; the current best estimates are given in table A1. Most of the radionuclides released in large quantities have short physical half-lives; the radionuclides with long half-lives had generally been released in small quantities. These release estimates are similar to those given in reference [U3], but the amounts of refractory elements released are now estimated to have been smaller.

A24. By 2005, most of the radionuclides released had long since decayed to negligible levels. Over the next few decades, ^{137}Cs will continue to be the most important radionuclide; ^{90}Sr will be of interest, but to a lesser extent, in the near zone. Over the very long term (hundreds to thousands of years), the only radionuclides of interest will be the plutonium isotopes and ^{241}Am. The initial amounts of ^{241}Am released were so small that they have not been estimated. However, ^{241}Am results from the radioactive decay of ^{241}Pu. With an initial amount of ^{241}Pu released into the environment of 2.6 PBq (see table A1) the decay of ^{241}Pu and the resulting ingrowth and subsequent decay of ^{241}Am are shown in figure A-III. The maximum total activity of ^{241}Am in the environment will be 0.077 PBq in the year 2058. This is a small amount compared to the initial 2.6 PBq of ^{241}Pu, but it is more than two times larger than the combined amounts of ^{239}Pu and ^{240}Pu that will be present at that time. Americium-241 is the only radionuclide whose amount is presently increasing with time; the amounts of the other radionuclides will continue to decrease with time.

Table A1. Revised estimates of the total release of principal radionuclides to the atmosphere during the course of the Chernobyl accident[a]

Radionuclide	*Half-life*	*Activity released (PBq)*
Inert gases		
^{85}Kr	10.72 a	33
^{133}Xe	5.25 d	6 500
Volatile elements		
^{129m}Te	33.6 d	240
^{132}Te	3.26 d	~1 150
^{131}I	8.04 d	~1 760
^{133}I	20.8 h	910
^{134}Cs	2.06 a	~47[b]
^{136}Cs	13.1 d	36
^{137}Cs	30.0 a	~85
Elements with intermediate volatility		
^{89}Sr	50.5 d	~115
^{90}Sr	29.12 a	~10
^{103}Ru	39.3 d	>168
^{106}Ru	368 d	>73
^{140}Ba	12.7 d	240
Refractory elements (including fuel particles)[c]		
^{95}Zr	64.0 d	84
^{99}Mo	2.75 d	>72
^{141}Ce	32.5 d	84
^{144}Ce	284 d	~50
^{239}Np	2.35 d	400
^{238}Pu	87.74 a	0.015

Radionuclide	*Half-life*	*Activity released (PBq)*
^{239}Pu	24 065 a	0.013
^{240}Pu	6 537 a	0.018
^{241}Pu	14.4 a	~2.6
^{242}Pu	376 000 a	0.00004
^{242}Cm	18.1 a	~0.4

[a] Most of the data are from references [D11, U3].
[b] Based on ^{134}Cs/^{137}Cs ratio 0.55 as of 26 April 1986 [M8].
[c] Based on fuel particle release of 1.5% [K13].

2. Physical and chemical form of released material; hot particles

A25. Radionuclides in the released material were in the form of gases, condensed particles and fuel particles. The presence of fuel particles was an important characteristic of the accident. During oxidation and dispersal of the nuclear fuel, volatilization of some radionuclides took place. After the initial cloud cooled, some of the more volatile radionuclides remained in the gaseous phase, while other volatile radionuclides, such as ^{137}Cs, condensed onto particles of construction materials, soot and dust. Thus, the chemical and physical forms of the radionuclides in the release were determined by the volatility of their compounds and the conditions inside the reactor. Radioactive material with relatively high vapour pressures (primarily isotopes of inert gases and of iodine in different chemical forms) were transported in the atmosphere in the gaseous phase. Isotopes of refractory elements (e.g. cerium, zirconium, niobium, and plutonium) were released into the atmosphere primarily in the form of fuel particles. Other radionuclides (isotopes of caesium, tellurium, antimony, etc.) were found in both fuel and condensed particles. The relative contributions of condensed and fuel components to the deposition at a given site can be estimated from the activity ratios of the radionuclides of different volatility classes.

A26. Fuel particles made up the most important part of the deposited material in the vicinity of the damaged reactor. Radionuclides such as ^{95}Zr, ^{95}Nb, ^{99}Mo, ^{141,144}Ce, ^{154,155}Eu, ^{237,239}Np, $^{238\text{-}242}$Pu, ^{241,243}Am and ^{242,244}Cm were released in a matrix of fuel particles only. More than 90% of the ^{89,90}Sr and ^{103,106}Ru activities that were released were also in fuel particles. The released fraction of ^{90}Sr, ^{154}Eu, ^{238}Pu, $^{239+240}$Pu and ^{241}Am (and, therefore, of the nuclear fuel itself) deposited outside the ChNPP industrial site has been recently estimated to be only 1.5±0.5% [K13], which is half that of earlier estimates.

A27. The chemical and radionuclide composition of fuel particles was close to that of irradiated nuclear fuel, but with a lower fraction of volatile radionuclides, a higher oxidation state of uranium, and the presence of various admixtures, especially in the surface layer. In contrast, the chemical and radionuclide composition of condensed particles varied widely. The specific activity of radionuclides in these particles was governed by the duration of the condensation process and the process temperature, as well as the particle characteristics. The radionuclide content of some of the particles was dominated by just one or two radionuclides, e.g. ^{103,106}Ru or ^{140}Ba/^{140}La.

A28. The form of a radionuclide in the release influenced the distance of its atmospheric transport. Even the smallest fuel particles consisting of a single grain of nuclear fuel crystallite had a relatively large size (up to 10 μm) and high density (8–10 g/cm^3). Because of their size, they were transported only a few tens of kilometres. Larger aggregates of particles were found only within distances of several kilometres from the power plant. For this reason, the deposition of refractory radionuclides strongly decreased with distance from the damaged reactor and only traces of refractory elements could be found outside the industrial site of the power plant. In contrast, significant deposition of gaseous radionuclides and sub-micron condensed particles took place at distances of thousands of kilometres from the site. Ruthenium particles, for example, were found throughout Europe.

A29. Another important characteristic of the deposited material is its solubility in aqueous solution. This determined the mobility and bioavailability of deposited radionuclides in soils and surface waters during the initial period after deposition. The contribution of the water-soluble and exchangeable (extractable with 1M ammonium acetate solution) forms of ^{137}Cs varied from 5% to more than 30% in deposited material sampled daily at the Chernobyl meteorological station from 26 April to 5 May 1986. The water-soluble and exchangeable forms accounted for only about 1% of the ^{90}Sr in material deposited on 26 April, and this value increased to 5–10% in material deposited on subsequent days.

A30. The low solubility of deposited ^{137}Cs and ^{90}Sr near the power plant indicates that fuel particles were the major part of the deposited material, even 20 km from the source. At shorter distances, the proportion of water-soluble and exchangeable forms of ^{137}Cs and ^{90}Sr was lower owing to the presence of larger particles; at further distances, the fraction of soluble condensed particles increased. As one example, almost all ^{137}Cs deposited in 1986 in the United Kingdom was water-soluble and exchangeable.

3. Meteorological conditions during the course of the accident

A31. The meteorological conditions during the accident have been described in references [I21, U3]. There are no new data, but efforts to understand better the meteorological conditions during the accident are the subject of continuing research [T5, T6]. In this case, the primary goal is to be able to reconstruct the pattern of ^{131}I deposition after the accident. This is because the reconstruction of doses to the thyroid due to radioiodine continues to be a major research effort, and reliable measurements of the deposition densities of ^{131}I are lacking, especially in Ukraine.

4. Concentration of radionuclides in air

A32. The activity concentration of radioactive material in air was measured at many locations in the former Soviet Union and throughout the world. Examples of the results of the measurements made are shown in figure A-IV for two locations: Chernobyl and Baryshevka, Ukraine. The location of the sampler at Chernobyl was the meteorological station in the City of Chernobyl, which is about 15 km southeast of the ChNPP. The initial concentrations of airborne materials were very high, but dropped in two phases. There was a rapid fall over a few months, and then a more gradual decrease over several years. Over the long term, the sampler at Chernobyl recorded consistently higher activity concentrations than the sampler at Baryshevka (about 150 km southeast of the ChNPP), presumably owing to higher levels of resuspended material [H5].

A33. Even with the data smoothed by a rolling average, there are some notable features in the data collected over the long term. The clearly discernible peak that occurred during the summer of 1992 (month 78) was due to widespread forest fires in Belarus and Ukraine.

5. Deposition of radionuclides on soil surfaces

A34. Mapping the deposition density of ^{137}Cs throughout the northern hemisphere was intensively pursued through 2000. Efforts continue to map the deposition density of ^{131}I, particularly in areas where an increase in the incidence of thyroid cancer in children has been noted. Because the half-life of ^{131}I is short, direct measurements of deposition densities are limited. In the absence of such data, three approaches are being used to reconstruct the pattern of ^{131}I deposition: *(a)* use of ^{137}Cs as a surrogate; *(b)* use of ^{129}I as a surrogate; and (c) use of advanced models of atmospheric transport and deposition.

A35. The use of ^{137}Cs as a surrogate for ^{131}I has been described in several publications but there is not a consistent relationship between the depositions of the two radionuclides. This is because the two elements have differing volatilities and rates of deposition on soil via dry and wet processes. Iodine-129 (half-life of 16 million years) is generally regarded as a more natural surrogate, but analysis is costly and time consuming. Nevertheless, such work is proceeding, and four major papers [M6, M7, P4, S17] have been published since 2000. If soil samples are taken to sufficient depths to capture the deposited ^{129}I, then the deposition density of ^{129}I can be calculated. Then, if the isotopic ratio of ^{129}I to ^{131}I at the time of deposition is known or can be inferred, the deposition density of ^{131}I can be calculated. There is substantial variability in the measured or derived values of this ratio. Pietrzak-Flis et al. [P4] used a value of 32.8 for deposition in Warsaw, Poland, whereas Straume et al. [S17] used a value of 12±3 for deposition in Belarus. Schmidt et al. [S11] have recommended that "…the smallest measured ^{129}I to ^{131}I atomic ratio should come closest to the real emission value". This is because it is much more likely that samples would have been contaminated with extraneous sources of ^{129}I than of ^{131}I.

A36. The effort by Talerko [T5, T6] to reconstruct the deposition densities of ^{131}I using an atmospheric transport model has been mentioned above. This type of calculation is dependent on a great many assumptions, which are based on very limited data; thus, the method is subject to large uncertainties.

B. Urban environment

A37. Deposited radioactive material resulted in both short- and long-term increases in the radiation levels over the natural background levels in thousands of settlements, which in turn resulted in additional external exposures of the inhabitants and internal exposures due to the consumption of food containing radionuclides. Near the ChNPP, the towns of Pripyat and Chernobyl and some other smaller settlements were subjected to substantial deposition from the "undiluted" radioactive cloud under dry meteorological conditions, whereas many more distant settlements incurred significant deposition owing to precipitation at the time of the passage of the cloud.

A38. The radioactive material deposited on exposed surfaces such as lawns, parks, streets, building roofs and walls. The level and composition of the deposited material was significantly influenced by whether the deposition was via dry or wet processes. Under dry conditions, trees, bushes, lawns and roofs became more contaminated than when there was precipitation. Under wet conditions, horizontal surfaces—including soil plots and lawns—received the highest deposition. These differences, including some marked changes with time, are illustrated in figure A-V.

1. Migration of radionuclides in the urban environment

A39. Radionuclides became detached from surfaces in urban environments owing to natural weathering processes (such as rain and snow melting) and human activities (including traffic, street washing and other clean-up activities). The major processes of removal of radionuclides were through run-off into storm and/or sanitary sewer systems and through seasonal abscission of vegetation. These natural processes and human activities significantly reduced the dose rates in inhabited and recreational areas during 1986 and thereafter.

A40. In general, vertical surfaces of houses do not exhibit the same degree of deposition or of weathering of deposited radioactive material as horizontal surfaces. After 14 years, the loss of radionuclides deposited on walls was typically 50–70% of the initial amount deposited. Levels of radionuclides on roofs in Denmark naturally decreased by 60–95% of those originally present over the same period, as illustrated in figure A-VI [A6].

A41. The level of radiocaesium on asphalt surfaces has decreased so much that generally less than 10% of the initial amount of deposited material is now left. Only a small fraction is associated with the bitumen of asphalt; most is associated with a thin layer of street dust, which is expected to be removed eventually by weathering.

A42. One of the consequences of these processes has been secondary contamination of sewerage systems and sludge storage, which necessitated special clean-up measures. Generally, radionuclides were not transferred from soil to other urban areas within cities, but migrated down into the soil through natural processes or mixing as a consequence of digging of gardens and parks.

2. Dynamics of exposure rate in urban environments

A43. Gamma radiation from radionuclides deposited in the urban environment has been a major contributor to the additional external exposure of humans due to the accident. Compared to the dose rate in open fields, the dose rate within a settlement has always been significantly lower, because of photon absorption by building structures, especially those made of brick and concrete. Lower dose rates have been observed inside buildings, especially on the upper floors of multi-storey buildings. Owing to radioactive decay of the initial radionuclide mixture, wash-off from solid surfaces and migration into soil, dose rates in air have been gradually decreasing with time.

A44. A relevant aspect is the time dependence of the ratio of the dose rate in air at an urban location compared to that in an open field (this ratio is often called the “location factor”). The dependence of location factors on time after the Chernobyl accident is shown in figure A-VII for measurements performed in Novozybkov in the Russian Federation [G4].

C. Agricultural environment

1. Radionuclide transfer in the terrestrial environment

A45. Radionuclides may behave differently in the environment. Some radionuclides, such as radiocaesium, radioiodine and radiostrontium, are environmentally mobile and transfer readily to foodstuffs. In contrast, radionuclides with low solubility, such as the actinides, are relatively immobile and largely remain in the soil. The main pathways leading to exposure of humans are shown in figure A-VIII [S13].

A46. Many factors influence the extent to which radionuclides are transferred through ecological pathways. If the transfer is high in a particular environment then that environment is referred to here as “radioecologically sensitive”, because such transfer can lead to relatively high radiation exposure [H7].

A47. During the short early phase after the Chernobyl accident (0–2 months), ^{131}I was the most important radionuclide for human exposure via agricultural food chains; in the longer term, ^{137}Cs was the most important.

A48. Radioecological sensitivity to radiocaesium in semi-natural ecosystems is generally higher than in agricultural ecosystems, sometimes by a few orders of magnitude [H9]. This difference is caused by a number of factors, the more important being the differing physicochemical behaviour in soils, the lack of competition between Cs and K which results in higher transfer rates for radiocaesium in nutrient-poor ecosystems, and the presence of specific food-chain pathways that lead to high activity concentrations in produce from semi-natural ecosystems. Also, forest soils are fundamentally different from agricultural soils; the former have a clear multilayered vertical structure characterized mainly by a clay-poor mineral layer, which supports a layer rich in organic matter. In contrast, agricultural soils generally contain less organic matter and higher amounts of clay.

2. Food-production systems affected by the accident

A49. The material deposited as a result of the Chernobyl accident had a major impact on the management of both agricultural and natural ecosystems. This was true not only within the former Soviet Union but also in many other countries in Europe.

A50. In the countries of the former Soviet Union, the prevailing food production system at the time of the accident consisted of two types: large collective farms and small private farms. Collective farms routinely used land rotation combined with ploughing and fertilization to improve productivity. In contrast, traditional small private farms seldom applied artificial fertilizers and often used manure for improving yield. Private farms had one or a few cows, and milk was produced mainly for family consumption. The grazing regime of private farms was initially limited to utilizing marginal land that was not used by the collective farms. Nowadays, private farms also use better quality pasture.

A51. In western Europe, poor soils are used for extensive agriculture, mainly for grazing of ruminants (e.g. sheep, goats, reindeer and cattle). Areas with poor soils include alpine meadows and upland regions in western and northern Europe with organic soils.

(a) Effects on agricultural systems soon after the accident

A52. At the time of the accident, vegetation was at different growth stages that depended on latitude and elevation. Initially, interception by plant leaves was the main pathway of contamination. In the medium and long-term, root uptake dominated. The highest activity concentrations of radionuclides in most foodstuffs occurred in 1986.

A53. In the early phase, ^{131}I was the main contributor to internal dose through the pasture–cow–milk pathway. Radioiodine ingested by cows was completely absorbed in the gut and then rapidly transferred to the animal's thyroid and milk (within about 1 day). Thus, peak concentrations occurred rapidly after deposition (in late April or early May 1986, depending on when deposition occurred in different countries). In several countries of the former Soviet Union and elsewhere in Europe, concentrations of ^{131}I in milk exceeded national and regional (European Union) action levels, which ranged from a few hundred to a few thousand becquerels per litre.

A54. In late April/early May 1986 in northern Europe, dairy cows and goats were not yet on pasture; therefore, there were very low activity concentrations of ^{131}I in milk. In contrast, in southern regions of the former Soviet Union, as well as in Germany, France and southern Europe, dairy animals were already grazing outdoors and there were significant levels of activity concentration in cow, goat and sheep milk. The activity concentration of ^{131}I in milk decreased with an effective half-life of 4–5 days owing to its short physical half-life and the processes that removed it from leaves. The mean "weathering" half-life for radioiodine on grass was 9 days; that for radiocaesium was 11 days [K15]. Consumption of leafy vegetables onto which radionuclides had been deposited also contributed to the intake of radionuclides by humans.

A55. Plants and animals also had elevated levels of radiocaesium in comparison with those caused by the fallout from atmospheric nuclear weapons testing. From June 1986 onwards, radiocaesium was the dominant radionuclide in most environmental samples (except within the 30-km zone) and in food products. As shown in figure A-IX, the levels of ^{137}Cs in milk decreased during the spring of 1986 with an effective half-life of about two weeks because of weathering, biomass growth and other natural processes. However, the concentration of ^{137}Cs increased again during the winter of 1986/87 owing to cows being fed contaminated hay that had been harvested in the spring/summer of 1986. This phenomenon was observed in many countries.

A56. The transfer to milk of many of the other radionuclides present in the terrestrial environment during the early phase was low. This was because of the low inherent absorption of the elements in the ruminant gut, compounded by their low bioavailability owing to their association within the matrix of fuel particles.

(b) Effects on agricultural systems during the longer term

A57. Since the autumn of 1986, the radionuclide levels in both plants and animals have been largely determined by interactions between the radionuclides and different soil components, because soil is the main reservoir of the long-lived radionuclides that were deposited on terrestrial ecosystems. These interactions control radionuclide bioavailability for uptake into plants and animals and also influence radionuclide migration down the soil column.

3. Physicochemistry of radionuclides in the soil-plant system

A58. Many measurements taken following the accident demonstrate that the amount and nature of clay minerals present in soils are key factors in determining radioecological sensitivity with regard to radiocaesium. These features are crucially important for understanding the behaviour of radiocaesium, especially in areas distant from the ChNPP where ^{137}Cs was initially deposited mainly in condensed, water-soluble, forms.

A59. Close to the ChNPP, radionuclides were deposited in a matrix of fuel particles, which have been slowly dissolving with time. The more significant factors influencing the dissolution rate of fuel particles in soil are the acidity of the soil solution and the physicochemical properties of the particles (notably the degree of oxidization). At low pH of 4, the time taken for 50% dissolution of particles was about 1 year, whereas at a higher pH of 7, as many as 14 years were needed [F4, K14]. Thus, in acid soils most of the fuel particles have now already dissolved. In neutral soils, the amount of mobile ^{90}Sr released from the fuel particles is still increasing, and this will continue for the next 10–20 years.

A60. In addition to soil minerals, microorganisms can significantly influence the fate of radionuclides in soils [K12, S21]. Microorganisms can interact with minerals and organic matter and consequently affect the bioavailability of radionuclides. In the specific case of mycorrhizal fungi, soil microorganisms may even act as a carrier transporting radionuclides from the soil solution to the associated plant.

A61. With use of sequential extraction techniques, the fraction of exchangeable ^{137}Cs was found to decrease by a factor of 3–5 within the decade after 1986. This time trend may be because of progressive fixation of radiocaesium in interlayer positions of clay minerals and to its slow diffusion and binding to frayed-edge sites of clay minerals. These processes reduce the exchangeability of radiocaesium so that is not then available to enter the soil solution from which plants take up radiocaesium via their roots. For ^{90}Sr, an increase with time of the exchangeable fraction has been observed, which is attributed to the leaching of the fuel particles [K14].

(a) Migration of radionuclides in soil

A62. Vertical migration of radionuclides down the soil column could arise from various transport mechanisms that include convection, dispersion, diffusion and biological mixing. High degrees of root uptake of radionuclides by plants are correlated with high degrees of vertical migration, because in both processes the radionuclides are relatively mobile. Typically, the rate of movement of radionuclides thus varies with soil type and physicochemical form. As an example, figure A-X shows the change with time in the depth profiles of the activity concentrations of ^{90}Sr and ^{137}Cs in soil measured in the Gomel oblast of Belarus. Although there has been a significant downward migration of both radionuclides, much of the radionuclide activity has remained within the rooting zone of plants (0–10 cm). At such sites where deposition occurred directly from the atmosphere, there is a low risk of radionuclide migration to groundwater.

A63. The rate of migration down the column of different types of soils varies for both radiocaesium and radiostrontium. Low rates of ^{90}Sr vertical migration were observed in peat soils, whereas ^{137}Cs migrated at the highest rate in these highly organic soils, but moved much more slowly in soddy–podzolic sandy soils. In dry meadows, migration of ^{137}Cs below the rooting zone (0–10 cm) was hardly detectable 10 years after the accident. Thus, the contribution of vertical migration to the decrease in activity concentration of ^{137}Cs in the rooting zone of mineral soils is negligible. On the contrary, in wet meadows and in peatland, downward migration can be an important factor that reduces the ^{137}Cs-activity concentration in the root zone.

A64. Higher rates of ^{90}Sr vertical migration were observed in low-humified sandy soil, soddy–podzolic sandy soil, and sandy-loam soil with low organic content (<1%) [S13]. Generally, the highest rate of ^{90}Sr vertical migration is characteristic of non-equilibrium soil conditions. This occurs in flood plains of rivers where soil is not fully structurally formed (light humified sands), arable lands in a non-equilibrium state, and in soils where the organic layers have been removed, for instance, as a consequence of forest fires and sites with sedimentary sand with a low content of organic matter (<1%). In such conditions, there is a high rate of vertical migration of radiostrontium to groundwater with convective moisture flow, and high activity in localized soil zones can occur. Thus, the spatial distribution of ^{90}Sr can be particularly heterogeneous in soils where there have been changes in sorption properties.

A65. Agricultural practices have a major impact on radionuclide behaviour. Depending on the type of soil tillage and on the tools used, a mechanical redistribution of radionuclides in the soil may occur. In arable soils, radionuclides are distributed fairly uniformly along the whole depth of the tilled layer.

A66. Lateral redistribution of radionuclides in catchments, which can be caused by both water and wind erosion, is significantly less than their vertical migration into the soil layer and the deep geological environment [S13]. The type and density of plant cover may significantly affect erosion rates. Depending on the intensity of erosive processes, the content of radionuclides in the arable layer on flat land with small slopes may vary by up to 75% [B16].

(b) Transfer of radionuclides from soil to crops

A67. The uptake of radionuclides by plant roots is a competitive process associated with plant physiology [E2]. For radiocaesium and radiostrontium, the main competing chemical elements are potassium and calcium, respectively. The major processes influencing radionuclide transport within the rooting zone are schematically represented in figure A-XI, although the relative importance of each component varies with the radionuclide and soil type.

A68. The main process controlling root uptake of radiocaesium is the interaction between the soil matrix and solution, which depends primarily on the cation-exchange capacity of the soil. For mineral soils, this is influenced by the concentrations and types of clay minerals and the concentrations of the major competitive cations, especially potassium and ammonium. Examples of these relationships are presented in figure A-XII for both radiocaesium and radiostrontium. Modelling of soil–solution physicochemistry, which takes into account these major factors, enables the uptake of both radionuclides by plant roots to be calculated [K16, Z5].

A69. The fraction of a deposited radionuclide taken up by plant roots differs by orders of magnitude depending primarily on the soil type. For radiocaesium and radiostrontium, the radioecological sensitivity of soils can be broadly divided into the categories listed in table A2. For all soils and all plant species, root uptake of plutonium is negligible compared to the direct contamination of leaves via rain splash or resuspension.

Table A2. Classification of radioecological sensitivity for soil–plant transfer of radiocaesium and radiostrontium [I21]

Sensitivity	*Characteristics*	*Mechanism*	*Example*
For radiocaesium			
High	Low nutrient content Absence of clay minerals High organic content	Little competition with potassium and ammonium in root uptake	Peat soils
Medium	Poor nutrient status, consisting of minerals including some clays	Limited competition with potassium and ammonium in root uptake	Podzol, other sandy soils
Low	High nutrient status Considerable fraction of clay minerals	Radiocaesium strongly held to soil matrix (clay minerals) Strong competition with potassium and ammonium in root uptake	Chernozem, clay and loam soils (used for intensive agriculture)
For radiostrontium			
High	Low nutrient status Low organic matter content	Limited competition with calcium in root uptake	Podzol sandy soils
Low	High nutrient status Medium to high organic matter content	Strong competition with calcium in root uptake	Umbric gley soils, peaty soils

A70. Transfer from soil to plants is commonly quantified using either the transfer factor (*TF*, a dimensionless quantity defined as the activity concentration in the plant, Bq/kg, divided by activity concentration in soil, Bq/kg) or the aggregated transfer coefficient (T_{ag}, m^2/kg, defined as the activity concentration in the plant, Bq/kg, divided by the deposition density on soil, Bq/m^2). It is common to use dry weights for soil and vegetation when computing such values.

A71. The highest ^{137}Cs uptake from soil to plants through the roots occurs for peaty, boggy soils, and is one to two orders of magnitude higher than that for sandy soils; this uptake often exceeds that of plants grown on fertile agricultural soils by more than three orders of magnitude. The high radiocaesium uptake from peaty soil became important after the Chernobyl accident, because in many European countries such soils are vegetated by natural unmanaged grassland used for the grazing of ruminants and the production of hay. Agricultural activity often reduces the transfer of radionuclides from soils to plants by physical dilution (e.g. ploughing) or by the addition of competitive elements (e.g. in fertilizers).

A72. There are also differences in radionuclide uptake among plant species. Although variations in transfer from soil to plant among species may exceed one or more orders of magnitude for radiocaesium, the impact of differing radioecological sensitivities of soils is often more important in explaining the spatial variation in transfer within agricultural systems. Accumulation of radiocaesium in crops and pastures is related to soil texture. In sandy soils, uptake of radiocaesium by plants is approximately twice as high as in loam, but this effect is mainly because of the lower concentration of its main competing element, potassium, in sand.

A73. Thus, differences in the radioecological sensitivities of soils explain why in some areas of relatively low deposition, there are high concentrations of radiocaesium in plants and mushrooms harvested from semi-natural ecosystems and, conversely, why areas of relatively high deposition may show only low to moderate concentrations of radiocaesium in plants.

(c) Dynamics of radionuclide transfer to crops

A74. In 1986, the ^{137}Cs content in plants was primarily determined by aerial deposition and reached its maximum value. During the first post-accident year (through 1987), the ^{137}Cs content in plants dropped by a factor of 3–100 as only the root uptake from different soil types remained important.

A75. For meadow plants in the first years after deposition, the behaviour of ^{137}Cs was considerably influenced by the radionuclide distribution between soil and mat. In this period, ^{137}Cs uptake from the mat exceeded significantly (up to 8 times) that from soil. Further, as a result of mat decomposition and subsequent radionuclide transfer to soil, the contribution of the mat decreased rapidly, and in the fifth year after the initial deposition, it did not exceed 6% for automorphous soils and 11% for hydromorphous ones [F4].

A76. For most soils, the transfer rate of ^{137}Cs to plants has continued to decrease since 1987, although the rate of decrease has slowed, as can be seen from figure A-XIII [F7]. A similar decrease with time has been observed in many studies of plant–root uptake with different crops.

A77. For the soil–plant transfer of radiocaesium, a decrease with time is likely to reflect: *(a)* physical radioactive decay;

(b) the downward migration of the radionuclide out of the rooting zone; and *(c)* physicochemical interactions with the soil matrix that result in decreasing bioavailability. In many soils, ecological half-lives of plant-root uptake of radiocaesium can be characterized by two components: *(a)* a relatively fast decrease with a half-life of between 0.7 and 1.8 years (this dominated for the first 4–6 years after the accident, and led to a reduction of concentrations in plants by about an order of magnitude compared with 1987); and *(b)* a slower decrease with a half-life of between 7 and 60 years [B20, F5, F7, P8].

A78. Caution should be used in generalizing these observations, because some data show almost no decrease of root uptake of radiocaesium with time beyond the first 4–6 years, which suggests no reduction in bioavailability in soil within the time period of observation. Furthermore, quantifying ecological half-lives that exceed the period of observation is highly uncertain. The successful application of any countermeasures aimed at reducing the concentrations of radiocaesium in plants will also modify the ecological half-life.

A79. Compared to radiocaesium, the uptake of ^{90}Sr by plants has often not shown such a marked decrease with time. In the areas close to the ChNPP, gradual dissolution of fuel particles has enhanced the bioavailability of ^{90}Sr and, therefore, there was an increase with time in the uptake of ^{90}Sr by plants [K14].

A80. In remote areas, where radiostrontium was predominantly deposited in condensed form, and in lesser amounts as fine dispersed fuel particles, the dynamics of long-term transfer of ^{90}Sr to plants were similar to those for radiocaesium, but with different ecological half-lives of plant-root uptake and with differing fractional amounts accorded to the two components. These differences reflected various mechanisms of transfer of these two elements in soil. The fixation of radiostrontium by soil components depends less on the clay content of soil than is the case for radiocaesium (see table A2). More generally, the values of parameters for the transfer of ^{90}Sr from soil to plants depend less on the soil properties than they do for radiocaesium [A3].

4. Transfer of radionuclides to animals

A81. Animals take up radionuclides in forage and through direct ingestion of soil. Milk and meat were major sources of internal radiation doses to humans after the Chernobyl accident, both in the short term (owing to ^{131}I) and in the long term (owing to radiocaesium).

A82. Levels of radiocaesium in animal products from extensively farmed ecosystems can be high and persist for a long time, even though the original deposition may have been relatively low. This is because: *(a)* the soils often allow significant uptake of radiocaesium; *(b)* some species accumulate relatively high levels of radiocaesium, e.g. ericaceous species and fungi; and *(c)* these areas are often grazed by small ruminants that accumulate higher concentrations of radiocaesium than larger ruminants [H8].

A83. Levels of radionuclides in animal products depend on the behaviour of the radionuclide in the plant–soil system, rate of absorption in the gut, metabolic fate in the animal and the rate of loss from the animal (principally in urine, faeces and milk). Ingestion of radionuclides in feed, and subsequent absorption through the gut, is the major route of entry of most radionuclides. Absorption of most elements from feed takes place in the rumen or the small intestine at rates that vary from almost negligible, in the case of actinides, to 100% for radioiodine, and varying between 60% and 100% for radiocaesium depending on its form [B15].

A84. After absorption, radionuclides circulate in the blood. Some concentrate in specific organs; for instance, radioiodine concentrates in the thyroid and many metal ions, including ^{144}Ce, ^{106}Ru, and ^{110m}Ag, in the liver. Actinides and radiostrontium tend to be deposited in the bone, whereas radiocaesium is distributed throughout the soft tissues.

A85. The long-term time trend of radiocaesium levels in meat and milk (e.g. see figure A-XIV) mimics that for vegetation, and can be divided into two time periods. For the first 4–6 years after the initial deposition of radiocaesium, there was an initial fast decrease with an ecological half-life of between 0.8 and 1.2 years. For later times, only a small decrease has been observed [F7].

A86. A significant amount of production in the former Soviet Union was confined to the grazing of privately owned cows on poor, unimproved meadows. Because of the poor productivity of these areas, radiocaesium uptake was relatively high compared to that for land used by collective farms. As an example of the differences for the two farming systems, changes in activity concentrations of ^{137}Cs in milk from private and from collective farms in the Rovno oblast, Ukraine, are shown in figure A-XV [P6]. The activity concentrations in milk from private farms exceeded the national action level (referred to in the countries of the former Soviet Union as Temporary Permissible Levels, TPLs), until 1991, when countermeasures for private farms were implemented.

5. Current levels of radionuclides in foodstuffs and expected future trends

A87. Table A3 presents a summary of activity concentrations of radiocaesium measured between 2000 and 2003 in grain, potatoes, milk and meat produced in the contaminated areas of Belarus, the Russian Federation and Ukraine; the results cover many different types of soil with widely differing radioecological sensitivities. The activity concentrations of ^{137}Cs were consistently higher in animal products than in plant products.

Table A3. Mean and range of current activity concentrations of ^{137}Cs in agricultural products across the contaminated areas of Belarus [B16], the Russian Federation [F7] and Ukraine [B14]
(Data are in Bq/kg fresh weight for grain, potato and meat and in Bq/L for milk)

^{137}Cs deposition density on soil	*Grain*	*Potatoes*	*Milk*	*Meat*
Belarus				
>185 kBq/m^2 (contaminated districts of the Gomel oblast)	30 (8–80)	10 (6–20)	80 (40–220)	220 (80–550)
37–185 kBq/m^2 (contaminated districts of the Mogilev oblast)	10 (4–30)	6 (3–12)	30 (10–110)	100 (40–300)
Russian Federation				
>185 kBq/m^2 (contaminated districts of the Bryansk oblast)	26 (11–45)	13 (9–19)	110 (70–150)	240 (110–300)
37–185 kBq/m^2 (contaminated districts of the Kaluga, Tula and Orel oblasts)	12 (8–19)	9 (5–14)	20 (4–40)	42 (12–78)
Ukraine				
>185 kBq/m^2 (contaminated districts of the Zhitomir and Rovno oblasts)	32 (12–75)	14 (10–28)	160 (45–350)	400 (100–700)
37–185 kBq/m^2 (contaminated districts of the Zhitomir and Rovno oblasts)	14 (9–24)	8 (4–18)	90 (15–240)	200 (40–500)

A88. In 2008, owing to both natural processes and agricultural countermeasures, the activity concentrations of ^{137}Cs in agricultural food products were generally below national, regional (EU) and international[1] action levels. However, in some limited areas with high radionuclide deposition (parts of Gomel and Mogilev oblasts in Belarus and of Bryansk oblast in the Russian Federation) or with poor organic soils (Zhitomir and Rovno oblasts in Ukraine) the activity concentrations of ^{137}Cs in food products, especially milk, still exceed the national TPLs of about 100 Bq/kg.

A89. Milk from privately-owned cows with activity concentrations of ^{137}Cs exceeding 100 Bq/L (the current TPL for milk) was being produced in more than 400, 200 and 100 Ukrainian, Belarusian and Russian settlements, respectively, 15 years after the accident. Concentrations of ^{137}Cs in milk higher than 500 Bq/L were occurring in six Ukrainian, five Belarusian and five Russian settlements in 2001.

A90. Scrutiny of the activity concentrations and associated transfer coefficients shows that there has been only a slow decrease in activity concentrations of ^{137}Cs in most plant and animal foodstuffs during 1998–2008. This indicates that radionuclides must be close to equilibrium within the agricultural ecosystems. However, continued reductions with time would be expected owing to continuing migration down the soil profile and to radioactive decay, even if there was an equilibrium established between ^{137}Cs in the labile and non-labile fractions of soil. Given the present slow declines and the large uncertainties in quantifying long-term effective half-lives based on data currently available, it is not possible to conclude that there will be any further substantial decrease over the next decades, except as a consequence of further radioactive decay of both ^{137}Cs and ^{90}Sr, each with half-lives of about thirty years.

A91. Activity concentrations of radionuclides in foodstuffs can increase in some limited geographic areas located close to the Chernobyl NPP through the dissolution of fuel particles, changes to the water table resulting from changes in the management of the currently abandoned land or the cessation of countermeasures.

D. Forest environment

1. Radionuclides in European forests

A92. Forest ecosystems were one of the semi-natural ecosystems significantly affected as a result of deposited material from the radioactive plumes. The primary concerns from a radiological perspective are the long-term levels of ^{137}Cs (owing to its 30-year half-life and bioavailability) in the forest environment and forest products. In the years immediately following the accident the shorter-lived ^{134}Cs isotope was also significant. In forests, other radionuclides (such as ^{90}Sr and the plutonium isotopes) are of limited significance for human exposure, except in relatively small areas in and around the 30-km zone. As a result, most of the available environmental data collected have been focused on the assessment of the behaviour of ^{137}Cs and the associated radiation doses. The emphasis of this subsection is on the distribution of ^{137}Cs in the forest environment and the relevant pathways of human exposure to radiation.

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[1] Current Codex Alimentarius Guideline Levels for ^{137}Cs in foods for use in international trade are equal to 1,000 Bq/kg [C12].

A93. Following the accident, substantial amounts of radioactive material were deposited on forests in Belarus, the Russian Federation and Ukraine and also in countries beyond the borders of the former Soviet Union, notably Finland, Sweden and Austria. The levels of ^{137}Cs deposition on the forests of these countries ranged from more than 10 MBq/m^2 in some locations down to between 10 and 50 kBq/m^2 in several countries of western Europe. In each of these countries, not only do forests represent an economic resource of major importance, but they also play a central role in many social and cultural activities. In some cases, these activities have been curtailed on account of concerns and restrictions relating to the ^{137}Cs levels.

A94. Previous studies related to the global fallout from the atmospheric testing of nuclear weapons had shown that the clearance rate of radionuclides from the forest ecosystems by natural processes is extremely slow. The net clearance rate for ^{137}Cs in forests contaminated by the radionuclides deposited following the Chernobyl accident has been less than 1% per year, so it is likely that, without artificial intervention, the physical radioactive decay rate will largely influence the long-term levels. Recycling of radiocaesium within the forest ecosystem is a dynamic process, in which two-way transfers between biotic and abiotic components of the ecosystem occur on a seasonal, or longer-term, basis. Much information on such processes has been obtained from experiments and field measurements, and many of these data have been used to develop predictive mathematical models [I18].

2. The dynamics of radionuclide levels during the early phase

A95. The levels of radioactivity in forests of the former Soviet Union located along the trajectory of the first radioactive plume were primarily the result of dry deposition, while farther afield, in countries such as Sweden and Austria, wet deposition also occurred and resulted in significant “hot spots” of activity. Radionuclides were also deposited with rain on other areas in the former Soviet Union, such as the Mogilev oblast in Belarus and the Bryansk oblast and other oblasts in the Russian Federation.

A96. The primary mechanism by which trees became contaminated after the accident was direct interception by the tree canopy (between 60% and 90% of the initial deposition of radiocaesium). Within a 7-km radius of the reactor, this led to very high levels of deposition on the canopies of pine trees, which consequently received lethal doses of radiation from the complex mixture of short- and long-lived radionuclides released by the damaged reactor. Gamma dose rates in the days and weeks immediately following the accident were in excess of 5 mGy/h in the area close to the reactor. The calculated absorbed gamma dose amounted to some 100 Gy to the needles of pine trees. This small area of forest became known as the “Red Forest”, as the trees died and became a reddish-brown colour; this was the most readily observable effect of radiation damage on organisms in the area.

A97. The levels of radionuclides in the tree canopies reduced rapidly over a period of weeks to months owing to the natural processes of wash-off by rainwater and of leaf/needle fall. Absorption of radiocaesium by leaf surfaces also occurred, although this was difficult to measure directly. By the end of the summer of 1986, approximately 15% of the initial radiocaesium burden in tree canopies remained and, by the summer of 1987, the amount remaining had been further reduced to approximately 5%. Within this roughly one-year period, therefore, most of the radiocaesium had been transferred from the tree canopy to the underlying soil.

A98. During the summer of 1986, radiocaesium levels in natural products, such as mushrooms and berries, increased and this led to increasing body burdens of forest animals, such as deer and moose. In Sweden, activity concentrations of ^{137}Cs in moose exceeded 2 kBq/kg fresh weight and those in roe deer were even higher.

3. The long-term dynamics of radiocaesium levels in forests

A99. By approximately one year after the initial deposition, the major fraction of radiocaesium in the forest was that contained in the soil. As radiocaesium migrated deeper into the soil, root uptake by trees and understorey plants became predominant over the longer term. Just as in the case of its chemical analogue, the nutrient potassium, the rate of radiocaesium cycling within forests is rapid and a quasi-equilibrium of its distribution is reached within a few years after the initial deposition [S12]. The upper, organic-rich soil layers act as a long-term store, but also as a general source of radiocaesium for forest vegetation, although individual plant species differ greatly in their ability to accumulate radiocaesium from this organic soil (figure A-XVI).

A100. Loss of radiocaesium from the ecosystem via drainage water is generally limited because the element fixes onto micaceous clay minerals. An important role of forest vegetation in the recycling of radiocaesium is partial and transient storage of radiocaesium, particularly in perennial woody components. Although the concentration in tree trunks and branches is low, their biomass can be large and the total storage of ^{137}Cs can be significant. A portion of radiocaesium taken up by vegetation from the soil, however, is recycled annually through leaching and needle/leaf fall, which results in long-lasting biological availability of radiocaesium in surface soil. The store of radiocaesium in the standing biomass of the forest amounts to approximately 10% of the total activity in the temperate forest ecosystem; most of this activity resides in trees.

A101. Because of biological recycling and storing of radiocaesium, migration within forest soils is limited and, in the long term, most of the radiocaesium resides in the upper organic horizons. Slow downward migration of radiocaesium continues to take place, however, although the rate of migration varies considerably depending on the soil type and climate.

A102. The hydrological regime of forest soils is an important factor governing radionuclide transfer in forest ecosystems. Depending on the hydrological regime, the radiocaesium T_{ag} for trees, mushrooms, berries and shrubs can vary over a range of more than three orders of magnitude. Minimal T_{ag} values were found for automorphic (dry) forests and soils developed on relatively flat surfaces with low run-off. Maximal T_{ag} values are related to hydromorphic forests developed under prolonged stagnation of surface waters. Among other factors influencing radionuclide transfer in forests, the distribution of root systems (mycelia) in the soil profile and the capacity of different plants to accumulate radiocaesium are of importance [F6].

A103. The vertical distribution of radiocaesium within soil has an important influence on the dynamics of uptake by herbaceous plants, trees and mushrooms. Another major consequence is a reduction in the external gamma dose rate with time, because the upper soil layers provide shielding against the radiation emitted as the radionuclide migrates deeper into the subsurface. The most rapid downward vertical transfer was observed for hydromorphic forests.

A104. After the initial deposition onto forests, large-scale geographical redistribution of radiocaesium is limited. Processes of small-scale redistribution include resuspension because of wind and fire, and erosion/runoff; however, none of these processes is likely to result in any significant further transport of radiocaesium beyond the area of initial deposition.

4. Uptake into edible products

A105. Edible products obtained from the forest include mushrooms, fruits and game animals; where radioactive material was deposited on the forest, radionuclides have been found in each of these products. The highest levels of radiocaesium have been observed in mushrooms, due to their great capacity to accumulate some mineral nutrients, including radiocaesium. Mushrooms provide a common and significant food source in many of the more affected countries, particularly those within the former Soviet Union. Changes with time in the activity concentrations in mushrooms reflect the bioavailability of ^{137}Cs in the various relevant nutrient sources utilized by different mushroom species.

A106. The high levels of radiocaesium in species of mushroom are due to generally high soil–mushroom transfer coefficients. However, these aggregated transfer coefficients (T_{ag}) are also subject to considerable variability and can range from 0.003 to 7 m^2/kg, i.e. by a factor of more than 2,000 [I15]. Significant differences in accumulation of radiocaesium occur among species of mushrooms; the rate of accumulation generally reflects the ecological niche that the individual species occupies. Like in plants, the agrochemical properties of forest soils and growth conditions strongly influence the aggregated transfer factors for ^{137}Cs from soil to different species of forest mushrooms [K12]. The degree of variability of radiocaesium levels in mushrooms is illustrated by figure A-XVII [I18], which also indicates a slowly decreasing trend during the 1990s.

A107. The level of radiocaesium in mushrooms in forests is often much higher than that in forest fruits such as bilberries. This is reflected in the aggregated transfer coefficients for forest berries, which range from 0.02 to 0.2 m^2/kg [I15]. Owing to the generally lower levels of radiocaesium and to the lower masses eaten, exposure due to consumption of forest berries is smaller than that due to consumption of mushrooms. However, both products contribute significantly to the diet of grazing animals and, therefore, provide a second route of exposure to humans via game consumption. Animals grazing in forests and other semi-natural ecosystems often produce meat with high activity concentrations of radiocaesium. Such animals include wild boar, roe deer, moose and reindeer, but also domestic animals such as cows and sheep, which may graze marginal areas of forests.

A108. Most data on levels of radionuclides in game animals such as deer and moose have been obtained from those western-European countries where the hunting and eating of game is commonplace. Significant seasonal variations occur in the body burden of radiocaesium in these animals owing to the seasonal availability of foods such as mushrooms and lichens; the latter are a particularly important component of the reindeer's diet. Particularly good time-series measurements have been made in the Nordic countries and in Germany. Figure A-XVIII shows a complete time series of annual average activity concentrations of radiocaesium in moose from one hunting area in Sweden between 1986 and 2003. A major factor for the radionuclide intake by game—roe deer, in particular—is the high activity concentration of radiocaesium in mushrooms. Aggregated transfer coefficients for moose range from 0.006 to 0.03 m^2/kg [I15]. The mean T_{ag} for moose in Sweden has been falling since the period of high initial levels, which indicates that the ecological half-life for radiocaesium in moose is measurably less than 30 years, the physical half-life of ^{137}Cs.

5. Radionuclides in wood

A109. The accident deposited radionuclides in many forests in Europe and countries of the former Soviet Union; most of these forests are planted and managed for the production of timber. Potentially, one of the significant exposure pathways to humans is through timber production. The export and subsequent processing and use of timber containing radionuclides are pathways that can lead to the exposure of people who would not normally be exposed in the forest itself. Uptake of radiocaesium from forest soils into wood is rather low; aggregated transfer factors range from 0.0003 to 0.003 m^2/kg. Hence, wood used for making furniture or the walls and floors of houses is unlikely to give rise to significant radiation exposure of people using these products [I19]. However, the manufacture of consumer goods such as paper involves the production of both liquid and solid wastes in which radiocaesium concentrates. Handling of these wastes by workers in paper-pulp factories can give rise to occupational exposure to radiation.

A110. Combustion of other parts of trees (such as needles, bark and branches) may give rise to the problem of disposal of radioactive wood ash. This practice has increased in recent years due to the upsurge in biofuel technology in the Nordic countries. The problem of radiocaesium in wood ash is particularly notable because the activity concentration of radiocaesium in ash is a factor of 50–100 times greater than in the original wood. Domestic users of firewood from these forests may be exposed externally to gamma radiation and internally through inhalation as a consequence of the build-up of ash in the home and/or garden [I19]. Such exposures however are generally insignificant.

E. Radionuclides in aquatic systems

1. Introduction

A111. Surface-water systems in many parts of Europe had elevated levels of radioactive material due to the Chernobyl accident. Most of the radioactive material, however, was deposited in the catchment area of the Pripyat River, which forms an important component of the Dnieper River–Reservoir system, one of the larger surface-water systems in Europe. After the accident, therefore, there was particular concern about possible radioactive contamination of the water supply for the area along the Dnieper cascade of reservoirs, which covers a distance of approximately 1,000 km to the Black Sea. Levels of radioactive material increased in other large river systems in Europe, such as the Rhine and the Danube, although the levels in the rivers were not significant [U3].

A112. Initial activity concentrations in river water in parts of Belarus, the Russian Federation and Ukraine were relatively high, compared both to those in other European rivers and to the standards for radionuclides in drinking water, owing to direct deposition onto river surfaces and to transport of radionuclides in run-off water from the catchment area. During the first few weeks after the accident, the activity concentrations in river waters rapidly declined, because of the physical decay of the short-lived radionuclides and as catchment soils and bottom sediments absorbed the radionuclides. In the longer term, the long-lived ^{137}Cs and ^{90}Sr became the dominant radionuclides in aquatic ecosystems. Although the levels of these radionuclides in rivers in the long term were low, temporary increases in the activity concentrations during flooding of the Pripyat caused serious concern in areas using water from the Dnieper cascade.

A113. Lakes and reservoirs had increased levels of radioactivity due to direct deposition of radionuclides onto the water surface and transfers of radionuclides in run-off water from the deposited material on the surrounding catchment area. The radionuclide concentrations in water declined rapidly in reservoirs and in those lakes with significant inflow and outflow of water (“open” lake systems). In some cases, however, the activity concentrations of radiocaesium in lakes remained relatively high because of run-off from organic soils in the catchment. In addition, internal cycling of radiocaesium in “closed” lake systems (i.e. lakes with little inflow and outflow of water) led to much higher activity concentrations in their water and aquatic biota than were typically seen in open lakes and rivers.

A114. Bioaccumulation of radionuclides (particularly radiocaesium) in fish resulted in activity concentrations (both in the most affected regions and in western Europe) that were in some cases significantly above national action levels for consumption, i.e. of the order of some hundreds to some thousands and even tens of thousands of becquerels per kilogram. In some lakes in Belarus, the Russian Federation and Ukraine, these problems have continued to the present day and may continue for the foreseeable future. Freshwater fish provide an important food source for many inhabitants of the affected regions. In the Dnieper cascade in Ukraine, commercial fisheries catch more than 20,000 tonnes of fish per year. In some other parts of Europe, particularly parts of Scandinavia, activity concentrations of radiocaesium in fish are still higher than action levels.

A115. The closest marine systems to the ChNPP are the Black Sea and the Baltic Sea, both several hundred kilometres from the site. The activity concentrations of radionuclides in water and fish of these seas have been intensively studied since the accident. Because the average direct deposition onto these seas was relatively low, and owing to the large dilution in marine systems, activity concentrations were much lower in these seas than in freshwater systems [I20].

2. Uptake of radionuclides to freshwater fish

A116. Consumption of freshwater fish is an important part of the aquatic pathway for transfer of radionuclides to humans. Although transfer of radionuclides to fish has been studied in many countries, most attention here will be focused on Belarus, the Russian Federation and Ukraine because of the relatively high activity concentrations in water bodies of these countries.

(a) ^{131}I in freshwater fish

A117. There are limited data on ^{131}I levels in fish. Iodine-131 was rapidly absorbed by fish in the Kiev Reservoir; maximum concentrations in fish were observed in early May 1986. Activity concentrations in fish muscle declined from around 6,000 Bq/kg fresh weight on 1 May 1986 to around 50 Bq/kg fresh weight by 20 June 1986. This represents a rate of decline similar to that of the physical decay of ^{131}I. Because of the rapid physical decay, activity concentrations of ^{131}I in fish became insignificant within a few months after the accident.

(b) ^{137}Cs in freshwater fish and other aquatic biota

A118. During the years following the Chernobyl accident, there have been many studies of the levels of radiocaesium in freshwater fish. As a result of high bioaccumulation factors for radiocaesium, fish have retained high radiocaesium levels in some areas, despite low levels in water. Uptake of radiocaesium in small fish was relatively rapid, the maximum concentration was observed during the first weeks after the accident. Because of the slow uptake rates of radiocaesium in large predatory fish (pike and eel) maximum activity concentrations were not observed until 6–12 months after the initial deposition, as shown in figure A-XIX [U19].

A119. In the Kiev Reservoir, activity concentrations of ^{137}Cs in fish were 0.6–1.6 kBq/kg fresh weight (in 1987) and 0.2–0.8 kBq/kg fresh weight (for 1990–1995) and declined to 0.2 kBq/kg or less for adult non-predatory fish in 2002. Values for predatory fish species were 1–7 kBq/kg during 1987 and 0.2–1.2 kBq/kg between 1990 and 1995.

A120. In the lakes of the Bryansk oblast of Russia, approximately 200 km from Chernobyl, activity concentrations of ^{137}Cs in a number of fish species varied within the range 0.2–19 kBq/kg fresh weight during the period 1990–1992. In shallow closed lakes such as Kozhanovskoe (Bryansk oblast, the Russian Federation) and Svyatoe (Kostiukovichy Raion, Belarus), activity concentrations of ^{137}Cs in fish have declined slowly in comparison with fish in rivers and open-lake systems, because of the slow decline in activity concentrations of ^{137}Cs in the water of the lakes [B22].

A121. The differences in bioaccumulation of radiocaesium in different fish species can be significant. For example, in Lake Svyatoe, Belarus, the activity levels in large pike and perch (predatory fish) were 5–10 times higher than in non-predatory fish such as roach. Similarly, bioaccumulation factors in lakes of low potassium concentration can be one order of magnitude higher than in lakes of high potassium concentration. Thus, it was observed [S15] that fish from lakes in agricultural areas of Belarus (where run-off of potassium fertilizer was significant) had lower bioaccumulation factors than fish from lakes in semi-natural areas.

(c) ^{90}Sr in freshwater fish

A122. Strontium behaves, chemically and biologically, in a similar way to calcium. Bioaccumulation of strontium occurs most strongly in low calcium (“soft”) waters. Relatively low bioaccumulation factors for ^{90}Sr in freshwater (of the order of 100 L/kg) and the lower deposition density of this radionuclide meant that the activity concentrations of ^{90}Sr in fish were typically much lower than those of ^{137}Cs. In 2000, for the lakes with higher activity levels around ChNPP, the maximum level of ^{90}Sr concentration in the muscles of predatory and non-predatory fish varied between 2 and 15 Bq/kg fresh weight. In 2002–2003, the activity concentrations of ^{90}Sr in fish in reservoirs of the Dnieper cascade were only 1–2 Bq/kg, which is close to the pre-accident levels. Freshwater molluscs showed significantly stronger bioaccumulation of ^{90}Sr than fish. In the Dnieper River, molluscs had approximately ten times more ^{90}Sr per kilogram in their tissues than fish muscle. Similarly, bioaccumulation of ^{90}Sr in the bones and skin of fish is approximately a factor of 10 higher than in muscle.

3. Radioactivity levels in marine ecosystems

A123. Marine ecosystems were not seriously affected by deposited material from the accident; the nearest seas to the reactor are the Black Sea (around 520 km) and the Baltic Sea (about 750 km). Activity levels increased in these seas primarily because of direct deposition from the radioactive cloud, with smaller inputs from riverine transport occurring over the years following the accident. The total surface deposition of ^{137}Cs was approximately 2.8 PBq on the Black Sea and 3.0 PBq on the Baltic Sea.

F. Countermeasures and remediation

A124. Since the very first days after the Chernobyl accident, countermeasures were instituted with the purpose of reducing doses to humans. The range of countermeasures applied was notably wide, i.e. from urgent evacuation in 1986 of inhabitants from the nearby areas of highest radionuclide deposition, to bans on the use of contaminated foodstuffs in many European countries [S16]. The whole spectrum of the applied countermeasures and their effectiveness has been considered in a number of international reports (e.g. [I17, U3]).

A125. This section does not consider specifically the past emergency mitigation actions at the ChNPP that were aimed at reducing and halting the radioactive releases to the environment. It considers neither the protection criteria and practices for workers involved in the emergency and mitigation actions, nor the practice and policy of evacuating 116,000 residents of the most contaminated areas of the former Soviet Union in 1986, and of subsequently relocating 220,000 additional residents in 1989–1992 [U3] from the contaminated areas to “clean” areas.

A126. Some countermeasures were applied directly to members of the general public, such as evacuation and relocation mentioned above. In addition, there was a variety of organized and self-selected temporary relocation of children from areas thought to be contaminated. In some cases, potassium iodide (KI) pills were distributed to residents with instructions on their use. Unfortunately, this distribution was not well organized and was of limited effectiveness in the more contaminated territories of Belarus, the Russian

Federation and Ukraine. The more successful experience of KI distribution in Poland is presented in appendix B in the context of the thyroid dose assessment.

A127. Countermeasures have been applied since 1986 in urban, agricultural, forest and aquatic environments. Many of these countermeasures were driven by the need to comply with relevant international or national radiological criteria; all countermeasures were driven by the goal of reducing doses to humans.

1. Decontamination of populated areas

A128. Decontamination of settlements was one of the main countermeasures applied to reduce external exposure of the public during the initial stage of the response to the accident. Analysis of the contributors to external dose for different population groups living in such areas revealed that a significant fraction of dose was received by people from radionuclides in soil, on coated surfaces like asphalt and concrete and, to a small extent, on building walls and roofs. This is why one of the more effective decontamination technologies involved removal of the upper soil layer.

A129. Following dry deposition, street cleaning, removal of trees and shrubs and ploughing gardens were efficient and inexpensive means of achieving substantial reductions in dose. Contaminated roofs were important contributors to dose, while contaminated walls were less important.

A130. Large-scale decontamination was performed in 1986–1989 in the cities and villages of the former Soviet Union with higher levels of activity. This was performed usually by military personnel and included washing of buildings with water or special solutions, cleaning of residential areas, removal of contaminated soil, cleaning and washing of roads, and decontamination of open water supplies. Special attention was paid to kindergartens, schools, hospitals and other buildings frequently visited by large numbers of persons. In total, about one thousand settlements were treated; this included cleaning tens of thousands of residences and social buildings and more than a thousand agricultural farms (e.g. [A7]).

A131. In the early period following the accident, there was concern that inhalation of resuspended radioactive particles of soil and nuclear fuel could significantly contribute to internal dose. To suppress dust formation, organic solutions were dispersed over contaminated plots, which after drying created an invisible polymer film. Streets in cities were sprayed with water to prevent dust formation and to wash the radionuclides into the sewerage system.[2]

A132. Depending on the decontamination technologies used, the dose rate over various measured plots was reduced by a factor of 1.5–15. But the high cost of these activities hindered their complete application to the areas deemed affected. Because of these limitations, the reduction in annual external dose was 10–20% for the average population, and ranged from about 30% for children attending kindergarten and schools to less than 10% for outdoor workers (herders, foresters, etc.). These data were confirmed by individual external dose measurements conducted before and after large-scale decontamination campaigns in 1989 in the Bryansk oblast of the Russian Federation [B12].

A133. Regular monitoring of decontaminated plots in settlements over a five-year period showed that after 1986 there was no significant recontamination and the exposure rate was decreasing over the long term. The averted collective dose from external exposure of 90,000 inhabitants of the 93 more affected settlements of the Bryansk oblast was estimated to be about 1,000 man Sv [B12].

A134. Since 1990, large-scale decontamination in the countries of the former Soviet Union has been abandoned, but particular plots and buildings with high measured radiation levels have been cleaned.

A135. Another continuing activity is the clean-up of industrial equipment and premises that were contaminated as a result of ventilation systems being operated during the release/deposition period in 1986 and immediately afterwards.

2. Agricultural countermeasures

A136. The implementation of agricultural countermeasures after the Chernobyl accident has been extensive, both in the most affected countries of the former Soviet Union and in western Europe. The main aim of agricultural countermeasures was the production of food products with activity concentrations of radionuclides below action levels. Many countermeasures were used extensively in the first few years after the accident and their application continues today. Generally, the earlier agricultural countermeasures were applied, the more cost-effective they were [P7]. Agricultural countermeasures have been reviewed by Fesenko et al. [F9].

(a) Early phase

A137. From 2–5 May 1986, about 50,000 cattle, 13,000 pigs, 3,300 sheep and 700 horses were evacuated from the 30-km zone together with the people [N8]. In the 30-km zone, more than 20,000 remaining agricultural and domestic animals were killed and buried. Owing to a lack of forage for the animals evacuated and difficulties in managing the large number of animals in the territories to which they were moved, many were subsequently slaughtered. In the acute period after the accident, it was not possible to differentiate the different levels of

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[2] The effectiveness of the early decontamination efforts in 1986 still remains to be quantified. However, according to Los and Likhtarev [L7] daily washing of streets in Kiev decreased the collective external dose to its 3 million inhabitants by 3,000 man Sv, and decontamination of schools and school areas saved an additional 600 man Sv.

contamination in animals and in the period of May–July 1986, the total number of slaughtered animals reached 95,500 cattle and 23,000 pigs.

A138. Many carcasses were buried and some were stored in refrigerators, but this presented great hygienic, practical and economic difficulties. Condemnation of meat was an immediately available and effective countermeasure to reduce potential doses from ingesting animal products and was widely used both in the former Soviet Union and elsewhere. However, this was very expensive and resulted in large quantities of contaminated waste.

A139. In the first weeks after the accident, the main aim of the countermeasures in the former Soviet Union was to lower the activity concentrations of ^{131}I in milk or to prevent milk with elevated radionuclide levels entering the human food chain. Recommendations were made to exclude contaminated pasture from animals' diets by changing to indoor feeding with "clean" feed; to conduct radiation monitoring and subsequently to reject milk at processing plants in which activity concentration of ^{131}I was above the national TPL (3,700 Bq/L at that time); and to process rejected milk (mainly by converting milk to storable products, such as condensed or dried milk, cheese or butter).

A140. In the first few days after the accident, the countermeasures were largely directed towards milk from collective farms and few private farmers were involved. Information on countermeasures for milk was confined to managers and local authorities and was not distributed to the private farming system of the rural population. This resulted in limited or delayed application of the countermeasures, especially in rural settlements where milk was privately produced; this resulted in low effectiveness of the countermeasures in some areas.

A141. Within a few weeks of the accident, feeding of animals with "clean" fodder began, because this had the potential to reduce ^{137}Cs levels in cattle to acceptable levels within 1–2 months. However, this countermeasure was not in widespread use at this stage, partly owing to a lack of "clean" feed early in the growing season.

A142. As early as the beginning of June 1986, maps were constructed of the density of radioactive deposition in the affected regions. This allowed estimates to be made of the extent of deposition on pasture and identification of where milk was likely to be contaminated.

A143. During the growing period of 1986, when there was still substantial surface contamination of plants, the major countermeasures in agriculture were of a restrictive nature. In the first few months, land severely contaminated was taken out of use, and recommendations were developed on suitable countermeasures that would allow continued production on less heavily contaminated land. In the more heavily contaminated regions, a ban was imposed on keeping dairy cattle. To reduce radionuclide levels in crops, an effective method was to delay harvesting of forage and food crops. Radiation control of products was introduced at each stage of food production, storage and processing.

A144. Based on a radiological survey performed from May to July 1986, approximately 130,000 ha, 17,300 ha and 57,000 ha of agricultural land were initially excluded from economic use in Belarus, the Russian Federation and Ukraine, respectively.

A145. From June 1986, other countermeasures aimed at reducing ^{137}Cs uptake into farm products were implemented as follows: banning cattle slaughter in regions where the levels of deposition of ^{137}Cs exceeded 555 kBq/m^2 (animals had to be fed clean food for 1.5 months before slaughter); minimizing external exposure and formation of contaminated dust by omitting some procedures normally used in crop production; limiting the use of contaminated manure for fertilization; preparing silage from maize instead of hay; restricting the consumption of milk produced in the private sector; obligatory radiological monitoring of agricultural products; and obligatory milk processing.

A146. Decontamination by removal of the top soil layer was found to be inappropriate for agricultural lands because of its high cost, destruction of soil fertility and severe ecological problems related to the burial of the contaminated soil.

A147. As early as August–September 1986, each collective farm received maps of ^{137}Cs deposition on their agricultural land and guidance on potential radionuclide levels in products, including instructions on farming of private plots.

A148. Sweden received some of the higher levels of deposition outside of the countries of the former Soviet Union. Initially, Sweden imposed controls on the ^{131}I and ^{137}Cs activities in imported and domestic foods. A range of other actions were taken: *(a)* cattle were not put onto pasture if the ground deposition exceeded 10 kBq/m^2 of ^{131}I or 3 kBq/m^2 of radiocaesium; *(b)* advice was given not to consume fresh leafy vegetables and to wash other fresh vegetables; *(c)* restrictions were placed on the use of sewage sludge as fertilizer for soil; *(d)* deep ploughing was recommended; and *(e)* a higher cutting level for harvesting grass was advised.

A149. In Norway, crops in fields were monitored after harvesting, and those with radiocaesium levels above 600 Bq/kg fresh weight were discarded and ploughed in. In addition, hay and silage harvested in June were monitored, and those with activity concentrations exceeding the guidelines were not used as forage.

A150. In Germany, some milk in Bavaria was diverted into food-processing plants to be converted into milk powder. It was intended to use the milk powder as feed for pigs, but this was not done owing to the high radiocaesium content.

A151. In the UK, advice was issued to regulate the consumption of some game in upland regions, and restrictions were imposed on the movement and slaughter of upland sheep from a number of the more affected areas.

A152. In Austria, there was advice not to feed fresh grass to cows for a short period in May 1986.

(b) Late phase

A153. Radiological surveys of agricultural products showed that by the end of 1986, four oblasts of the Russian Federation (Bryansk, Tula, Kaluga, and Orel), five oblasts of Ukraine (Kiev, Zhitomir, Rovno, Volyn and Chernigov) and three oblasts of Belarus (Gomel, Mogilev and Brest) had food products with activity concentrations of radiocaesium that exceeded the national TPLs. In the more affected areas of Gomel, Mogilev, Bryansk, Kiev and Zhitomir oblasts in the first year after the accident, the proportion of grain and milk exceeding the TPLs was about 80% [I17, N8].

A154. From 1987, high activity concentrations of radiocaesium in agricultural products were only observed in animal products; application of countermeasures aimed at lowering the activity concentrations of ^{137}Cs in milk and meat was the key focus of the remediation strategy for intensive agriculture. Potatoes and root vegetables were being produced in which the radiocaesium levels were acceptably low. In the second year, the activity concentrations of radiocaesium in grain were much lower than in the first year, and therefore countermeasure application ensured that most grain was below the TPLs. By 1991, less than 0.1% of the grain in all three countries had radiocaesium levels above 370 Bq/kg.

A155. The most difficult issue remaining was the production of milk in compliance with the adopted standards. However, large-scale application of a range of countermeasures (described below) made it possible to achieve a sharp decrease in the amount of animal products with activity concentrations of radiocaesium above the TPL in all three countries. The changes with time in the quantity of milk exceeding the TPLs can be seen in figure A-XX [N8]; however, it is important to note that the values of the TPLs have been reduced with time in each of the three countries, so the data are not directly comparable. Changes in the action levels in each country are shown in figure A-XXI [S14].

A156. Differences in the time trend in figure A-XX among the countries largely relate to changes in the national TPLs, but also to the scale of countermeasure application. This is particularly clear for Russian milk, where the activity concentrations of radiocaesium rose after 1997 owing to a reduction in the use of the countermeasure. The recent reduction in the quantity of meat above the national TPLs in Belarus and Ukraine is because animals are monitored before slaughter to ensure that the meat is below the required level. In the Russian Federation, where animals are also monitored before slaughter, the concentration values are higher, because they refer to meat from both private and collective farms. The small quantity of meat in each country now above the national TPL is largely due to the slaughter of animals that have been injured and have not been fed clean feed.

A157. The maximum dose-reduction effect due to countermeasure application was achieved in the period 1986–1992. Thereafter, because of financial constraints in the mid-1990s, the use of agricultural countermeasures was drastically reduced. However, by optimizing available resources the effectiveness of countermeasures remained at a level sufficient to maintain an acceptable ^{137}Cs content in most animal products.

(c) Countermeasures applied to intensive agricultural production

A158. The main countermeasures used in the former Soviet Union and later in the independent three countries are briefly described below. The focus was on chemical amendments to improve soil fertility and to reduce the uptake of radiocaesium by crops and plants used for fodder. The extent to which each measure was used varied among the three countries. The recommendations on which countermeasures to use were repeatedly revised and updated [A4, B19, P5].

(i) Soil treatment

A159. Soil treatment reduces the uptake of radiocaesium (and radiostrontium). The procedure can involve ploughing, reseeding and/or the application of nitrogen, phosphorus, potassium (NPK) fertilizers and lime. Ploughing dilutes the radioactive content originally in the upper soil layers where most plant roots absorb their nutrients. Both deep and shallow ploughing were used extensively; skim and burial ploughing was also used. The use of fertilizers increases plant production, thereby diluting the activity concentration in the plant. In addition, the use of fertilizers reduces plant–root uptake by decreasing the Cs:K ratio in the soil solution [A5].

A160. In the first few years after the accident, the focus was on radical improvement, which included greatly increased use of fertilizers. Commonly, high value legume and cereal grasses were grown on the treated land. The nature of the action and the efficiency of the radical improvement of hay fields and pastures strongly depended on the type of meadow and the soil properties. Traditional surface improvement, involving soil discing, fertilization and surface liming was less effective. Acid soil was limed. Some marshy plots were drained, deep ploughed, improved and used as grassland. In the 1990s, there was a greater focus on site-specific characteristics to ensure that the soil treatment used was the most appropriate and effective for the prevailing conditions. With time, repeated fertilization of already treated soils was necessary, but the appropriate application rates were carefully assessed. However, actual rates of application were sometimes constrained by availability of funds [A5, V1].

A161. The effectiveness of soil treatment is influenced by soil type, nutrient status and pH, and also the plant species selected for reseeding. In addition, the application rates of NPK fertilizers and lime affect the reduction achieved. Several studies have shown that the reduction factors achieved for soil–plant transfer of radiocaesium following radical improvement, liming and fertilization were in the range of 2–4 for poor, sandy soils and 3–6 for more organic soils. An added benefit was the reduction in external dose rate by a factor of 2–3 due to the dilution of the surface layer of radiocaesium after ploughing.

A162. Even though problems associated with ^{90}Sr were less acute than those with ^{137}Cs, some countermeasures were developed and a reduction of 2–4 in soil–plant transfer of radiostrontium following discing, ploughing and reseeding was achieved.

A163. Despite these countermeasures, in the more highly affected districts (raions) of the Bryansk oblast, levels of radiocaesium in 20% of pasture and hay on farms in the south-western zone still exceeded the national TPL in 1997–2000. Concentrations of ^{137}Cs in hay varied between 650 and 66,000 Bq/kg dry weight.

(ii) Change in fodder crops grown on affected land

A164. Some plant species take up less radiocaesium than others, as can be seen in figure A-XXII for experimental data collected in Belarus over the period 1997–2002 [B18]. The extent of the difference is considerable and fodder crops, such as lupin, peas, buckwheat and clover, which accumulate relatively high amounts of radiocaesium, were completely or partly excluded from cultivation.

A165. In Belarus, rapeseed is grown on affected areas with the aim of producing two products: edible oil and protein cake as animal fodder. Varieties of rapeseed are grown that are known to have a 2–3-fold lower uptake rate of ^{137}Cs and ^{90}Sr than many other varieties. When the rapeseed is grown, additional fertilizers (liming 6 t/ha and fertilization with $N_{90}P_{90}K_{180}$) are used to reduce the uptake of radiocaesium and radiostrontium into the plant by a factor of about two. This reduces the levels of radiocaesium in the seed used for the protein cake. During processing of the rapeseed, both radiocaesium and radiostrontium are effectively removed. During the last decade, the area under rapeseed cultivation has increased fourfold to 22,000 ha [B17].

(iii) Clean feeding

A166. The provision of uncontaminated feed or pasture to animals for an appropriate period before slaughter (so called “clean feeding”) effectively reduces the radionuclide content in meat and milk at a rate depending on the biological half-life for each radionuclide in the animal. The activity concentration of radiocaesium in milk responds rapidly to changes in the diet, as the biological half-life is a few days. For meat, the response time is longer owing to the longer biological half-time in muscle [P5].

A167. Clean feeding has been one of the more important and frequently used countermeasures for meat from agricultural animals in both the countries of the former Soviet Union and those of western Europe after the Chernobyl accident. Official estimates of the number of cattle treated were between 5,000 and 20,000 annually in the Russian Federation and 20,000 in Ukraine (supported by the government up to the year 1996). Clean feeding is routinely used in all three countries of the former Soviet Union for meat production and is combined with live monitoring of animals so that if the radionuclide concentrations in the animals’ muscles are above the national TPL, they can be returned to the farm for further clean feeding.

(iv) Administration of caesium binders

A168. Hexacyanoferrate compounds (commonly referred to as “Prussian Blue”) are highly effective radiocaesium binders; such compounds may be added to the diet of dairy animals and to meat-producing animals to reduce radiocaesium transfer to milk and meat by reducing absorption in the gut. These binders have a low toxicity and are safe to use. Many different formulations of hexacyanoferrates have been developed in different countries, partly to identify the most effective compound and partly to produce a cheaper, locally available product. Hexacyanoferrate compounds can achieve reduction factors in animal products of up to 10 [I16].

A169. Prussian Blue has been added to the diet of animals as a powder, incorporated into pelleted feed during manufacturing, or mixed with sawdust. In the Russian Federation, a locally manufactured hexacyanoferrate called ferrocyn (a mixture of 5% $KFe[Fe(CN)_6]$ and 95% $Fe_4[Fe(CN)_6]$) was developed. It has been administered as 98% pure powder, salt licks (10% ferrocyn) and in sawdust with 10% adsorbed ferrocyn (called bifege) [R5].

A170. Slow release boli containing hexacyanoferrate have also been developed, which are introduced into the animals rumen and gradually release the caesium binder over a few months. The boli, originally developed in Norway, consist of a compressed mixture of 15% hexacyanoferrate, 10% beeswax and 75% baryte [H6].

A171. Prussian Blue has been used to reduce the ^{137}Cs levels in animal products since the beginning of the 1990s. Prussian Blue application has been especially useful and effective in settlements where there is a lack of meadows suitable for radical improvement. In initial trials, Prussian Blue reduced the ^{137}Cs transfer from fodder to milk and meat by a factor of 1.5–6.0. In Belarus, a special concentrate with Prussian Blue is produced and distributed at a rate of 0.5 kg of concentrate per cow daily and an average reduction factor of 3 for milk has been achieved. Boli are given to dairy cows in intensive systems in both Belarus and the Russian Federation.

A172. In Ukraine, locally available clay-mineral binders have been used on a small scale. These local products are somewhat less effective than Prussian Blue, but cheaper.

A173. However, the use of Prussian Blue and similar compounds has not been universally successful. Boli can be difficult to administer, and adequate intake via salt licks has not always been achieved.

(d) Countermeasures applied to extensive agricultural production

A174. Extensive production in the three countries of the former Soviet Union is largely confined to the grazing of privately owned cows on poor, unimproved meadows. Because of the poor productivity of these areas, radiocaesium uptake is relatively high compared to that on land used by collective farms. Radical improvement of the meadows used by privately owned cows has been applied in all three countries since the early 1990s. Clean feeding is not generally used by private farmers, although on occasion, collective farms may supply private farmers with uncontaminated feed or pastures. Prussian Blue is used by private farmers in both Belarus and the Russian Federation. In the Russian Federation, all three Prussian Blue delivery systems are used, according to availability and preference.

A175. In extensive systems, such as the upland grazed areas in western Europe, the most commonly used countermeasures for free-ranging animals have been clean feeding, administration of caesium binders, monitoring of live animals, management restrictions, and changes in slaughter times. Many of these countermeasures were still in use in 2004. The application of long-term countermeasures has been most extensive in Norway and Sweden, but has also been applied in the United Kingdom and Ireland.

A176. AFCF, also called Prussian Blue, is a highly effective hexacyanoferrate compound achieving up to a 5-fold reduction in ^{137}Cs in lamb and reindeer meat and up to a 3-fold reduction in cow's milk and 5-fold reduction in goat's milk. The use of AFCF has been temporarily authorized in the EU and some other countries. AFCF as a caesium binder is effective in extensive production systems, in contrast to many other countermeasures where the applicability is limited. Boli are particularly favourable for infrequently handled free-grazing animals, as the boli can be administered when the animals are gathered for routine handling operations. For use in extensive systems, the boli can be given a protective surface coating of wax to delay the onset of AFCF release, so that its effectiveness is increased at the time when the animals are collected for slaughter. Brynildsen et al. [B21] estimated that the use of boli as a countermeasure for sheep was 2.5 times as cost-effective as feeding with uncontaminated feed. Salt licks containing AFCF have also been used, but are less effective.

A177. Management regimes have been modified for some animals in affected areas. For instance, slaughter times are modified to ensure that the activity concentrations of ^{137}Cs are relatively low. In the United Kingdom, the movement and slaughter of upland sheep in some areas are restricted and the animals are monitored to ensure that the activity concentration of ^{137}Cs is below the national action level before they are slaughtered. The use of monitoring is also important in maintaining public confidence in the products from affected areas. Such management regimes in some areas have proven to be more useful and practical countermeasures than the use of Prussian Blue.

3. Forest countermeasures

A178. Prior to the Chernobyl accident, countermeasures to offset doses due to large-scale radioactive contamination of forests had not been given significant international attention. However, in the three countries of the former Soviet Union, actions were taken to restrict activities in the more affected zones, which included significant areas of forestry [F3]. These actions were, in general, rather simple and involved restrictions on basic activities, such as access to forests and gathering wild foods and firewood. A major question remains as to whether any more complex or technologically based countermeasures can be applied in forests on a realistic scale.

4. Aquatic countermeasures

A179. In the context of an atmospheric deposition of radionuclides on both terrestrial and aquatic systems, it has been shown that doses to humans from terrestrial foodstuffs are, in general, much more significant than doses from drinking water and aquatic foodstuffs. However, for the Dnieper system, the river water transported radionuclides to areas that were not significantly affected by atmospheric deposition. This created significant anxiety in the population and a demand on decision makers to reduce radionuclide fluxes from the zone via the aquatic system. Many remediation measures were put in place, but because actions were not taken on an objective basis of dose reduction, most of these measures were ineffective. Moreover, radiation exposures to workers implementing these countermeasures were relatively high.

A180. To the Committee's knowledge, no countermeasures were required, or applied, in marine systems after the Chernobyl accident.

III. SUMMARY

A181. The largest nuclear reactor accident occurred at the Chernobyl nuclear power plant on 26 April 1986. It occurred during a low-power engineering test of the Unit 4 reactor. Improper, unstable operation of the reactor allowed an uncontrollable power surge to occur, resulting in successive steam explosions that severely damaged the reactor building and completely destroyed the reactor.

A182. The radionuclide releases from the damaged reactor occurred mainly over a 10-day period, but with varying release rates. Iodine-131, ^{134}Cs and ^{137}Cs were the more important radionuclides, because they were responsible for most of the radiation exposure of the general population. The releases of ^{131}I, ^{134}Cs and ^{137}Cs are estimated to have been 1,760 PBq, 47 PBq and 85 PBq, respectively. However, doses resulting from the accident have been estimated on the basis of environmental and thyroid or body measurements; thus, knowledge of the quantities released was not needed for that purpose.

A183. The three main areas of contamination, defined as those with a deposition density of ^{137}Cs greater than 37 kBq/m^2 (1 Ci/km^2), are in Belarus, the Russian Federation and Ukraine; they have been designated the Central, Gomel–Mogilev–Bryansk and Kaluga–Tula–Orel areas. Altogether, territories with an area of approximately 150,000 km^2 were designated as “contaminated” in the former Soviet Union. More than six million people lived in these areas.

A184. Outside the former Soviet Union, there were many areas in western Europe with a deposition density of ^{137}Cs in the range of 37–200 kBq/m^2. These regions represent an area of 45,000 km^2, or about one third of the contaminated areas found in the former Soviet Union.

A185. The environmental behaviour of deposited radionuclides depends on the physical and chemical characteristics of the radionuclide considered, on the type of deposition (i.e. whether dry or wet), and on the characteristics of the environment. For short-lived radionuclides, such as ^{131}I, the main pathway of exposure to humans was the transfer of radionuclides deposited on pasture grazed by cows or goats to milk. The consumption by humans of contaminated leafy vegetables was also an important pathway for some humans within a few weeks of the accident. Radionuclides deposited on vegetation are retained with an ecological half-time of about two weeks before removal to the ground surface and to the soil. For long-lived radionuclides such as ^{137}Cs, the long-term transfer processes from soil to foods consumed several weeks or more after deposition needed to be considered.

A186. Strontium and plutonium radioisotopes were also released, but were mostly deposited close to the reactor and were associated with fuel particles. The environmental mobility of these radionuclides contained in fuel particles has been low, but is increasing with time as the fuel particles dissolve. Most of the originally released radionuclides have disappeared by radioactive decay and ^{137}Cs is currently of most concern. For the future (more than 100 years) only plutonium isotopes and ^{241}Am will remain. However, the contribution of these very long-lived radionuclides to human exposure will be minimal.

A187. The deposition in urban areas in the nearest city of Pripyat and the surrounding settlements could have initially given rise to substantial external doses, which were averted by the evacuation of the public. The deposition of radioactive material in other urban areas has provided substantial contributions to dose during subsequent years after the accident up to the present.

A188. During the first weeks to months after the accident, the transfer of short-lived radioisotopes of iodine to milk was rapid and high, leading to substantial radiological problems in the former Soviet Union. Owing to the emergency situation and the short half-life of ^{131}I, there are few reliable data on the spatial distribution of the deposited radioiodine. Current measurements of ^{129}I may assist in estimating the ^{131}I deposition better, thereby improving the reconstruction of doses to the thyroid.

A189. The high concentrations of radioactive substances in surface water directly after the accident fell rapidly, and drinking water as well as water used for irrigation have very low concentrations of radionuclides today.

A190. At present, in most of the settlements subjected to radioactive deposition, the dose rates in air above solid surfaces have returned to the pre-accident background levels. Elevated dose rates in air remain mainly over undisturbed soil.

A191. From the summer of 1986 onwards, ^{137}Cs and ^{134}Cs in milk and meat were the dominant radionuclides of concern in agricultural products. During the first few years, substantial amounts of food were removed from human consumption. The highest activity concentrations of radiocaesium have been found in food products from forested areas, especially mushrooms, berries, game and reindeer. High activity concentrations of radiocaesium in fish occurred in lakes with slow or no turnover of water, particularly if the lake was also shallow and poor in mineral nutrients.

A192. There has been a particularly slow decrease since the initial deposition in activity concentrations of ^{137}Cs in some products from the forest, and some species of mushrooms are expected to have high activity concentrations of ^{137}Cs for decades to come. Under certain weather conditions, the biomass of mushrooms in autumn can be much higher than normal leading to relatively high seasonal increases in the activity concentrations of ^{137}Cs in game. Thus, it must not always be assumed that the activity concentrations of ^{137}Cs in animals will remain as they are now or decline each year.

A193. There have been large long-term variations in the activity concentrations of ^{137}Cs in food products owing not only to differences in deposition levels, but also to differences in soil types and management practices. In many areas, there are still food products, particularly from extensive agricultural production systems and forests, with activity concentrations of ^{137}Cs exceeding the action levels.

A194. The major and persistent problems in the affected areas occur in extensive agricultural systems with soils having a high organic content and animals grazing on unimproved pastures. This particularly affects rural residents in the former Soviet Union, who are commonly subsistence farmers with privately owned dairy cows.

A195. In general, there has been an initial substantial reduction in the transfer of ^{137}Cs to vegetation and animals, as would be expected because of weathering, physical decay, migration of radionuclides down the soil column and reductions in bioavailability. However, in the last decade, there has been little further obvious decline and long-term effective half-lives have been difficult to quantify.

A196. Because of dilution, there was never a high concentration of ^{137}Cs in marine fish in the Black Sea or the Baltic Sea.

A197. The Chernobyl accident led to an extensive set of actions by the authorities of the former Soviet Union who introduced a range of short- and long-term environmental countermeasures aimed at reducing the negative consequences. The countermeasures involved a great amount of human, economic and scientific resources.

A198. Some of the more important comments on countermeasures are as follows:

- Countermeasures applied in the early phase of the Chernobyl accident were only partially effective in reducing radioiodine intake via milk, because of the lack of timely information about the accident and advice on appropriate actions, particularly for private farmers.
- The most effective countermeasures in the early phase were exclusion of affected pasture from animal diet and rejection of milk (with further processing) based on radiation monitoring data. Feeding animals with “clean” fodder was effectively performed in some countries.
- The greatest long-term problem has been the radiocaesium content of milk and meat. In the former Soviet Union and later in the three independent countries, this has been addressed by the treatment of land used for fodder crops (including enhanced fertilization and cultivation changes), clean feeding and the application of caesium binders to animals that enabled most farming practices to continue in the affected areas and resulted in a large reduction in dose.
- Decontamination of settlements was widely applied in regions of the former Soviet Union during the first few years after the accident as a means of reducing external exposure of the public.
- The following forest-related restrictions widely applied in the former Soviet Union and later in the three independent countries and partially in Scandinavia, have reduced human exposure that would have resulted from residence in forests and use of forest products: restrictions on public and forest-worker access as a countermeasure against external exposure; restricted harvesting by the public of food products, such as game, berries and mushrooms (in the affected countries, mushrooms are readily consumed and, therefore, this restriction has been particularly important); and alteration of hunting practices aimed at avoiding consumption of meat with high seasonal levels of radiocaesium.
- The early restriction of drinking water and changing to alternative supplies reduced internal doses from aquatic pathways in the initial period. Restrictions on the consumption of freshwater fish have also proved effective in Scandinavia and Germany. It is expected that restrictions on the consumption of fish will remain, in a few cases (for so-called “closed lakes”) for several more decades.

Figure A-I. Estimated plumes for instantaneous releases on the dates and at the times (UTC) indicated taking into account the prevailing meteorological conditions [B24]

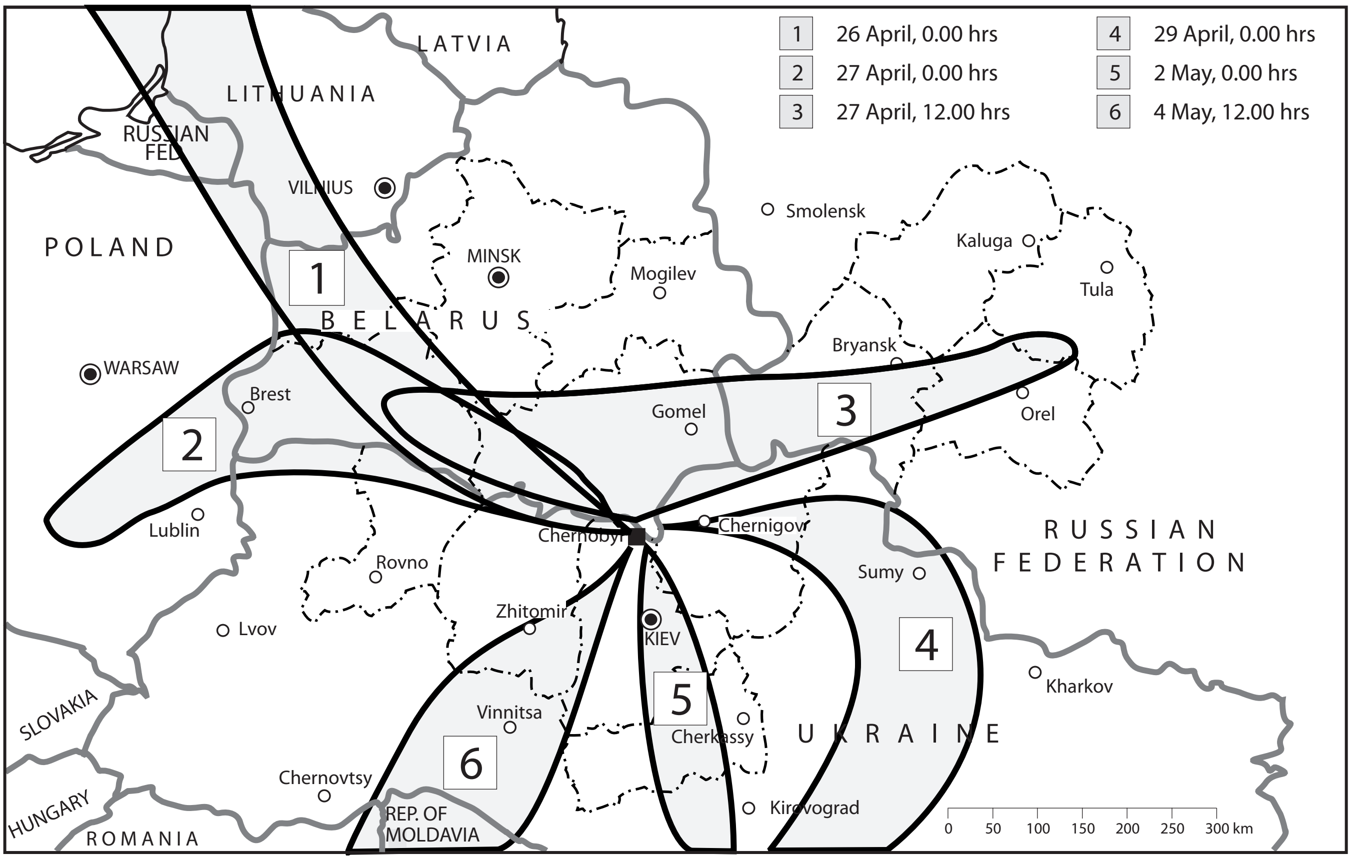


Figure A-II. Map of levels of ^{137}Cs deposition in 1989 in Belarus, the Russian Federation and Ukraine [I28]

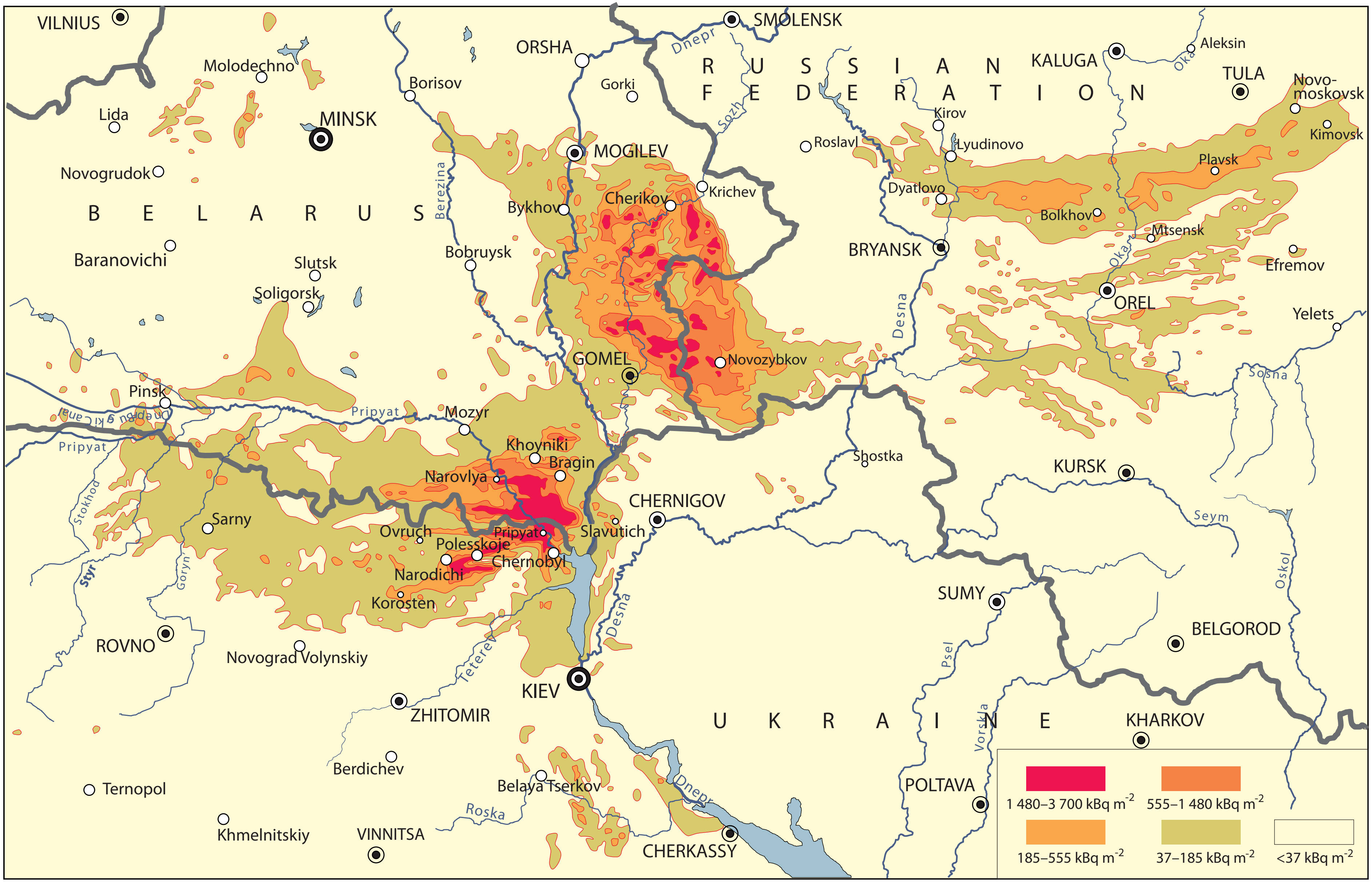


Figure A-III. The total amounts in the environment of various released radionuclides and their progeny as a function of time after the accident

While the amount of ^{241}Am originally released was very small, the total activity of ^{241}Am will increase with time due to the decay of ^{241}Pu. It will reach a peak after 72 years, after which it will slowly decline. After 320 years, the total activity of ^{241}Am will be the highest of all the remaining radionuclides

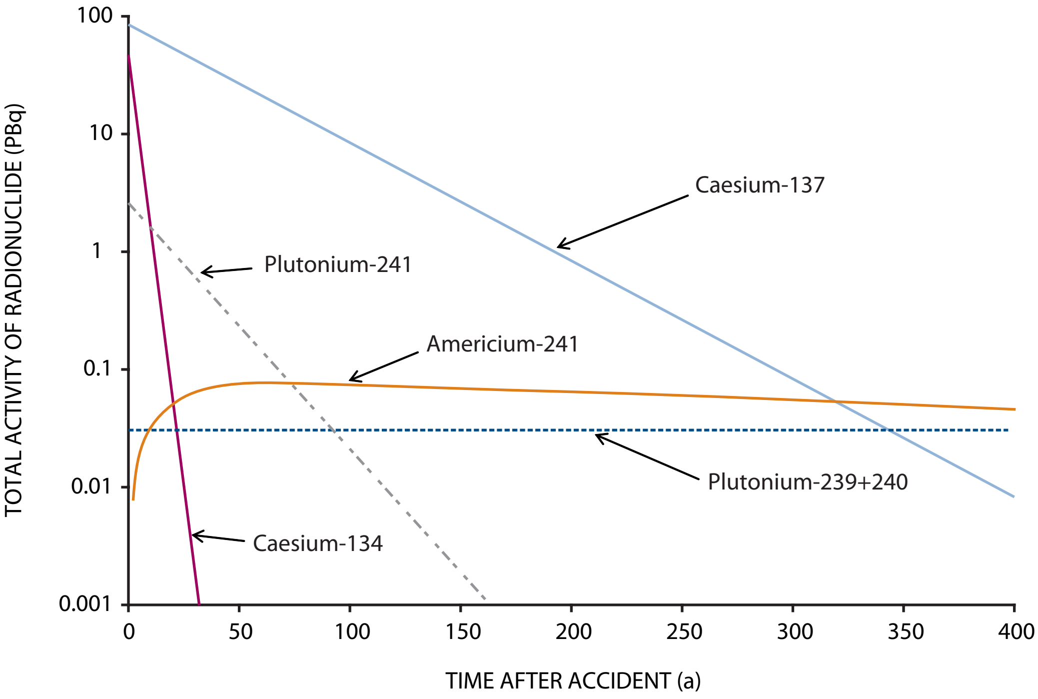


Figure A-IV. Rolling seven month mean concentration of ^{137}Cs in air at Baryshevka and Chernobyl (June 1986 to August 1994) [H5]

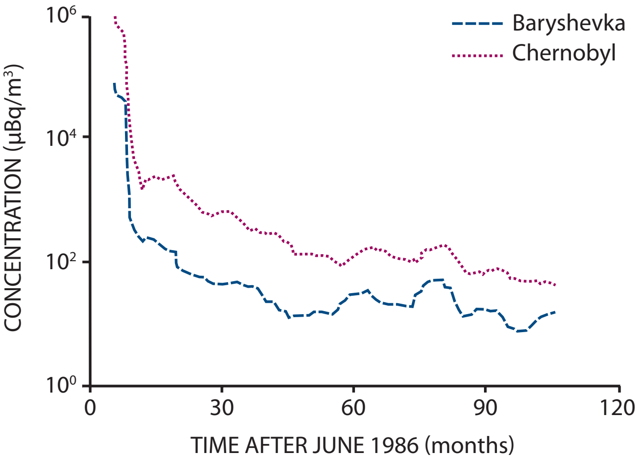
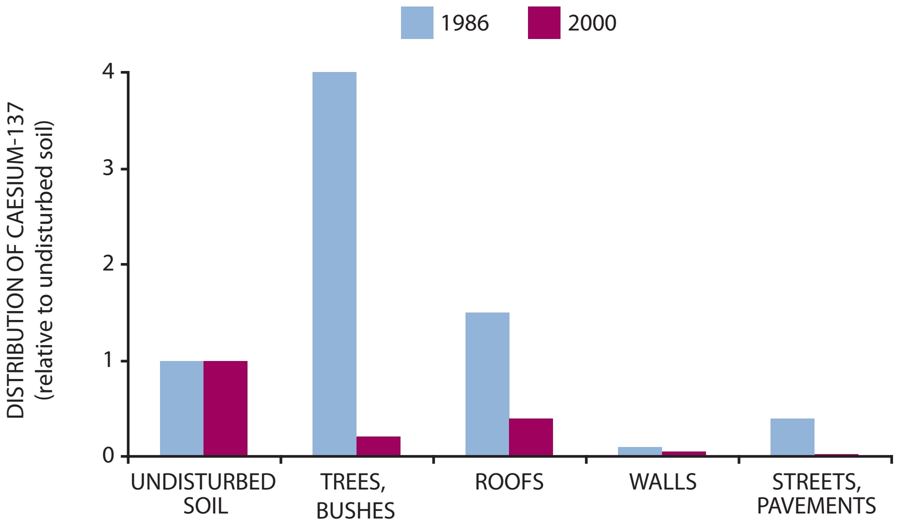


Figure A-V. Typical relative distribution of ^{137}Cs on different surfaces within settlements in 1986 and 14 years later (undisturbed soil deposition in 1986 or 2000 is taken equal to 1) [R10]

(a) Dry deposition



(b) Wet deposition

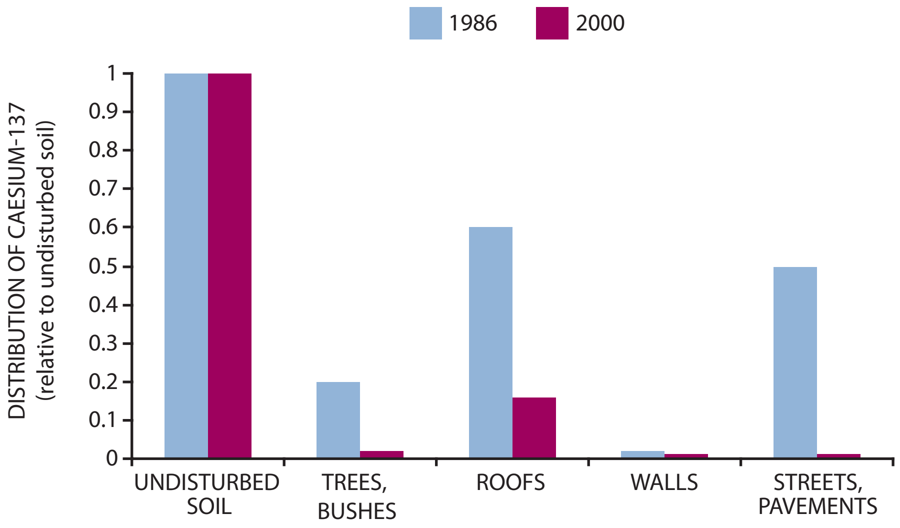


Figure A-VI. Measured ^{137}Cs activity levels (relative to the initial deposition on soil) on three types of roof at Risø, Denmark [A6]

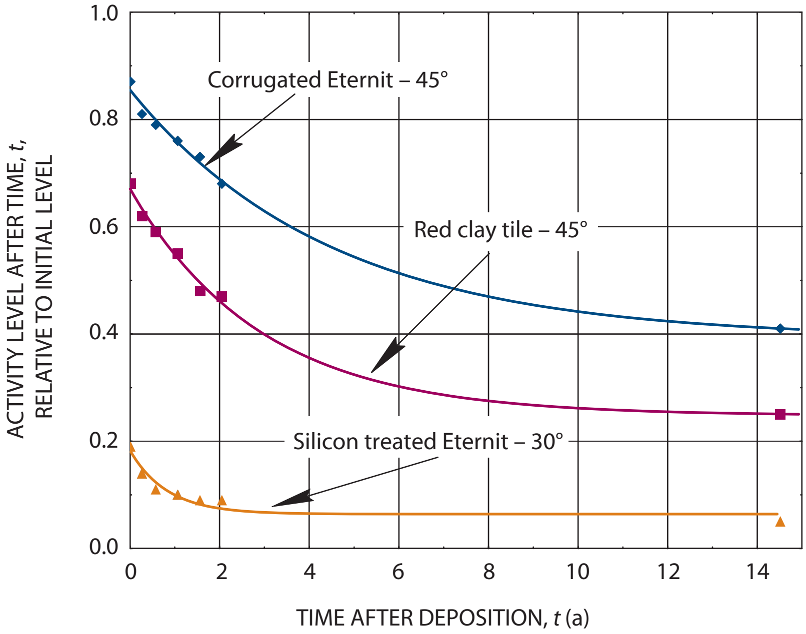


Figure A-VII. Ratio of the dose rate above different surfaces to that in open fields for the town of Novozybkov, the Russian Federation [G4]

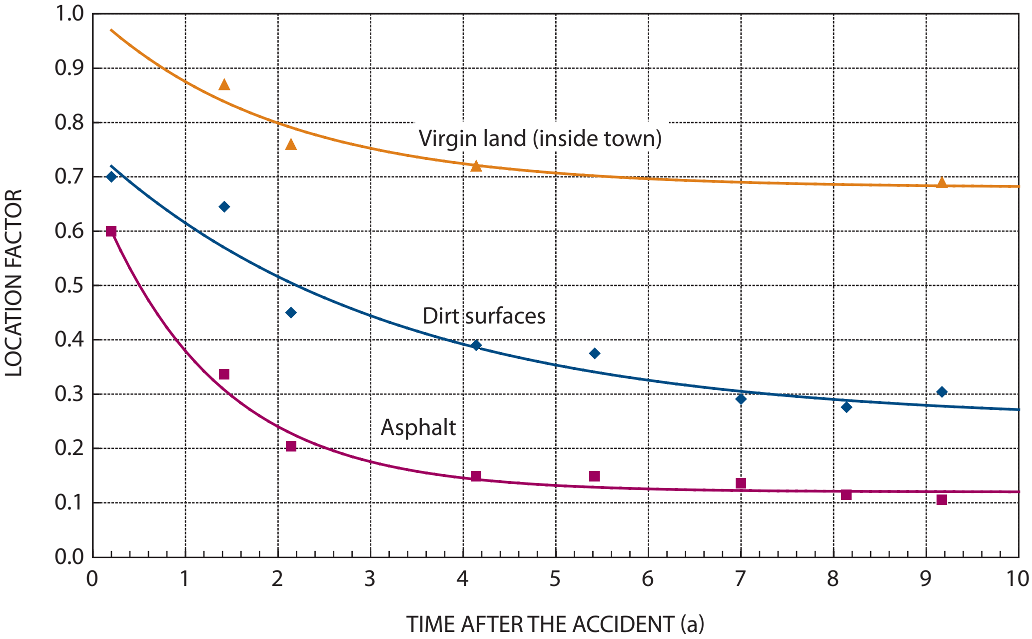


Figure A-VIII. The main transfer pathways of radionuclides in the terrestrial environment [S13]

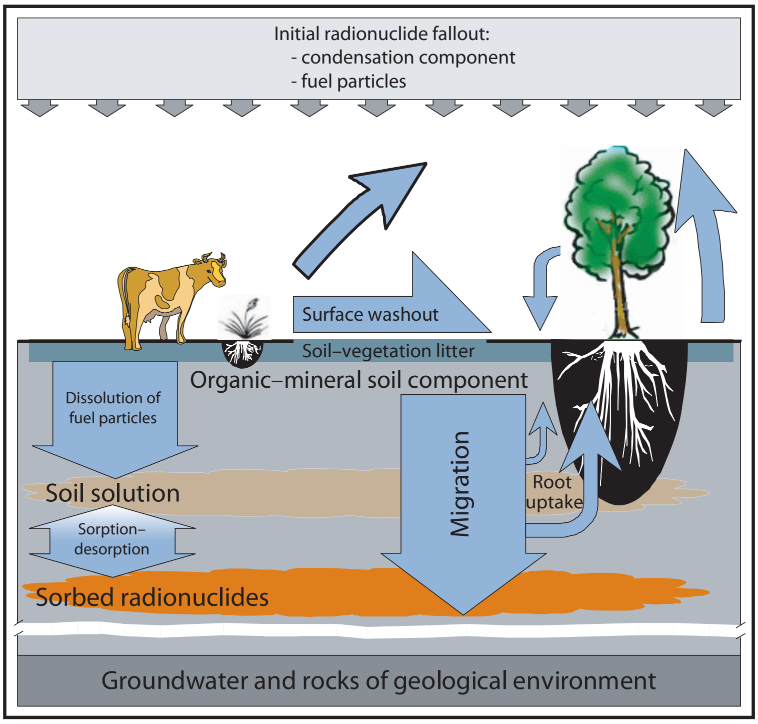


Figure A-IX. The activity concentrations of ^{137}Cs in cow milk near Munich following the Chernobyl accident as observed and as simulated by the ECOSYS-87 model [M9]

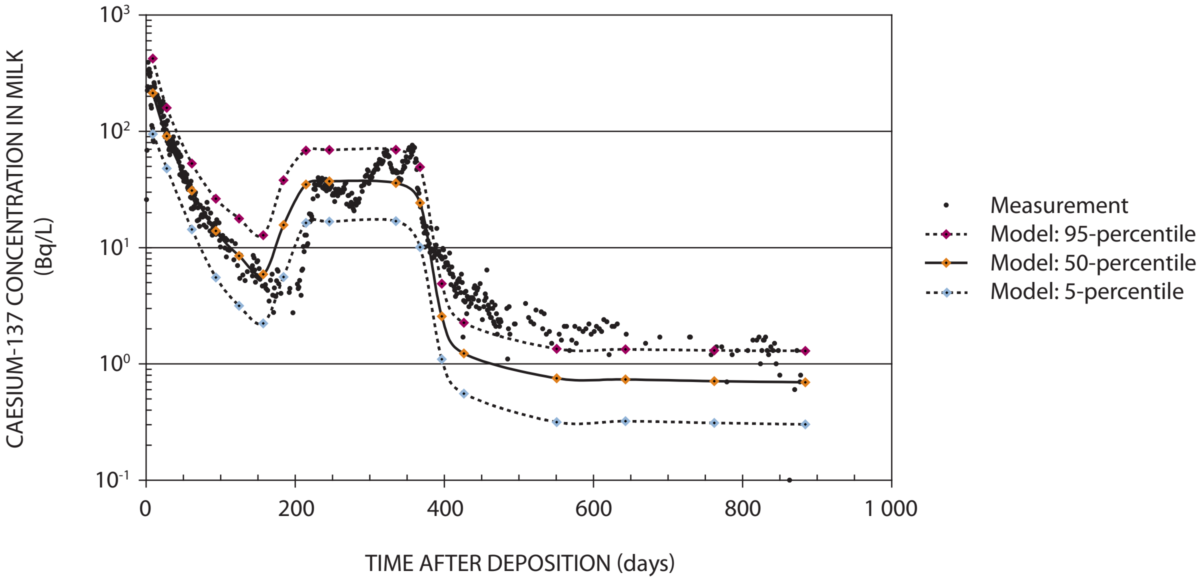


Figure A-X. Depth profiles for ^{137}Cs and ^{90}Sr measured in 1987 and 2000 in a soddy–gley–sandy soil (in % of total activity) [S14]

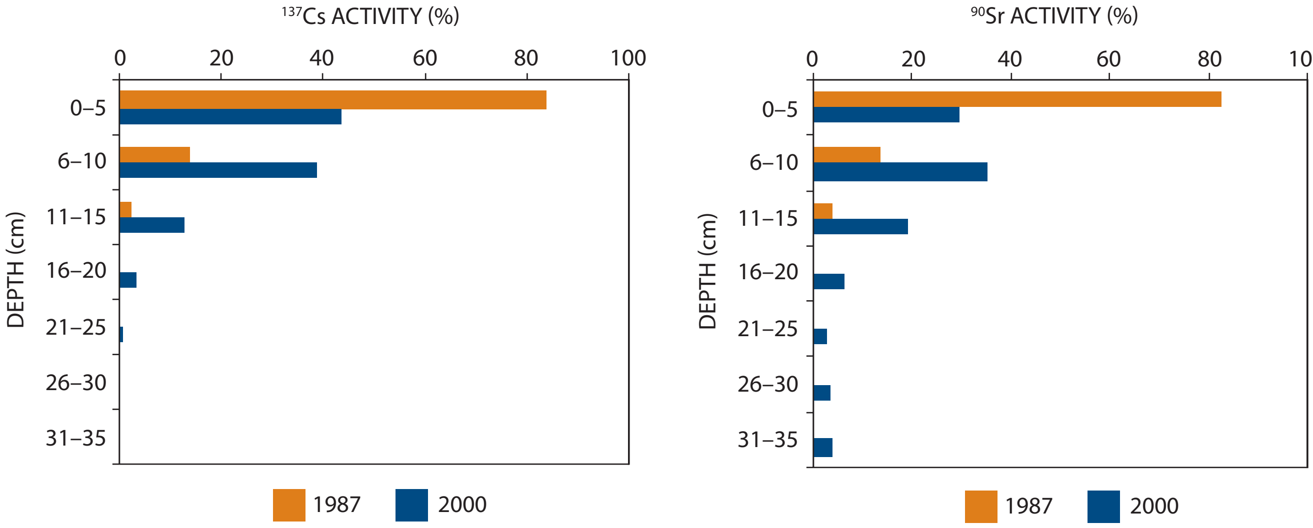


Figure A-XI. Pathways of radionuclide transfer from soil to plants, taking into account both biotic and abiotic processes [T8]

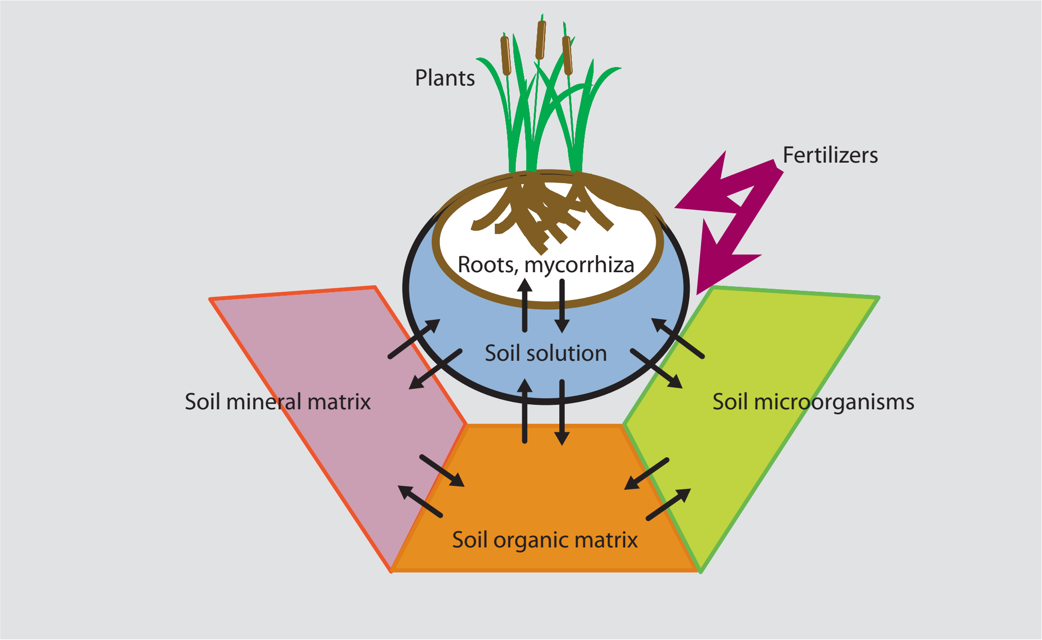
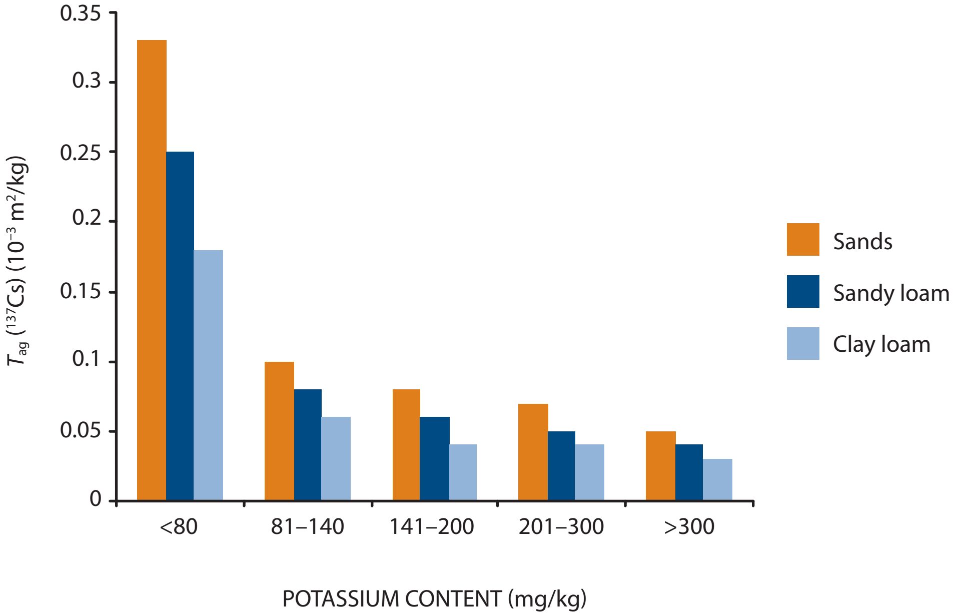


Figure A-XII. ***(a)*** **Transfer of ^{137}Cs into oat grain in soddy–podzolic soils of various textures with varying potassium contents [B25] and** ***(b)*** **transfer of ^{90}Sr into seeds of winter rye with varying concentrations of exchangeable calcium in different soils [K20]**

(a)



(b)

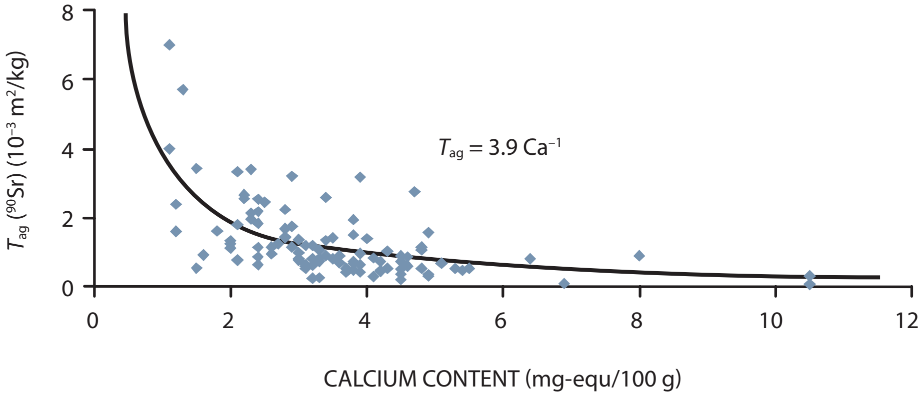


Figure A-XIII. Concentrations of ^{137}Cs in grain and potato produced in contaminated districts of the Bryansk oblast, the Russian Federation [F7]

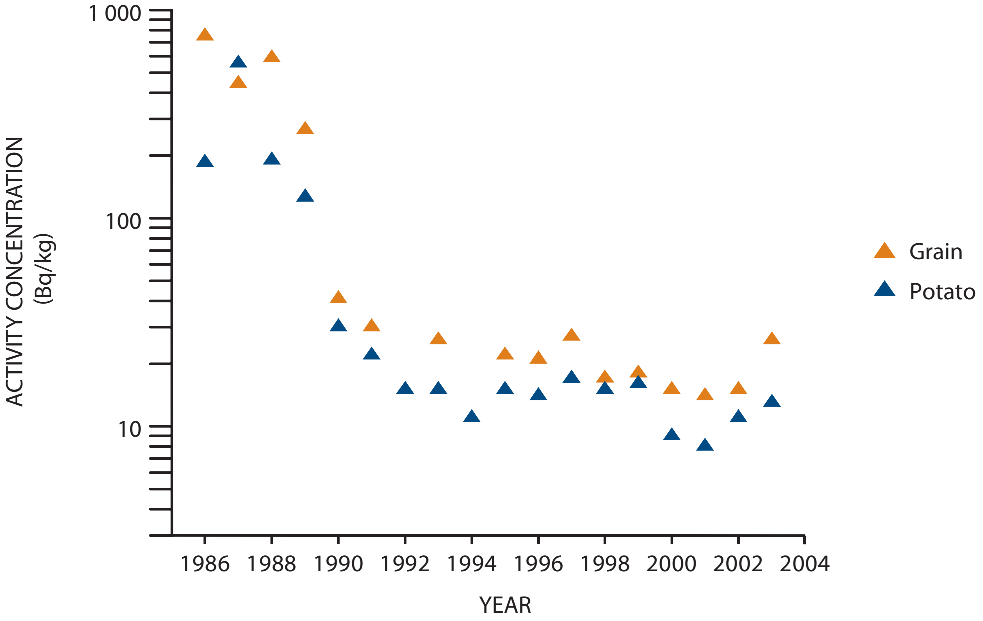


Figure A-XIV. Mean activity concentration of ^{137}Cs in meat and milk produced in contaminated districts of the Bryansk oblast, the Russian Federation [F7]

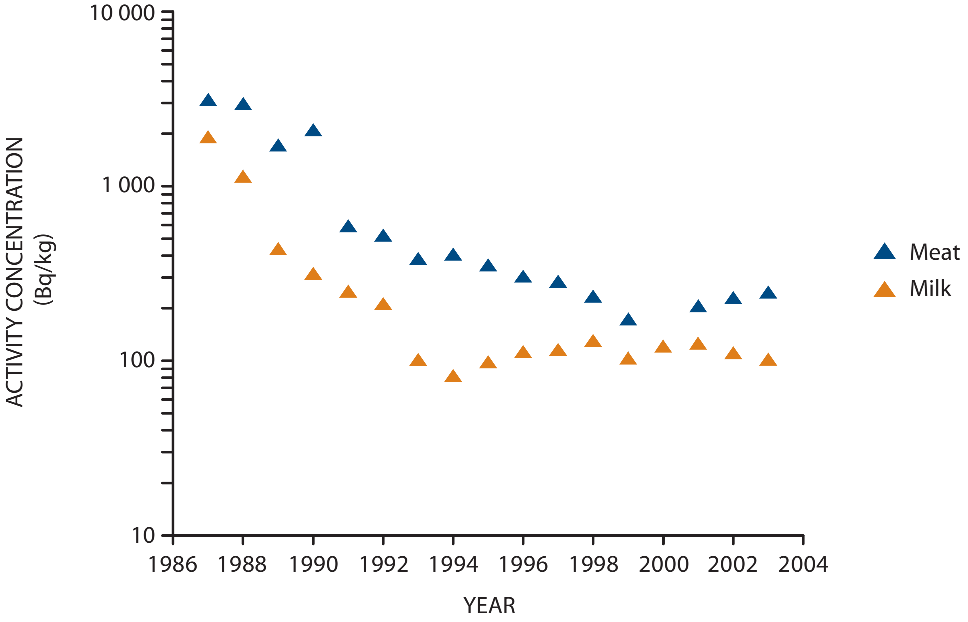
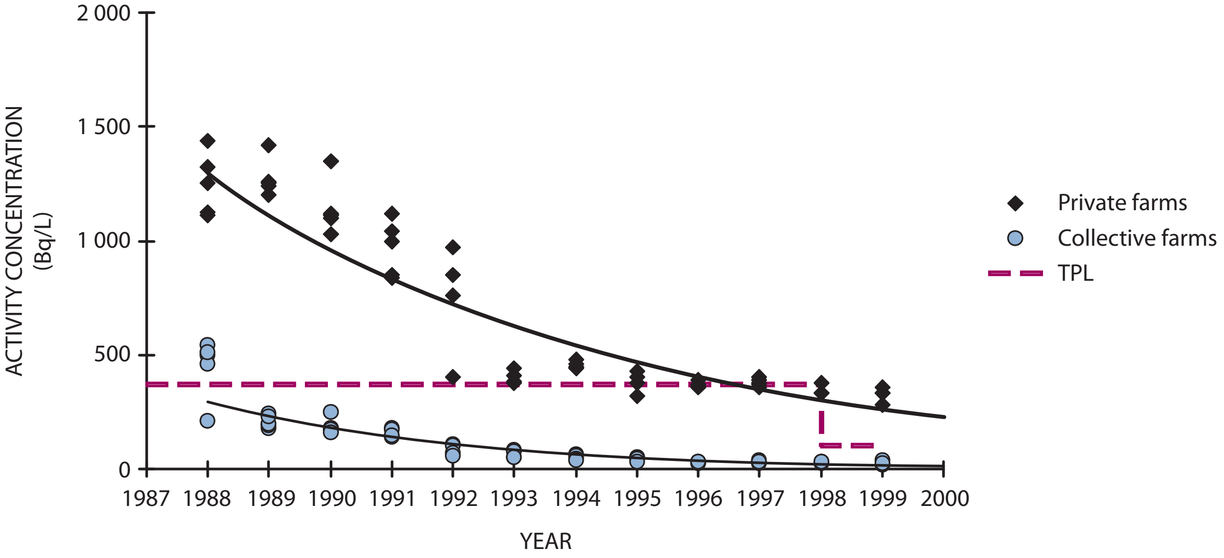


Figure A-XV. Typical dynamics of activity concentrations of ^{137}Cs in milk produced on private and collective farms in the Rovno oblast, Ukraine with a comparison to the national temporary permissible level (TPL) [P6][a]



[a] The current Codex Alimentarius Guideline Level for ^{137}Cs in food for use in international trade is 1,000 Bq/kg [C12].

Figure A-XVI. Estimated percentage distributions of radiocaesium among various components of coniferous forest ecosystems [S22]

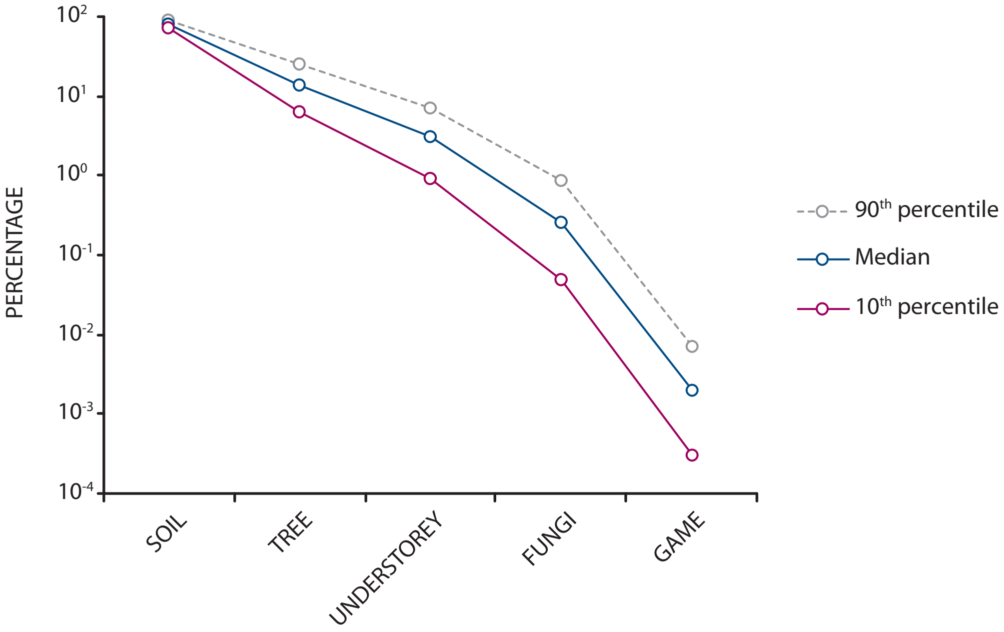


Figure A-XVII. Activity concentrations of ^{137}Cs in selected mushroom species

The mushrooms were harvested from a pine forest in the Zhytomir oblast of Ukraine, approximately 130 km southwest of Chernobyl (Bq/kg dry weight). The deposition density of ^{137}Cs in soil at this site in 1986 was 555 kBq/m^2 [I18]

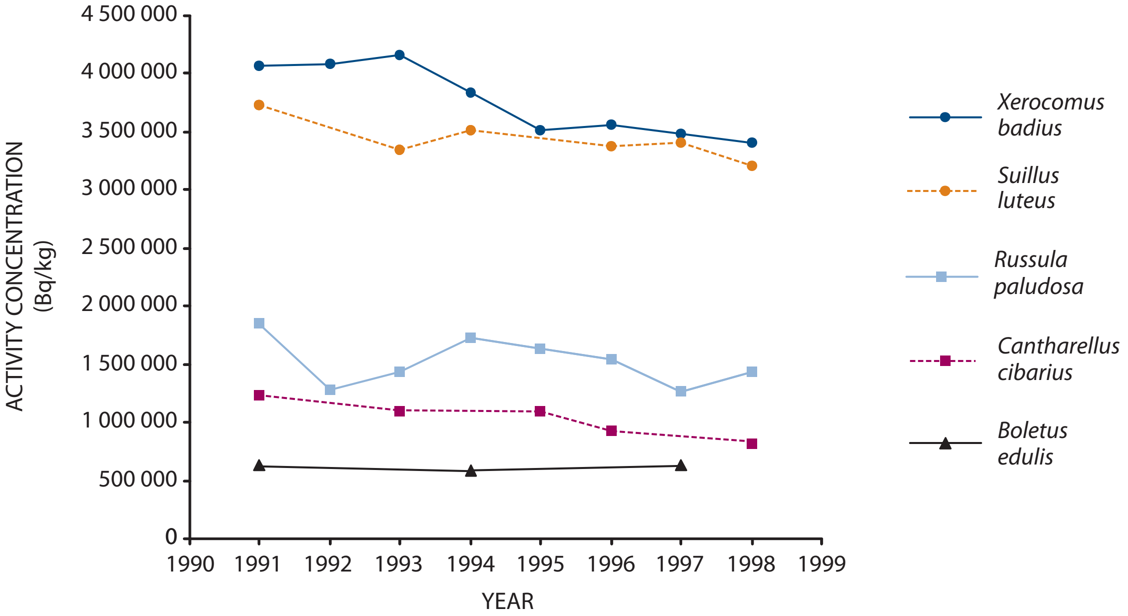


Figure A-XVIII. The average concentration of ^{137}Cs in moose in one hunting area in Sweden

The data are based on measurements of approximately 100 animals each year [J5]

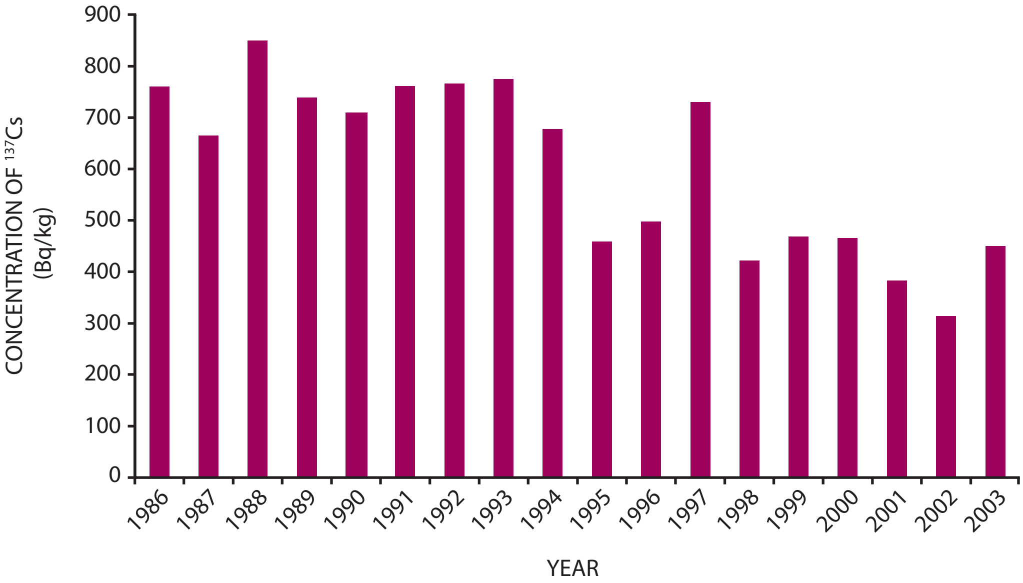


Figure A-XIX. Averaged activity concentrations of ^{137}Cs in fish from the Kiev reservoirs [U19]

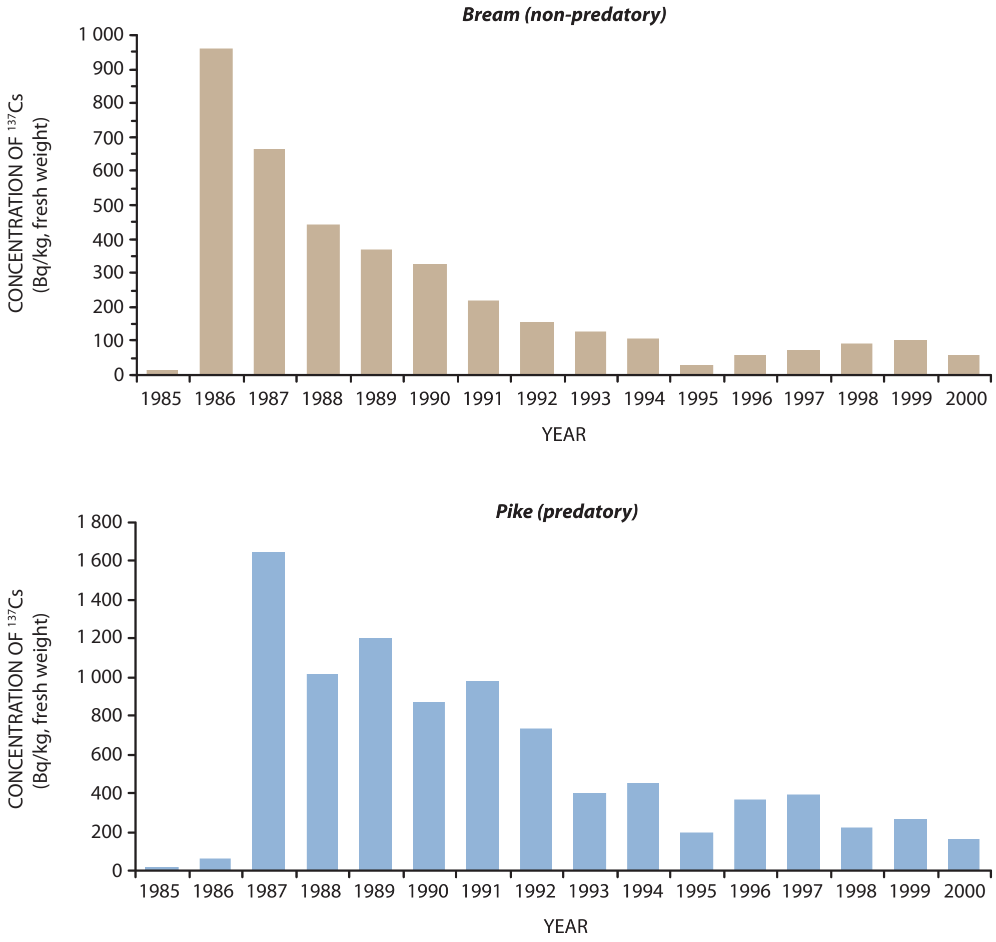


Figure A-XX. Amounts of milk and meat exceeding the temporary permissible levels in the Russian Federation (from collective and private farms), Ukraine and Belarus [N8]
These figures relate to milk and meat entering processing plants

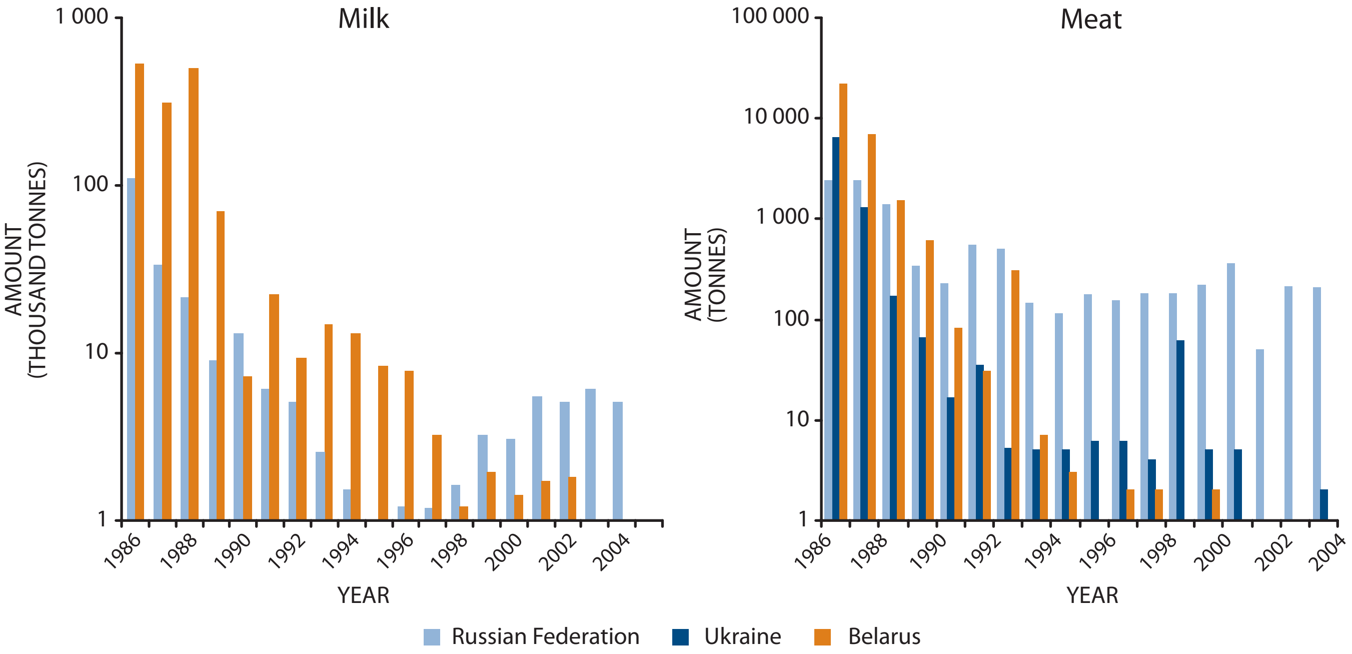
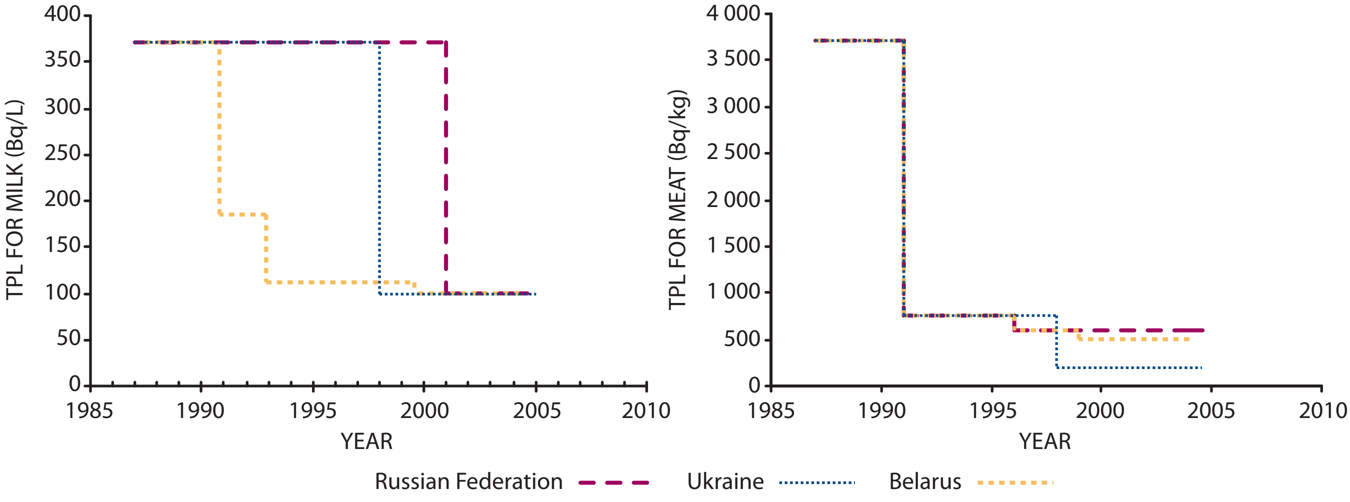


Figure A-XXI. Changes with time in temporary permissible levels (TPLs) in the former Soviet Union (until 1991) and later in the three independent countries [S14][a]



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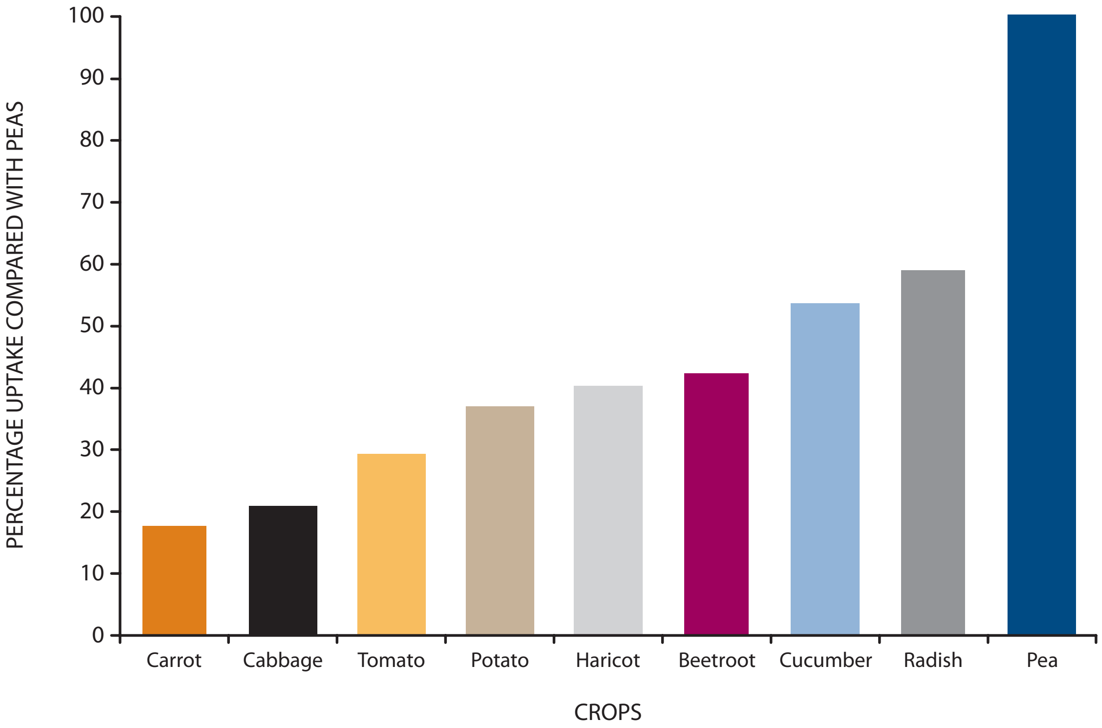
[a] The current Codex Alimentarius Guideline Level for ^{137}Cs in food for use in international trade is 1,000 Bq/kg [C12].

Figure A-XXII. Comparison of ^{137}Cs uptake in different crops normalized to that for peas [B18]



APPENDIX B.
RADIATION DOSES TO EXPOSED POPULATION GROUPS

I. SUMMARY FROM PREVIOUS UNSCEAR REPORTS

B1. Average doses from the radioactive fallout from the Chernobyl accident to populations of countries and some subregions within countries of the northern hemisphere were assessed in the annex D, “Exposures from the Chernobyl accident”, of the UNSCEAR 1988 Report [U7]. In its assessment, the Committee relied on the numerous environmental measurements performed during the first year following the accident and on general modelling. Occupational exposures were not included as information on the doses to workers participating in the accident mitigation and restoration work in the former Soviet Union was not then available. Furthermore, relatively little information was available on the radiation exposures of members of the public in the former Soviet Union.

B2. The general conclusion from the assessment of doses to members of the public was that “although populations were exposed in the countries of Europe and, to a lesser extent, in countries throughout the northern hemisphere, the radiation exposures were, in perspective, not of great magnitude” [U7].

B3. In Europe, the highest national average effective doses in the first year were 760 µSv in Bulgaria, 670 µSv in Austria, 590 µSv in Greece and 570 µSv in Romania. These were followed by other countries in northern, eastern and south-eastern Europe. The doses in countries further to the west in Europe and in the countries of Asia, Africa, and North and South America were much less, which is in accord with the radionuclide deposition patterns.

B4. The Committee predicted [U7] that “exposures, mainly from released ^{137}Cs, will continue for a few tens of years from the external irradiation and ingestion pathways”. Estimates of dose commitments were made for larger geographical regions, based on projection models that had been developed from measurements of the global fallout from the atmospheric testing of nuclear weapons. Doses to the entire population of the northern hemisphere were estimated from information on the relationship between the levels of ^{137}Cs deposition and distance from Chernobyl. The collective effective dose commitment to members of the public was estimated to be of the order of 600,000 man Sv.

B5. Updated information on radiation doses was provided in annex J, “Exposures and effects of the Chernobyl accident”, of the UNSCEAR 2000 Report [U3]. Doses were estimated for: *(a)* the workers who had been involved in the mitigation of the accident during the accident itself (“emergency workers”), and those who had been involved after the accident (“recovery operation workers”); and *(b)* members of the public who had been evacuated to avert excessive radiation exposures, and those who were still resident in the contaminated areas (defined as those areas in Belarus, the Russian Federation and Ukraine with a ^{137}Cs deposition density greater than 37 kBq/m^2). A large number of radiation measurements (with film badges, TLDs, whole-body counters, thyroid counters, and so on) had been made to evaluate the radiation exposures of the population groups that were considered.

B6. The highest doses were received by the emergency workers—of which there were approximately 600—who had been on the site of the Chernobyl nuclear power plant during the night of the accident. The most important exposures were due to external irradiation, because the intake of radionuclides via inhalation was relatively small in most cases. Acute radiation sickness was confirmed in 134 of the emergency workers. Forty one of these had received whole-body doses due to external irradiation of less than 2.1 Gy. Ninety three had received higher doses and had more severe acute radiation sickness: 50 persons had doses between 2.2 and 4.1 Gy; 22 between 4.2 and 6.4 Gy; and 21 between 6.5 and 16 Gy. The skin doses due to beta-radiation exposure, which were evaluated for eight of those with acute radiation sickness, ranged from 10 to 30 times the whole-body doses due to external irradiation.

B7. About 600,000 persons (civilian and military) received special certificates confirming their status as recovery operation workers (also known as “liquidators”), according to laws promulgated in Belarus, the Russian Federation and Ukraine. Of those, about 240,000 were military servicemen. The principal tasks carried out by the recovery operation workers included decontamination of the reactor block, reactor site and roads, as well as construction of the “sarcophagus” to cover the damaged reactor, a town for reactor personnel and waste repositories. These tasks had been completed by 1990.

B8. An official registry of recovery operation workers had been established in 1986. This registry included estimates of doses due to external irradiation, which was the predominant pathway of exposure for these workers. The registry data showed that the average recorded doses decreased from year to year, being about 0.17 Sv in 1986, 0.13 Sv in 1987, 0.03 Sv in 1988, and 0.015 Sv in 1989. It was generally difficult, however, to assess the validity of the results that had been reported for a variety of reasons, including: *(a)* the fact that different dosimeters had been used by different organizations, without any intercalibration; *(b)* the large number of recorded doses that were very close to the dose limit; and *(c)* the large number of rounded values, such as 0.1 Sv, 0.2 Sv or 0.5 Sv. Nevertheless, it seemed reasonable to assume that the average effective dose due to external gamma irradiation to recovery operation workers in the years 1986–1987 was about 0.1 Sv.

B9. The radionuclide releases from the damaged reactor had led to deposition of radioactive material over large areas, which resulted in radiation doses to members of the public. The radionuclide releases occurred mainly over a 10-day period, with varying release rates. The most important radionuclides to consider were ^{131}I and ^{137}Cs. Iodine-131 was the main contributor to the thyroid doses, received mainly via internal irradiation within a few weeks after the accident. In contrast, ^{137}Cs was (and remained) the main contributor to the doses to organs and tissues other than the thyroid, due to either internal or external irradiation; these doses would continue to be received at low rates over several decades.

B10. Within a few weeks of the accident, approximately 116,000 persons had been evacuated from the areas of Belarus and Ukraine with the highest deposition levels of radionuclides. The thyroid doses received by the evacuees varied according to their age, place of residence and date of evacuation. For example, for the residents of Pripyat, who had been evacuated essentially within 48 hours after the accident, the population-weighted average thyroid dose was estimated to be 0.17 Gy, and to range from 0.07 Gy for adults to 2 Gy for infants. For the entire population of evacuees, the population-weighted average thyroid dose was estimated to be 0.47 Gy. Doses to organs and tissues other than the thyroid had been, on average, much smaller.

B11. Thyroid doses were also estimated for residents of the contaminated areas who had not been evacuated. In each of the three republics, thyroid doses exceeding 1 Gy were estimated for the most exposed infants. For residents of a given locality, thyroid doses to adults were smaller than those to infants by a factor of about 10. The average thyroid dose received by the population of the three republics was estimated to be 7 mGy.

B12. Following the first few weeks after the accident when ^{131}I had been the main contributor to the radiation exposures, doses were delivered at much lower dose rates by radionuclides with much longer half-lives. Since 1987, the doses received by the populations of the contaminated areas resulted essentially from external exposure due to ^{134}Cs and ^{137}Cs deposited on the ground and from internal exposure due to incorporation of ^{134}Cs and ^{137}Cs into foodstuffs. Other, usually minor, contributions to the long-term radiation exposures included that due to the consumption of foodstuffs containing ^{90}Sr and to the inhalation of aerosols containing isotopes of plutonium. Both external irradiation and internal irradiation due to ^{134}Cs and ^{137}Cs resulted in relatively uniform doses to all organs and tissues of the body. The average effective doses due to ^{134}Cs and ^{137}Cs that had been received during the first 10 years after the accident by the residents of contaminated areas were estimated to be about 10 mSv. The median effective dose was about 4 mSv and only about 10,000 people were estimated to have received effective doses greater than 100 mSv. The lifetime effective doses were expected to be about 40% greater than the doses received during the first 10 years following the accident.

II. UPDATE

B13. The Committee has updated the dose estimates for the same population groups as in annex J, “Exposures and effects of the Chernobyl accident”, of the UNSCEAR 2000 Report [U3]. In addition, dose estimates have been updated for the populations residing in all areas of Belarus and Ukraine, as well as for those residing in specific areas of the Russian Federation. Some information is also provided for the populations exposed in more distant European countries.

B14. A thorough analysis of the possible radiation-induced health effects in emergency and recovery operation workers and in members of the public requires an adequate dosimetric basis so as to determine such matters as the radiation risk coefficients and the dose–effect relationship. It is generally recognized that the most suitable dosimetric parameters for epidemiological studies are absorbed doses in organs or tissues, complemented by information on the linear energy transfer (LET) of the radiation and the dose rate. Following the Chernobyl accident, both workers and members of the public were exposed, externally and internally, to low-LET beta and gamma radiation.

B15. In the studies that focused on the acute radiation effects in emergency workers [U7], the absorbed dose in the whole body (red bone marrow) and to the skin were used. These doses were reconstructed from biological indicators, such as blood cell concentration and cytogenetic parameters. However, in many studies of the long-term radiation-induced health effects in various cohorts exposed as a consequence of the accident, also including those undertaken for this report, some other dosimetric quantities were used that were not originally intended for use in an analysis of the dose–effect relationship. For example, the exposures of the recovery operation workers to external gamma radiation were usually recorded in terms of the physical quantity “exposure in air” (expressed in units of roentgen) and later, for storing in electronic databases, converted to absorbed doses (expressed in milligray) by simple multiplication by a factor of ten. Although exposure in air is generally not sufficient for determining the dose in the human body, nevertheless, for the typical conditions of post-accident exposure (360º rotational geometry and mean gamma radiation energy of 0.6-0.8 MeV), the absorbed dose calculated in this way is close to the absorbed dose in surface body tissues. However, the absorbed dose in organs and tissues located deeper is a factor of 1.2-1.8 lower for the same exposure conditions [G11, I33]. The lengths of time that the recovery operation workers were exposed to radiation were estimated using information on the duration of work on-site or in other radioactively contaminated areas; these usually ranged from a few days to some months.

B16. The dosimetric assessments for the studies of the radiation effects on the thyroid were, from the very beginning, based on the mean absorbed dose in the thyroid (expressed in gray or milligray), which was considered to be an adequate quantity for this purpose. The duration of thyroid exposure was estimated from the physical half-life, the half-time of reduction of the activity concentrations in food, and the retention in the thyroid of ^{131}I, which was the major contributor to the thyroid dose. The effective half-life of ^{131}I in the thyroid was five to seven days, depending on age, which corresponds to a duration of exposure of about one month.

B17. The external and internal exposure of members of the general public due to the mixture of radionuclides in the environment (dominated by ^{137}Cs and ^{134}Cs) were usually presented in terms of effective dose (expressed in millisieverts). However, as stated elsewhere, effective dose is a quantity developed for radiation protection purposes and is not directly applicable to the interpretation of data on health effects. The quantity, effective dose, incorporates judgements on radiation quality and on the relative radiosensitivity of organs and tissues with regard to stochastic health effects, and its use, therefore, is not applicable to dose–effect analysis. The fact that it was widely used is due to its importance in modern radiation protection [I30, I33] and the availability of nominal dose coefficients for both external and internal exposures that have been developed by the ICRP. However, for relatively isotropic external exposure of a human body to gamma radiation from radionuclides distributed in the environment and for relatively uniform internal exposure due to incorporated ^{137}Cs and ^{134}Cs, the numerical values of absorbed dose (in milligray) in many organs and tissues are within about 30% of the numerical values of effective dose (in millisieverts). The estimates of effective dose due to internal irradiation that are presented in this appendix do not include any contribution from the intakes of radioiodine and radiotellurium, whereas the contribution from these radionuclides was taken into consideration in the estimation of doses due to external irradiation. Public exposure due to radionuclides deposited in the environment following the accident has extended over several decades, with the contribution of the first year's dose being 30-40% of the lifetime dose. The estimates of effective dose due to external irradiation represent the dose received during the period under consideration, whereas doses due to internal irradiation (i.e. committed doses) reflect the doses over the entire period that the radionuclide is present in the body until its decay and clearance.

B18. A very large number of scientific papers, books, reports and conference proceedings have been published in Russian, English and other languages on various dosimetric aspects of the Chernobyl accident. Key references in the English literature include the two main reports of the Chernobyl Forum [I21, W5], the two previous reports of the Committee [U3, U7] and many books and conference proceedings [A8, E4, I25, I29, I34, K21, K29, M12, M17, N13, N15, N16, V2, V3, Y2, Y3]. Most of the material presented here is based on the four main reports prepared by the United Nations or its agencies [I21, U3, U7, W5], with complementary information taken from recent publications and submitted by focal points in Belarus, the Russian Federation and Ukraine.

A. Workers involved in response and recovery

B19. The emergency workers were those involved in responding to the accident, such as fire-fighting, during the first day (26 April 1986). The recovery operation workers were those involved during 1986–1990 at the power station or in the zone surrounding it in decontamination work, sarcophagus construction and other recovery operation activities. Those workers who operated the other units of the nuclear power plant were also included in this group.

1. Emergency workers

B20. Information on the emergency workers who received very high doses was reviewed in detail in annex J, "Exposures and effects of the Chernobyl accident", of the UNSCEAR 2000 Report [U3]. The 134 emergency workers who had been diagnosed with acute radiation sickness received whole-body (or bone-marrow) doses due to external gamma radiation ranging from 0.8 to 16 Gy. The skin doses to some individuals exceeded the bone-marrow doses by a factor of 10–30; some received skin doses that were estimated to be in the range of 400 to 500 Gy [M13]. Doses had been estimated mainly using clinical dosimetry methods, i.e. analysis of blood counts and/or cytogenetic parameters of blood lymphocytes [U3]; these methods are appropriate for small numbers of human subjects but not for large-scale epidemiological studies.

2. Recovery operation workers

B21. The main pathway of exposure of the recovery operation workers was external gamma irradiation from the radioactive material deposited on the ground and building surfaces.

These external doses were recorded in national registries for about half of the workers. Effective doses and absorbed doses to the skin and the lens of the eye from external beta irradiation, and to the thyroid from internal irradiation were only estimated for a limited number of workers.

(a) Doses due to external irradiation by gamma-ray emitters

B22. Estimates of doses to the recovery operation workers resulting from external gamma irradiation could be obtained from assessments conducted either at the time of exposure or subsequently. At the time of exposure, three methods were used: *(a)* individual dosimetric measurements for atomic energy workers and a small fraction of the military personnel after June 1986; *(b)* group dosimetric measurements (i.e. through the use of an individual dosimeter worn by one member of a group of recovery operation workers assigned to perform a particular task; all members of the group were assumed to receive the same dose); and *(c)* prior assessment of dose to a group of recovery operation workers based on the dose rate at the work location and the planned duration of work. Methods *(b)* and *(c)*, either separately or combined, were used to assess the doses to the majority of the military personnel at all times. Subsequently, retrospective assessments of dose were undertaken. The methods included: *(d)* time-and-motion studies (i.e. measurements of gamma-radiation levels were made at various points of the reactor site, and an individual's dose was estimated as a function of the points where he or she worked and the time spent in these places); and *(e)* biodosimetry (i.e. electron paramagnetic resonance (EPR) measurements on teeth, or fluorescence in-situ hybridization (FISH) measurements on blood lymphocytes). So far, method *(e)* has only been used for validation purposes on a limited number of workers [W5]. At the time of the clean-up work in 1986–1990, all radiometric and dosimetric devices were calibrated in terms of the physical quantity, exposure rate (expressed in units with symbols, mR/h or R/h), but the results that are reported in the scientific literature are usually in terms of absorbed dose (expressed in milligray) or of effective dose (expressed in millisieverts), using the approximation that 1 R = 10 mGy = 10 mSv. In this appendix the results are given in terms of absorbed dose.

B23. The main sources of uncertainty associated with the different methods of dose estimation are as follows: for *(a)* individual dosimetry: incorrect use of dosimeters (inadvertent or deliberate actions leading to either an overexposure or an underexposure of the dosimeters); for *(b)* and *(c)* group dosimetry: very high gradient of exposure rate at the working places at the reactor site; for *(d)* time-and-motion studies: deficiencies in data on itineraries and time spent at the various working places, combined with uncertainties in the exposure rates; and for *(e)* biodosimetry: a relatively high signal from background radiation, which prevents additional low doses from being measured precisely, and a lack of knowledge of the doses from other natural and artificial sources of radiation exposure [W5]. A high degree of conservatism was used in the early applications of method *(e)*. Uncertainties associated with the different methods of dose estimation have been assessed to be: up to 50% for method *(a)* (if the dosimeter was correctly used); up to a factor of 3 for method *(b)*; and up to a factor of 5 for methods *(c)* and *(d)* [P1]. The uncertainty of the EPR dosimetry used in method *(e)* has been assessed to have an absolute value of 25 mGy (one standard deviation) at doses below about 250 mGy, and a relative value of about 10% at doses above 250 mGy [C15].

B24. Altogether, the national registries of Belarus, the Russian Federation, Ukraine, Estonia, Latvia and Lithuania include, as of 2006, information on about 500,000 recovery operation workers and the recorded doses due to external gamma irradiation for about 250,000 of them (table B1). These numbers are different from those of the previous UNSCEAR report [U3] and from those of the more recent Chernobyl Forum report [W5] because: *(a)* updating of the national registries has continued since 2000; and *(b)* data on workers from the three Baltic countries are now included. As a result, the information includes data on 38% more recovery operation workers than in 2000 [U3]. The number of workers who were designated as recovery operation workers decreased from year to year. The average of the recorded doses also decreased; the mean dose was about 150 mGy in 1986, 100 mGy in 1987, and 40–50 mGy in 1988–1990. The decrease in recorded doses with time after the accident reflects the decreases in both the dose rates and the dose limit (for most workers, the dose limit was 250 mGy in 1986, 100 mGy in 1987, and 50 mGy in a year since 1988). The percentage of recovery operation workers with a recorded dose was lowest (35%) in 1986, because it took time for the dosimetric monitoring system to become fully operational [C13]; it increased to 64% in 1987; and then remained fairly constant until 1990. Although the dose values presented in table B1 provide an indication of the radiation exposures, they cannot be relied upon for epidemiological studies without further analysis because of biases introduced by some of the methods of dose estimation and because the data for a small percentage of workers may have been falsified [B11, C13].

B25. The mean external dose to all recovery operation workers was about 120 mGy (table B1). Among the countries supplying emergency recovery workers, the highest mean dose (about 150 mGy) was received by the Ukrainian workers, who were involved in the most difficult early operations at the Chernobyl site and within the 30-km zone. The lowest mean dose (about 50 mGy) was received by the Belarusian workers, because they were not assigned to work in the industrial zone. A study of the Russian recovery operation workers [I14, I25] seems to indicate that the average dose to them was relatively independent of the time that they spent on site during their first mission (table B2). This table also shows that most recovery operation workers spent less than six months on site during their first mission. However, some of the recovery operation workers were subsequently involved in multiple missions, representing several years in total spent on site [C16].

B26. The distribution, with respect to external dose, of the approximately 250,000 recovery operation workers who had doses recorded is given in table B3 for Belarus, the Russian Federation, Ukraine, Estonia, Latvia and Lithuania, as well as for all those countries together. For most countries, the largest number of workers was in the dose interval, 50–500 mGy. The doses vary from less than 10 mGy to more than 1,000 mGy, but about 85% of these workers received doses within the range of 20 to 500 mGy. Doses greater than 1 Gy were recorded for 219 workers; the reliability of the doses to these workers was established. The average dose to all workers with a recorded dose was 110 mGy; the average for each country ranges from 43 mGy for the workers from Belarus to 180 mGy for the workers from Latvia.

B27. The dosimetric information needed for analytical epidemiological studies is the absorbed dose in the organ of interest (bone marrow for blood diseases, breast for breast cancer, and so on) for all individuals enrolled in the particular study, as well as an assessment of the uncertainty associated with the dose estimates. In order to carry out such a study, the registry data was supplemented or substituted with other information, including some obtained during personal interviews. Studies performed in Ukraine to evaluate the validity of the dose records of military recovery operation workers (about half of the total number of workers) revealed that the majority (90–95%) of these dose records were unlikely to have been falsified [C14], but that the doses had been overestimated by a factor of about 2 [C13, C17]. Ongoing epidemiological studies are using a time-and-motion study method, called RADRUE [C16, K5, K30]. This method relies on knowledge of the locations occupied by the worker (which were obtained by means of personal interviews) and the radiation field at these locations. Biodosimetric methods can also be used to calibrate the dosimetry results recorded in the registries or obtained with RADRUE, although, at the present time, the accuracy and precision of these methods are insufficient for epidemiological studies at low doses [B11].

(b) Doses to the skin and to the eye lens due to external beta irradiation

B28. The dose to unprotected skin resulting from exposures to beta radiation is estimated to have been several times greater than the gamma dose. The ratios of the total dose rates from beta plus gamma exposures to those from the gamma exposures alone, measured at the height of the face, ranged from 2.5 to 11 (average of about 5) for general decontamination work, and from 7 to 50 (average of about 28) for decontamination of the central hall of the Unit 3 reactor [O1]. The clothes shielded most of the skin and therefore the beta dose to protected skin was much smaller than that to unprotected skin. The assessment of the beta dose to the lens of the eye was addressed in the framework of the Ukrainian–American Chernobyl Ocular Study, which is a cohort study of cataracts among 8,607 Ukrainian recovery operation workers. Beta doses were derived from the gamma exposure of the subjects. Gamma–beta dose conversion coefficients were calculated using Monte-Carlo methods for a variety of beta-energy spectra and conditions of exposure. It was found that the distribution of individual beta/gamma ratios was quite broad, ranging from essentially 0 to 3.5, with 56% of the ratios being less than 0.5 and 32% greater than or equal to 1 [C17].

(c) Doses due to internal irradiation

B29. Because of the abundance of ^{131}I and shorter-lived isotopes of iodine in the vicinity of the reactor during the evolution of the accident, those recovery operation workers who were on site during the first few weeks after the accident may have received substantial thyroid doses due to internal irradiation [U3]. On the basis of a limited number of measurements made from 30 April to 7 May 1986, thyroid doses to more than 600 workers were estimated to average 0.21 Gy [K6, U3], assuming a single intake on the date of the accident and no stable iodine prophylaxis. The median value of the ratio of the thyroid dose to the effective dose was estimated to be 0.3 [K6]. In comparison to the external doses that were incurred after May 1986, the internal doses due to intakes of ^{131}I were negligible. More detailed information is provided in annex J of the UNSCEAR 2000 Report [U3].

B30. Limited information on the internal doses resulting from intakes of ^{90}Sr, ^{137}Cs, ^{239}Pu and other radionuclides was also provided in annex J of the UNSCEAR 2000 Report [U3]. The average value of the committed effective dose from the intake of those radionuclides was estimated to be 85 mSv for about 300 recovery operation workers who had been selected for study on the basis of their high levels of external exposure.

3. Collective doses

B31. The collective dose due to external exposure received in 1986–1990 by about half a million registered emergency and recovery operation workers at the Chernobyl site and in other areas contaminated with radionuclides is estimated to be about 60,000 man Gy. Of that dose, 73% was incurred in 1986, 22% in 1987 and the remaining 5% in the subsequent three years. More than half of the collective dose (56%) was incurred by Ukrainian workers, 33% by Russian workers, and the remaining 11% by workers from Belarus, Estonia, Latvia and Lithuania. Doses received by workers from other countries within the former Soviet Union have not been assessed.

B32. The distribution of the collective dose according to individual dose level is also presented in table B3 for Belarus, the Russian Federation, Ukraine, Estonia, Latvia and Lithuania, as well as for all those countries together. About 85% of the collective dose to all the workers with recorded doses was delivered to those in the interval 50–500 mGy.

B. Doses to general population

B33. Regarding doses incurred by the members of the general public resulting from the deposition of radioactive material, it is essential to deal separately with the dose to the thyroid and that to the whole body. Iodine-131 was the main contributor to the thyroid doses, received mainly via internal irradiation within a few weeks after the accident. However, ^{137}Cs was and still is the main contributor to the doses to other organs and tissues, from both internal and external irradiation; these doses will continue to accumulate at low rates for several decades more.

B34. There were four components to the thyroid doses resulting from the Chernobyl accident: *(a)* the dose due to internal irradiation resulting from intakes of ^{131}I; *(b)* the dose due to internal irradiation resulting from intakes of other short-lived isotopes of iodine (^{132}I, ^{133}I and ^{135}I) and of short-lived isotopes of tellurium (^{131m}Te and ^{132}Te); *(c)* the dose due to internal irradiation resulting from intakes of long-lived radionuclides such as ^{134}Cs and ^{137}Cs; and *(d)* the dose due to external irradiation resulting from the deposition of radionuclides on the ground and other materials. For most individuals, the dose due to internal irradiation resulting from intakes of ^{131}I was by far the most important and has received almost all of the attention by the scientific community.

B35. The assessment of the thyroid doses that resulted from the intakes of ^{131}I was based on the results of measurements of gamma radiation performed by means of radiation detectors placed against the neck. Within a few weeks after the accident, approximately 350,000 of these measurements (called “direct thyroid measurements”) were made in Belarus, the Russian Federation and Ukraine [G1, L1, S31, U6, Z1]. Usually, individuals were only measured once, so that just the thyroid dose rate at the time of the measurement could be readily obtained. To calculate the thyroid dose, the variation of the thyroid dose rate with time was assessed, taking into account the relative rate of intake of ^{131}I, both before and after the direct thyroid measurement, and the metabolism of ^{131}I in the body, which may have been affected by the intake of stable iodine for prophylactic purposes.

B36. Following the first few weeks after the accident, during which ^{131}I was the main contributor to the radiation exposures, doses were also delivered at much lower dose rates by radionuclides with much longer half-lives. There was a transition period of a few months, during which radionuclides with intermediate half-lives, such as ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{141}Ce and ^{144}Ce, variously contributed to the doses due to external irradiation. Since 1987, the doses received by the populations in the contaminated areas have resulted essentially from external exposure due to ^{134}Cs and ^{137}Cs deposited on the ground, and from internal exposure due to ^{134}Cs and ^{137}Cs in foodstuffs. Both external irradiation and internal irradiation due to these radionuclides result in relatively uniform doses to all organs and tissues of the body. These doses resulting from the Chernobyl accident have been reported either as whole-body doses (in milligrays) or as effective doses (in millisieverts) and, by convention, do not include the thyroid doses due to the ^{131}I intakes that were received during the first few weeks after the accident.

B37. The Committee has considered three population groups: *(a)* the evacuees; *(b)* the populations of Belarus, the Russian Federation and Ukraine who lived on territories deemed contaminated; and *(c)* the populations of most of the other European countries. For the first two population groups, thyroid doses were estimated for four age groups: pre-school children (aged 0–6), school children (aged 7–14), adolescents (aged 15–17) and adults. For each age group, the distributions of the numbers of people and of the collective dose according to dose level have been assessed. The effective doses due to both external and internal irradiation have also been calculated for the first two population groups. For the populations of Belarus, the Russian Federation and Ukraine, the distributions of the numbers of people and of the collective dose according to the level of ^{137}Cs deposition density have been assessed. For the populations of most of the other European countries, only national average thyroid and effective doses have been estimated for the purpose of comparison with the doses received in Belarus, the Russian Federation and Ukraine.

1. Evacuees

B38. In its 2000 report, the Committee estimated that about 116,000 people had been evacuated in 1986 from the most contaminated areas of Belarus, the Russian Federation and Ukraine mainly during the months of April–June, but also in August and September of that year. The number of evacuees has been re-evaluated and is now estimated to be about 115,000, consisting of about 25,000 persons from Belarus, 200 from the Russian Federation and 90,000 from Ukraine. The areas from which people were evacuated form what is called the “exclusion zone”, which includes not only the 30-km zone, which is the area within a 30-km radius centred on the location of the Chernobyl reactor, but also highly-contaminated areas adjacent to the 30-km zone and more distant areas where high levels of ^{137}Cs deposition density were measured.

(a) Thyroid doses

B39. The thyroid doses received by the evacuees varied according to their age, place of residence, consumption habits and date of evacuation. For example, for the residents of Pripyat, who were evacuated essentially within 40 h after the accident, the population-weighted average thyroid dose is estimated to be 370 mGy and to range from 275 mGy for adults to about 1,000 mGy for pre-school children [B35]. Much higher doses are estimated for the population of Belarus that was evacuated in May 1986; the values are about 1,400, 920 and 4,600 mGy for the population-weighted average, adults and pre-school children, respectively (table B4).

For the entire population of evacuees, the population-weighted average thyroid dose is estimated to be 490 mGy, while the corresponding rounded values for the evacuees from Belarus, the Russian Federation and Ukraine are 1,100, 440 and 330 mGy, respectively (table B4).

B40. The distribution of the Belarusian and Ukrainian evacuees according to thyroid dose interval is presented in table B5. Thyroid doses of evacuees varied from less than 0.05 Gy to more than 5 Gy; nearly 5% of the evacuated pre-school children received thyroid doses of more than 5 Gy. Two groups of Belarusian evacuees were considered; those evacuated in May, and those evacuated in June–September 1986. For those Belarusians who had been evacuated in May, the category with the largest number of pre-school children was that with thyroid doses greater than 5 Gy; the category with the largest number of school children was that with thyroid doses from 2 to 5 Gy; and the category with the largest numbers of adolescents and adults was that with thyroid doses from 0.2 to 0.5 Gy. In general, thyroid doses were lower for the Ukrainian evacuees and for the Belarusians who were evacuated in June–September 1986. However, the category with the largest numbers of adolescents and adults was consistently that with thyroid doses ranging from 0.2 to 0.5 Gy.

B41. For most of the evacuees, except for those evacuated from Pripyat, the dominant contributor to thyroid dose was the consumption of milk containing ^{131}I, with only minor contributions from other radionuclides and pathways. The largest contribution made by the intake of the short-lived radionuclides (^{132}I and ^{133}I) to the thyroid dose was for those people who inhaled radioiodine soon after the accident and were then evacuated from the areas deemed contaminated; for these people, the dominant pathway for thyroid exposure was inhalation. The analysis of the early in-vivo counting data of Pripyat residents, who had inhaled radioiodine over about 1.5 days before they were evacuated, showed that the contribution of the short-lived isotopes of iodine to their thyroid doses was very substantial [B4]. Thus, for people in this group who could not or did not employ stable iodine prophylaxis (specifically, oral intake of KI tablets), the mean contribution of ^{132}I to the thyroid dose is estimated to be about 9% and that of ^{133}I, about 21%. In total, about 30% of the thyroid dose due to internal exposure of people who did not take stable iodine derived from the short-lived radioiodine. However, for persons who took KI tablets on 26–27 April, the contribution was significantly higher, i.e. about 40% from ^{132}I and about 14% from ^{133}I. Thus, in this group, more than half of the thyroid dose due to internal exposure originated from the short-lived isotopes of iodine. Furthermore, in this group stable iodine prophylaxis reduced the committed thyroid dose due to ^{131}I by an order of magnitude and the total thyroid dose due to radioiodine by a factor of about five. Those people who spent most of the time indoors before being evacuated, received, on average, a thyroid dose due to ^{131}I that was about half that received by people who spent most of their time outdoors [B4].

(b) Effective doses

B42. The (arithmetic) mean effective doses due to external irradiation were estimated to have been about 30 mSv for the Belarusian evacuees, about 25 mSv for the Russian evacuees, and about 20 mSv for the Ukrainian evacuees [U3]. These values are at least 10 times smaller than the corresponding numerical values of thyroid doses resulting from internal irradiation [B31]. The (arithmetic) mean effective doses due to internal irradiation were estimated to have been about 6 mSv for the Belarusian evacuees and about 10 mSv for the Ukrainian evacuees [U3], and about 10 mSv for the Russian evacuees [B28]. These values are at least half of the corresponding effective doses due to external irradiation. Estimates of the average effective doses to the evacuees from Belarus, the Russian Federation and Ukraine are summarized in table B6.

(c) Collective doses

B43. The distribution of the collective dose to the thyroid with respect to ranges of individual dose is presented in table B7. The largest contributions to the collective doses to the thyroid were from the category of doses greater than 5 Gy for the Belarusian evacuees and in the dose interval from 0.2 to 0.5 Gy for the Ukrainian evacuees. For the entire population of evacuees, the greatest contribution to the collective dose to the thyroid was from those who received doses in the interval from 0.2 to 0.5 Gy. The total collective dose to the thyroid for the evacuees from the two countries is estimated to have been about 60,000 man Gy.

B44. A summary of the estimated collective effective doses to populations of areas evacuated in 1986 is presented in table B6. The total collective effective dose is estimated to be about 3,600 man Sv. Ukraine represented the largest component of the collective effective dose, mainly because it had the largest number of evacuees.

2. Inhabitants of Belarus, the Russian Federation and Ukraine

B45. In its 2000 report [U3], the Committee focused its attention on the approximately five million residents of the contaminated areas, defined as those areas with a ^{137}Cs deposition density greater than 37 kBq/m^2. In this appendix, thyroid and effective doses have been estimated for the entire populations of Belarus and Ukraine, as well as for the population of the regions of the Russian Federation deemed affected;[1] altogether, this represents a population of about one hundred million persons. In addition, special attention has been paid to the estimation of the thyroid doses received by the subjects of ongoing epidemiological studies.

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[1] These are the 19 regions of the Russian Federation in which there are some areas deemed "contaminated" (i.e. with deposition densities greater than 37 kBq/m^2).

(a) Thyroid doses

B46. As was the case for the evacuees, the dominant contributor to the thyroid doses received by the inhabitants of Belarus, the Russian Federation and Ukraine was the consumption of fresh milk containing ^{131}I. As previously indicated, the assessment of thyroid doses resulting from the intake of ^{131}I was based on the results of direct thyroid measurements performed within a few weeks of the accident using radiation detectors placed against the neck. The developments in thyroid dosimetry since the UNSCEAR 2000 Report [U3] have focused on the reconstruction of doses for use in various epidemiological studies that have either been extended or initiated since that report.

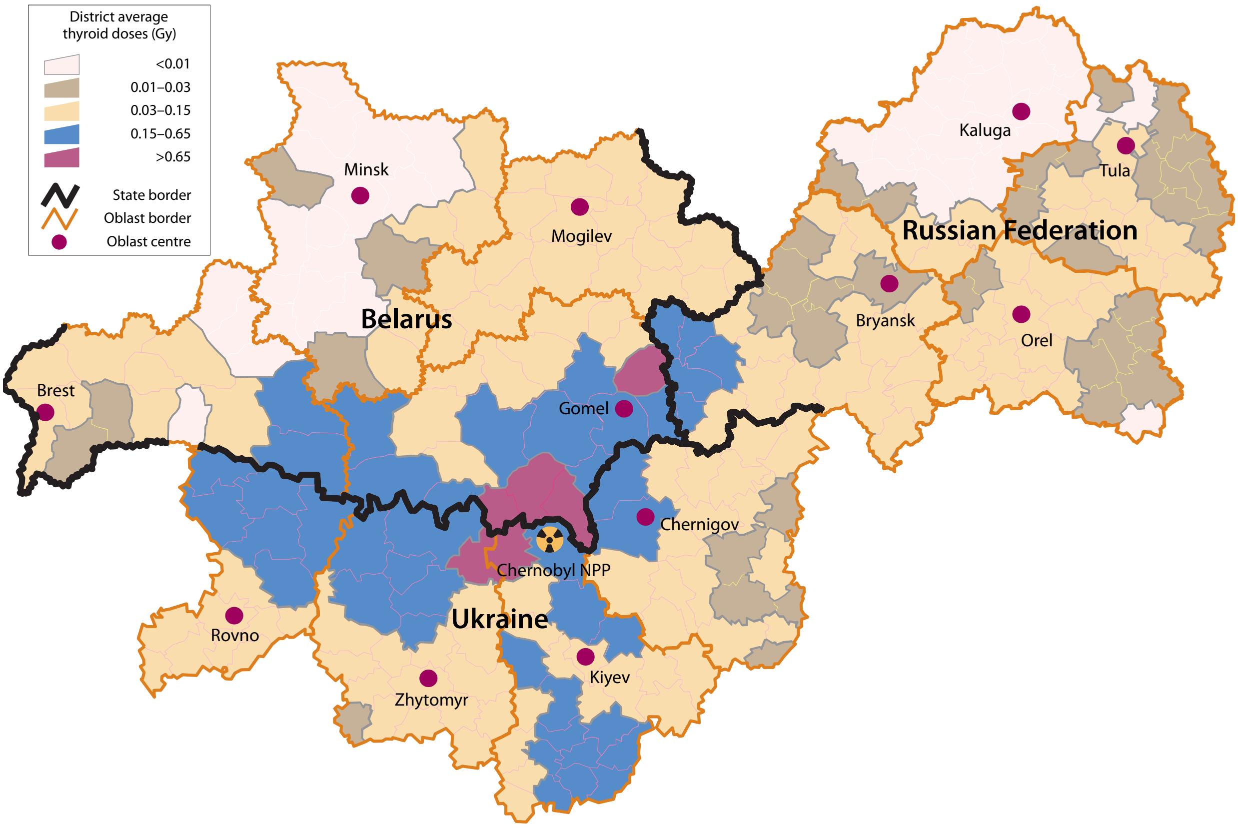
B47. Thyroid doses were estimated for those individuals who were not directly monitored but who lived in areas where many persons had been monitored. These were estimated on the basis of the statistical distribution of the thyroid doses reconstructed for those people with direct measurements, together with knowledge of the dietary habits of the individuals under consideration. In addition, thyroid doses were reconstructed for people who lived in areas where very few or no direct thyroid measurements were made within a few weeks of the accident. This was conducted using relationships established between the available data on ^{131}I or ^{137}Cs deposition, exposure rates or concentrations of ^{131}I in milk and the thyroid doses [U3].

B48. There are, therefore, different types of thyroid dose estimates, each having different quality and associated levels of uncertainty:

(a) Dose estimates for specific individuals (called “individual doses”) are needed for analytical epidemiological studies. The most reliable individual thyroid doses are those that derived from direct thyroid measurements on individuals and that make use of personal information on residence history and dietary habits obtained during interviews. Environmental and metabolic models, simulating the behaviour of ^{131}I in the environment and in man, are also necessary to estimate the relative variation with time of the content of ^{131}I in the thyroid, both before and after the direct thyroid measurement. The thyroid dose estimates obtained in this manner for the approximately 25,000 cohort members of two epidemiological studies conducted in Belarus and Ukraine are presented in table B8; the distributions of the thyroid doses are similar in the two countries, with median thyroid doses of about 0.5 Gy and 0.3 Gy, respectively (table B9). A substantial proportion of the studied populations received doses in excess of 1 Gy (table B8).

(b) Less reliable individual thyroid dose estimates were obtained for the case-control studies conducted, in which no direct thyroid measurements had been made on a large number of individuals. The thyroid doses to these individuals were assessed by means of models. Personal information on the residential history and dietary habits of the subjects was obtained during interviews [G2, S32].

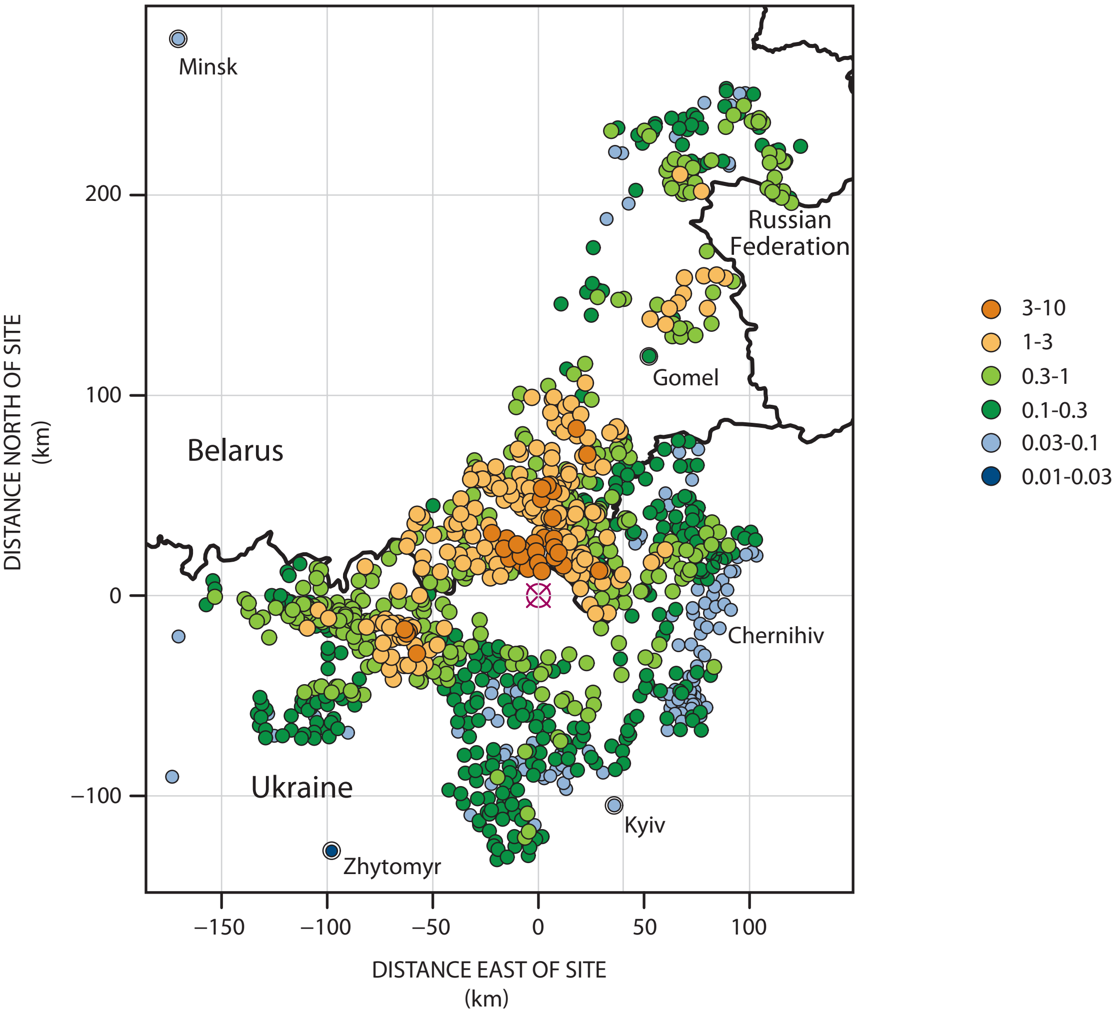
Figure B-I. Spatial distribution of the estimated thyroid doses to children and adolescents living at the time of the accident in the most affected regions of Belarus, the Russian Federation and Ukraine [K8, L4, R6, Z4]



(c) In geographical correlation (often termed "ecological") studies, it is sufficient to have doses to unspecified individuals (called "group doses"), who are representative of the average dose received by the members of the group of a given age living in a specified area (settlement, district, or part of an oblast). Average thyroid doses to individuals in particular age groups in settlements, which have been obtained from a sufficient number of measurements of the ^{131}I content in the human thyroid have, in general, the lowest uncertainty. This is because the individual dose uncertainties due to the unknown thyroid mass of the individual contribute less to the average dose uncertainty [J4, L8]. For example, in the Russian Federation, an official method for reconstructing the average thyroid dose for a settlement has been adopted [B3]. Using this method, average thyroid doses were calculated for six age groups in more than 3,500 settlements of the four most contaminated regions of the Russian Federation: Bryansk, Tula, Orel and Kaluga. They were published in a reference book of average thyroid doses [B31] and are used now for geographical correlation (ecological) epidemiological studies in the Russian Federation. A similar catalogue of thyroid dose estimates is also available for the exposed populations of Ukraine. Estimated average and collective doses to the thyroid for different population groups in Belarus, the Russian Federation and Ukraine (for the entire countries and for the contaminated areas) are presented in tables B10, B11 and B12, as well as in the form of a map, see figure B-I.

B49. There are differences in the methods used to estimate the thyroid doses in the three countries, but the concepts used are similar. The methods are basically of two types: semi-empirical; and environmental-transfer based. It would be very difficult to merge them in order to develop a common method. However, the results of limited intercomparison studies conducted by the International Agency for Research on Cancer (IARC) show that the methods used give results that are in reasonably good agreement, except for areas with low deposition density [B35]. A comparison of the estimates of mean doses in settlements, in which large numbers of direct measurements of the ^{131}I activity in the human thyroid were performed in May/June 1986, showed a high consistency of dosimetric results in Belarus and Ukraine. Dose estimates for the Belarusian and Ukrainian settlements close to the border of the two countries were also very similar (figure B-II) [J4].

Figure B-II. Average thyroid dose (Gy) of the birth cohort 1968-85 in 608 Ukrainian and 426 Belarusian settlements for which more than 10 measurements of the ^{131}I activity in human thyroids were performed in May–June 1986 [J4]



B50. *Uncertainties associated with the ^{131}I thyroid dose estimates.* Extensive efforts have been made to evaluate the uncertainties associated with the estimates of individual and group thyroid doses used in epidemiological studies. As an example, thyroid dose estimates were made in the framework of cohort studies conducted in Belarus and Ukraine jointly with the US National Cancer Institute. The distributions of the uncertainties in dose estimates, expressed as geometric standard deviations, vary from one individual to another, and range from 1.6 to more than 5.0 [L3] for all those dose estimates based on direct thyroid measurements. The medians of the distribution of the geometric standard deviations were 1.7 for the Ukrainian subjects and 2.1 for the Belarusian subjects. In another study [J4], the uncertainty distribution of average age-specific thyroid dose estimates for Belarusian settlements with more than 10 measurements of the ^{131}I activity in the human thyroid was estimated to correspond to a geometric standard deviation of 1.6.

B51. A sensitivity analysis has been conducted of the contributions that various parameter uncertainties make to the uncertainty in the dose estimates. The results show that the uncertainties in the thyroid mass and those related to the determination of the content of ^{131}I in the thyroid at the time of the direct thyroid measurement are most significant. Because the uncertainties in the direct thyroid measurements were greater for Belarus than for Ukraine, the uncertainties in the thyroid dose estimates are, on average, greater for the Belarusian subjects than for the Ukrainian subjects. Larger uncertainties would be expected to occur for subjects of case-control studies, for which doses were reconstructed by means of models.

B52. Reasonably accurate assessments of the uncertainties in the thyroid dose estimates are important as they can be used to identify those parameters that give rise to the largest uncertainties, and thence prompt research aimed at reducing them. In addition, the values of any risk coefficients that are derived from the epidemiological studies may be strongly influenced by the magnitude of the dosimetric uncertainties and by the structure of the measurement errors.

B53. *Influence of dietary iodine deficiency.* Published results [Z2] indicate that the thyroid dose estimates based on assessing radioiodine intake are roughly independent of the level of stable iodine intake in the diet, because the variation in radioiodine uptake into the thyroid among individuals is compensated to some degree by the variation in the thyroid mass. For that reason, the models for estimating thyroid dose that have been applied so far use the reference values recommended by the ICRP. However, there are regions of Belarus, the Russian Federation and Ukraine with endemic iodine deficiency, for which it is expected that the uptake of radioiodine into the thyroid would have been exacerbated. Unpublished recent results [L4] seem to show that the thyroid dose per unit intake of radioiodine may indeed have been higher for people with lower levels of stable iodine intake. If this is confirmed, it will be necessary to re-evaluate the thyroid dose estimates taking into account the dietary level of stable iodine intake. In any case, as indicated above, it is important to adjust the thyroid mass according to the level of stable iodine intake in the diet when estimating thyroid doses from direct thyroid measurements.

B54. *Role of iodine prophylaxis.* In order to protect efficiently against doses due to ^{131}I intake, iodine prophylaxis needs to be conducted before or immediately after exposure to ^{131}I [I2]. Unfortunately, this does not seem to have been the case for large segments of the affected population. Iodine prophylaxis was only applied in a satisfactory manner for *(a)* the residents of Pripyat city by local medical experts who were aware of the risks resulting from exposure to ^{131}I, and *(b)* the recovery operation workers, who were offered stable iodine tablets on their arrival at the Chernobyl site during the first few weeks after the accident [U3]. Sixty to seventy percent of Pripyat residents took KI pills within 1.5 days following the accident [B4, G8].

B55. *Estimation of doses received in utero.* The thyroid doses received in utero vary substantially with the stage of pregnancy, but are in any case smaller than the doses received by infants. The in-utero doses have so far been estimated using a model published by Johnson in 1982 [J3], which was based on sparse human data. Recently, Berkovski [B6] published a model that makes use of animal as well as human data. This model has been adopted by ICRP [I4] and leads to thyroid dose estimates that are larger than those obtained using Johnson's model for foetuses exposed during the last two months of pregnancy.

B56. *Thyroid doses due to other radionuclides and pathways.* As previously indicated, usually minor contributions to the thyroid dose include: *(a)* the dose due to intakes of short-lived radioiodine (^{132}I, ^{133}I and ^{135}I) and of short-lived radiotellurium (^{131m}Te and ^{132}Te); *(b)* the dose due to external irradiation resulting from the deposition of radionuclides on the ground and other materials; and *(c)* the dose due to internal irradiation resulting from intakes of long-lived radionuclides, such as ^{134}Cs and ^{137}Cs.

B57. The contributions of these radionuclides and exposure pathways to the thyroid doses received by the subjects of an epidemiological study of children from Belarus [A1] have been evaluated and presented in two publications [G2, M16]. Short-lived radionuclides, in general, played a minor role for the populations that were not evacuated within a few days after the accident. For those populations, the contribution of the short-lived radionuclides was estimated to have been up to 20% of the ^{131}I thyroid dose, if the radionuclide intake occurred only via inhalation and, of the order of a few percent, if contaminated foodstuffs were consumed [G2].

B58. External exposure of the population after the Chernobyl accident was mainly due to deposition of the gamma-emitting radionuclides ^{132}Te, $^{131/132}$I, ^{140}Ba, ^{140}La, ^{95}Zr, ^{95}Nb, ^{99}Mo, $^{103/106}$Ru, $^{141/144}$Ce and $^{134/136/137}$Cs. Because ^{137}Cs was the radionuclide most commonly measured throughout the contaminated areas, deposition densities of the other radionuclides have generally been related to that for ^{137}Cs. The external doses due to ^{137}Cs and the other relatively long-lived radionuclides are delivered at low dose rate and accumulate only slowly with time because of the long radioactive half-lives (about 30 years for ^{137}Cs). The contribution of external exposure to the thyroid dose of the study subjects was generally larger and more variable than that of short-lived radioiodine, with median and mean contributions of 1.2% and 1.8% of the total thyroid doses, respectively [M16].

B59. After the decay of ^{131}I within a few weeks after the accident, ingestion of radiocaesium contained in locally produced foodstuffs became the main pathway of internal exposure. Thyroid doses due to ingestion of radiocaesium (^{134}Cs and ^{137}Cs) depended in the first year after the accident on the external contamination of the plants and later on the level of root uptake and consequently on the type of soil on which the deposition occurred. Analysis showed that ingestion of the long-lived radionuclides, primarily radiocaesium, typically contributed less than 3% of the thyroid dose received by the study subjects. The median and mean fractional contributions were 0.76% and 0.95%, respectively [M16].

(b) Other organ doses and effective doses

B60. The principal contributors to the doses to organs other than the thyroid, and to effective doses were ^{137}Cs and, to a minor degree, ^{134}Cs in the environment. Both external and internal irradiation due to ^{134}Cs and ^{137}Cs result in relatively uniform doses to all organs and tissues of the body. By convention, the effective doses due to internal irradiation that were calculated in the framework of studies concerning the Chernobyl accident do not include the contribution from the thyroid doses. Consequently, the estimated effective doses, expressed in millisieverts (mSv), are to a first approximation numerically equal to the doses to any organ (other than the thyroid) of the body, expressed in milligray (mGy).

B61. Methodologies for the estimation of dose have been prepared in Belarus, the Russian Federation and Ukraine, and applied for the populations of the contaminated areas (e.g. for the Russian Federation, see references [B2, B30]). The doses due to external irradiation were based on *(a)* the large number of measurements of exposure rates and of radionuclide (especially ^{137}Cs) concentrations in soil that were made in the three countries, and *(b)* population surveys of indoor and outdoor occupancy as a function of age, season, occupation and type of building [I21, U3]. The models used for radiation transport took into account the environmental behaviour of the deposited activity in urban and in rural areas [E6, G3, G4, L2, U3, U7]. The estimates of doses due to internal irradiation, which mainly resulted from ingestion, were based on whole-body measurements of ^{134}Cs and ^{137}Cs, when available (see, for example, references [H14, H15]), but more often on the estimation of dietary intake from measured concentrations of ^{134}Cs and ^{137}Cs in foodstuffs and standard assumptions about consumption [I21, U3].

B62. Catalogues of estimated average doses to those in all settlements located in the contaminated areas of the Russian Federation and Ukraine are available [B28, B36, M5]. Effective doses due to internal and external irradiation have been estimated for the approximately one hundred million residents of Belarus, the Russian Federation and Ukraine (tables B13, B14 and B15). The average effective doses due to ^{134}Cs and ^{137}Cs that were received during the first twenty years after the accident by the residents of contaminated areas are estimated to be about 0.9 mSv due to external irradiation and 0.4 mSv due to internal irradiation. Because doses have been delivered at a varying rate since 1986, and will continue to be delivered over the next several decades, it is of interest to compare the doses in relative terms over different time periods. For the populations of the contaminated areas, it was estimated [I21] that, with regard to external irradiation, typically 25% of the lifetime (taken to correspond to the period 1986–2056) effective dose will have been due to the radiation exposure during 1986; corresponding values for 1987–1995, 1996–2005, and 2006–2056 are 40%, 15% and 20%, respectively. In comparison to external irradiation, more of the dose due to internal irradiation was delivered in 1986 and less remains to be delivered in the future. Consequently, more than 80% of the internal lifetime dose was delivered by 2005, and less than 20% remains to be delivered, at a low rate, over the next 50 years.

B63. The dosimetric information needed for analytical epidemiological studies consists of individual absorbed doses in the tissue of interest for all subjects, as well as estimates of the associated uncertainty. The method currently used to derive the individual dose estimates consists in modifying the average dose estimates provided in the catalogues, using information obtained by means of personal interviews. For external irradiation, the information required is the residence history, together with the type of buildings where the subject worked and resided. For internal irradiation, information on foodstuffs (type, origin and consumption rates) is needed. In order to assess or reduce the uncertainties in the individual dose estimates, validation studies have been conducted [G3] using personal dosimeters for external irradiation and data on whole-body content or radionuclide concentrations in foodstuffs (usually milk) for internal irradiation [B12, B32]. Routine personal thermoluminescent dosimeters are able to provide only the value of the dose that was accumulated during the relatively short time when the dosimeter was worn. Validation of the cumulated dose for the whole period—starting from the time of the accident until the time of interest for the epidemiological study—can be performed directly, using Electron Paramagnetic Resonance (EPR) on samples of human tooth enamel [I36, S28] or indirectly, using Luminescence Retrospective Dosimetry (LRD) on samples of quartz inclusions in bricks [B26, B27]. It should be noted, however, that the uncertainty of EPR estimates of absorbed doses below 100 mGy is too large to allow a validation of the other estimates of individual doses. Further, since LRD may only be used to validate absorbed doses in environmental media, it is of limited value in the validation of internal dose estimates.

(c) Collective doses

B64. Estimates for the collective dose to the thyroid are presented for four age categories and the total population in table B10 according to the region/oblast or city of residence and for contaminated areas of the three countries (all of Belarus and Ukraine and 19 regions of the Russian Federation). In table B12, the estimates of the collective dose to the thyroid are presented according to 8 individual dose intervals, ranging from less than 0.05 Gy to more than 5 Gy; the number of people in each age category and dose interval is given in table B11. Similarly disaggregated information on the estimated collective effective doses is provided in tables B13, B14 and B15. In table B13, the estimated collective effective doses for 1986–2005 is given for each region and large city and for five intervals of ^{137}Cs deposition density, ranging from less than 37 to more than 1,480 kBq/m^2. In table B15, the estimated collective effective doses are presented separately for the dose committed in 1986 and for the dose committed during 1986–2005 for each of the 8 dose intervals. The numbers of people in each dose category are provided in table B14.

B65. At the regional level, the highest estimated collective dose to the thyroid was in the Gomel oblast, where about 320,000 man Gy were distributed over a population of 1.6 million, corresponding to an average thyroid dose of about 200 mGy. However, at the country level, the collective dose to the thyroid is estimated to have been highest for Ukraine, with 960,000 man Gy distributed over a population of 51 million, even though the average thyroid dose estimate for Ukraine was about three times lower than for Belarus. Altogether, the collective dose to the thyroid received by the 98 million people considered in the three countries is estimated to have been 1,630,000 man Gy; most of the people received less than 0.05 Gy, and only 1% received doses greater than 0.2 Gy. Only 40% of the collective thyroid dose was received by residents of contaminated areas; the remaining 60% was received by inhabitants of the areas in the three countries where ^{137}Cs deposition density was less than 37 kBq/m^2. As expected, the average thyroid dose generally decreased with age: the dose to pre-school children is estimated to have been 2 to 4 times greater than the average dose to the population; and 4% of the pre-school children are estimated to have received thyroid doses greater than 0.2 Gy and 0.005% received doses greater than 5 Gy (table B11).

B66. In the UNSCEAR 1988 Report [U7], the Committee estimated a dose to the thyroid, averaged over a population of the former Soviet Union of 279.1 million, of 5 mGy for infants and 1.4 mGy for adults. These 1988 estimates correspond to a collective dose to the thyroid of about 500,000 man Gy. Because the 1988 data were provided to the Committee with little explanation, it is not feasible to investigate the reasons why the two estimates differ by a factor of about 3. However, it can be reasonably assumed that the populations considered to be “affected” are the same in both the UNSCEAR 1988 Report and in this appendix. Given the fact that comprehensive efforts to reconstruct the thyroid doses in Belarus, the Russian Federation and Ukraine had not been undertaken at the time of preparation of the UNSCEAR 1988 Report, the two estimates of collective doses to the thyroid can nevertheless be considered to be reasonably close.

B67. The collective effective dose received over the period 1986–2005 by the 98 million people considered in the three countries is estimated to have amounted to 125,000 man Sv; about half of this collective dose was to people who lived in areas with ^{137}Cs deposition densities of less than 37 kBq/m^2. The corresponding average effective dose for 1986–2005 is estimated to have been 1.25 mSv, which is about 3 times greater than the estimate of the average effective dose in 1986. A factor of about 3 is also observed for both the external and internal dose components of the total dose. Regarding the estimate for the effective dose received over the period 1986–2005, about 70% of the population received doses in the <1 mSv dose interval, and 20% received doses in the 1–2 mSv dose interval. The collective effective dose to those who received doses in the <1 mSv, 1–2 mSv and 2–5 mSv dose intervals is estimated to be about 20% of the total. As was the case for the thyroid doses, the estimates of the average effective dose are greater for Belarus than for Ukraine or the Russian Federation, but the collective effective dose estimate is greater for Ukraine than for the Russian Federation (19 regions deemed affected) and Belarus, principally because of the larger Ukrainian population.

B68. The collective effective dose of 125,000 man Sv to the inhabitants of Belarus, Ukraine and the Russian Federation (19 regions deemed affected) for the period 1986–2005 can be compared with the estimate previously published by the Committee in the UNSCEAR 1988 Report [U7]. The Committee had estimated a value of 0.82 mSv for the effective dose equivalent commitment averaged over a population of the former Soviet Union of 279.1 million, which would correspond to a collective effective dose equivalent commitment of about 230,000 man Sv. Assuming that (1) the populations deemed affected are the same, and (2) the effective dose during 1986–2005 represents 80% of the effective dose commitment [I21], the two estimates of collective effective dose differ only by 50%. This is a remarkably close agreement, as most of the effective dose commitment in the UNSCEAR 1988 Report had to be predicted using environmental transfer models. Furthermore, while the original estimate took account of countermeasures that had been imposed immediately, there was no attempt to consider the effects of possible long-term countermeasures.

3. Inhabitants of distant countries

B69. In the UNSCEAR 1988 Report [U7], the Committee estimated thyroid and effective doses for most countries of the northern hemisphere in part based on the predictions of models of future environmental transfer. Since that time, however, numerous measurements have been made of radionuclide levels in the environment, in foodstuffs and in humans, including a comprehensive monitoring programme undertaken in order to prepare an Atlas of ^{137}Cs deposition in Europe after the Chernobyl accident [E5]. Drozdovitch et al. [D13] have recently re-evaluated the deposition density values for the most important radionuclides as well as the dose estimates for the populations of all European countries (excluding Turkey, Andorra, San Marino and the Republics in the Caucasus).

B70. The estimates of average ^{137}Cs deposition densities in the various countries resulting from the Chernobyl accident are presented in table B16. Subsequent to the information presented in the UNSCEAR 1988 Report [U7] or reported in the Atlas prepared for the European Commission [E5], updated data on the deposition densities of ^{137}Cs have been obtained for Belarus [S29], Bulgaria [A9], Estonia [R14], the Russian Federation [R13], Serbia and Montenegro [K27] and Ukraine [N12]. The data for Belarus, the Russian Federation and Ukraine are included for the purpose of consistency with the corresponding values for other European countries. Average levels of ^{137}Cs deposition density greater than 50 kBq/m^2 are estimated only for some regions of Belarus, the Russian Federation and Ukraine; average levels in the range from 10 to 20 kBq/m^2 are estimated for Austria, Finland, Liechtenstein, Moldova and Slovenia. Estimates for the average ^{137}Cs deposition densities are lower than 5 kBq/m^2 for most other countries. The ^{137}Cs deposition densities presented in table B16 do not include pre-existing levels of ^{137}Cs deposition from the fallout from the atmospheric testing of nuclear weapons, levels of which are currently in the range of 1 to 3 kBq/m^2 in various parts of Europe [E5].

B71. Information on the deposition densities of other radionuclides (^{95}Zr, ^{103}Ru, ^{106}Ru, ^{131}I, ^{132}Te, ^{134}Cs and ^{140}Ba) is presented in table B16 in terms of the ratios of deposition density of the radionuclide to that of ^{137}Cs at the time of deposition. Most of the ^{132}Te values were derived from the measured concentrations of ^{132}Te and ^{137}Cs in air at ground level, based broadly on the assumption that the activity ratio in the deposited material was equal to the activity ratio in air. In comparison to the information presented in the UNSCEAR 1988 Report [U7], additional or revised data were obtained for Austria [B34], Belarus [M16], Bulgaria [A9], Croatia [I35], Czechoslovakia [B37], Finland [A10], Greece [K26], Lithuania [N19], the Russian Federation [B30] and Ukraine [L2]. The activity ratios, which were averaged over large regions or countries, are, as expected, constant for ^{134}Cs, vary within a small range for ^{103}Ru and ^{106}Ru, but show a large degree of variability for ^{95}Zr, ^{131}I, ^{132}Te and ^{140}Ba (table B16).

(a) Thyroid doses

B72. Drozdovitch et al. [D13] estimated the average age-dependent thyroid doses for the European countries considered,[2] using, whenever available, information from the direct thyroid measurements or on ^{131}I concentrations in milk [A9, A10, B37, H16, N19, U7]. Estimates of the thyroid doses incurred by pre-school children, school children, adolescents and adults are presented in table B17, while figure B-III illustrates in the form of a map the thyroid dose estimates for pre-school children, aged 0–6 years. In figure B-III, the estimates for Belarus, the Russian Federation and Ukraine are those presented earlier in this appendix, whereas the estimates for all other countries were derived from Drozdovitch et al. [D13]. The thyroid dose estimates reflect, to a first approximation, the ^{137}Cs deposition densities, but were also influenced by a number of factors, including the ^{131}I to ^{137}Cs ratio in the deposited activities, the start of the grazing season, the human consumption rate of fresh cow's milk, and the application of countermeasures. In general, the dominant component of the thyroid dose was due to the ingestion of ^{131}I in milk and fresh vegetables. However, the inhalation pathway played a substantial role for those countries where countermeasures had been applied shortly after the accident to reduce the ingestion of radionuclides in locally produced foodstuffs, as well as for the countries of northern Europe [D13].

B73. The methodology for reconstructing the thyroid doses to inhabitants of distant European countries was based on the assessment of radioiodine intakes via inhalation and ingestion. This is fundamentally different from the methodology for thyroid dose reconstruction applied in Belarus, the Russian Federation and Ukraine, which was rather based on the direct measurements of ^{131}I in human thyroids performed in May–June 1986 and radioecological patterns. The comparison of the estimates of internal dose based on intake assessment methodology with the methodology based on measurements on human shows that the former are usually systematically higher and more uncertain than the latter [I46, U7]. Furthermore, dose assessments based on intake via ingestion [D13, U7] do not usually account for the contribution from foods imported from regions of the world that were not affected by the Chernobyl accident, e.g. from other continents. The likely overestimation of the thyroid doses to inhabitants of distant European countries associated with those factors needs to be taken into account in any risk assessment process.

B74. Poland was the only country that implemented iodine prophylaxis for almost all its children at the time of the accident [K7, N7]. The presence of radionuclides in air and the increase in the background gamma dose rate were registered during the night of 27 April, and ^{131}I concentrations in milk reached 500 Bq/L on 29–30 April [K7]. A governmental commission decided to undertake compulsory stable iodine prophylaxis for the population group most at risk—11 million children and adolescents up to 16 years old—and to allow voluntary prophylaxis for other people. Altogether, about 18 million Poles were given single doses of KI starting on 29 April. According to assessments made by Polish authors, a single dose of KI taken on 29 April would have reduced the thyroid dose by 40%, whereas the same dose of KI taken on 30 April would have reduced it by about 25% [N7].

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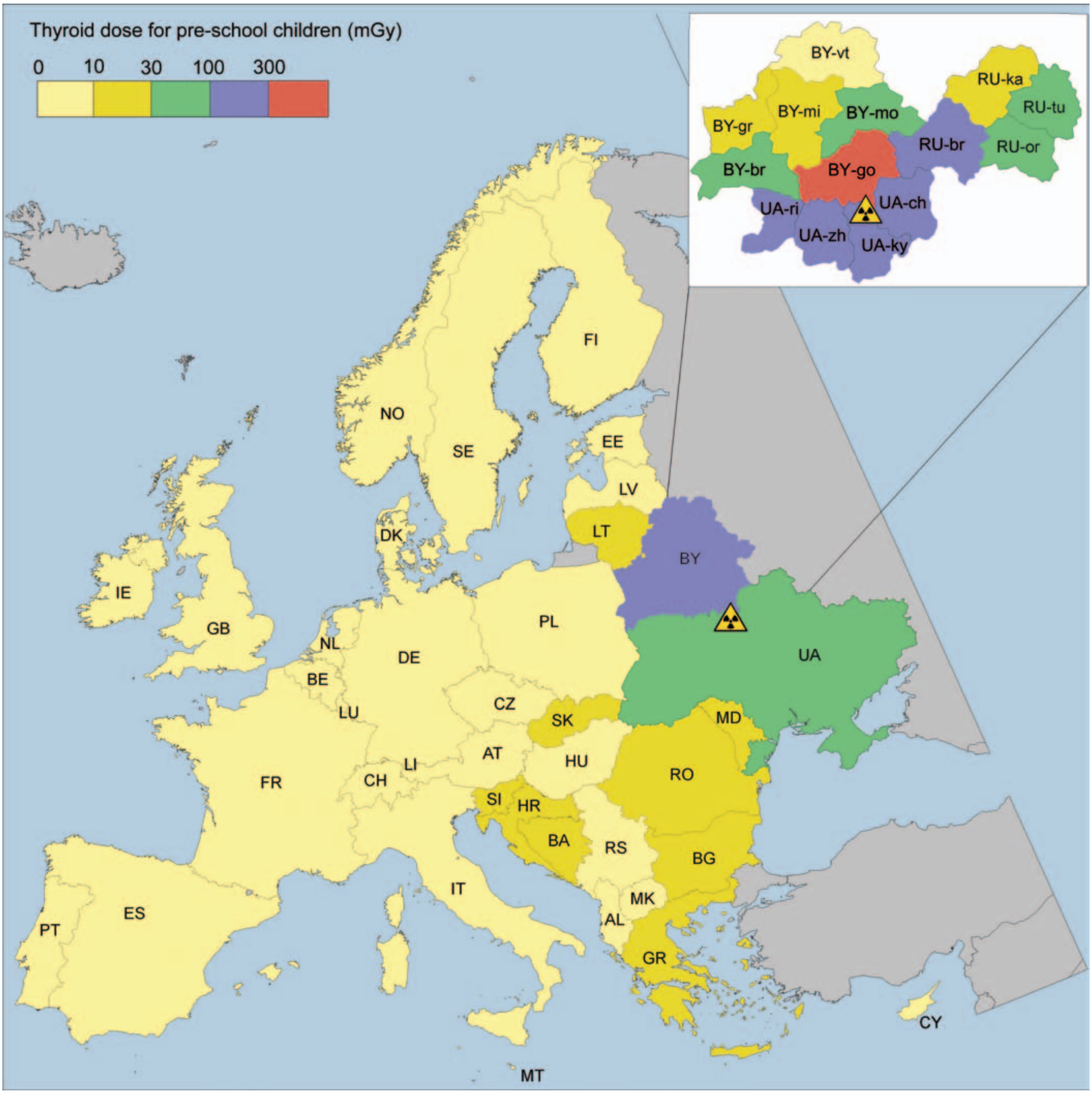
[2] The values quoted in reference [D13] have not necessarily been endorsed by the individual countries concerned.

Figure B-III. Spatial distribution of the average thyroid doses to the populations of pre-school children in Europe at the time of the accident [based on D13]

The radiation trefoil symbol denotes the location of the Chernobyl nuclear power plant. Names of countries are abbreviated according to ISO. For Belarus, the Russian Federation and Ukraine, the spatial distribution of doses is also given by oblast. The oblasts are abbreviated as follows:
Belarus: Brest, BY-br; Gomel, BY-go; Grodno, BY-gr; Minsk, BY-mi; Mogilev, BY-mo; Vitebsk, BY-vt;
The Russian Federation: Bryansk, RU-br; Kaluga, RU-ka; Orel, RU-or; Tula, RU-tu;
Ukraine: Chernihiv, UA-ch; Kyiv, UA-ky; Rivno, UA-ri; Zhytomir, UA-zh.



However, in another study involving direct ^{131}I measurements on the thyroids of 578 Warsaw citizens [K7], no statistically confirmed effect of stable iodine prophylaxis was observed. The explanation given was that in spite of local food bans, people still continued to consume contaminated foods. The overall reduction in dose to the thyroid when KI was taken on 28 April, 30 April and 1 May was estimated by the author as 28%, 25% and 10%, respectively [K7]. Because of the uncertainties involved, the effect of stable iodine prophylaxis was not taken into account in the current European dose estimates.

B75. As shown in figure B-III, the average thyroid doses to pre-school children are estimated to be greater than 100 mGy for at least one oblast in each of Belarus, the Russian Federation and Ukraine. In the other European countries, the average thyroid doses to pre-school children are estimated to be less than 20 mGy. Thyroid doses from 10 to 20 mGy were mostly observed in the southern part of Europe, where the grazing season started earlier than in the northern part.

(b) Effective doses

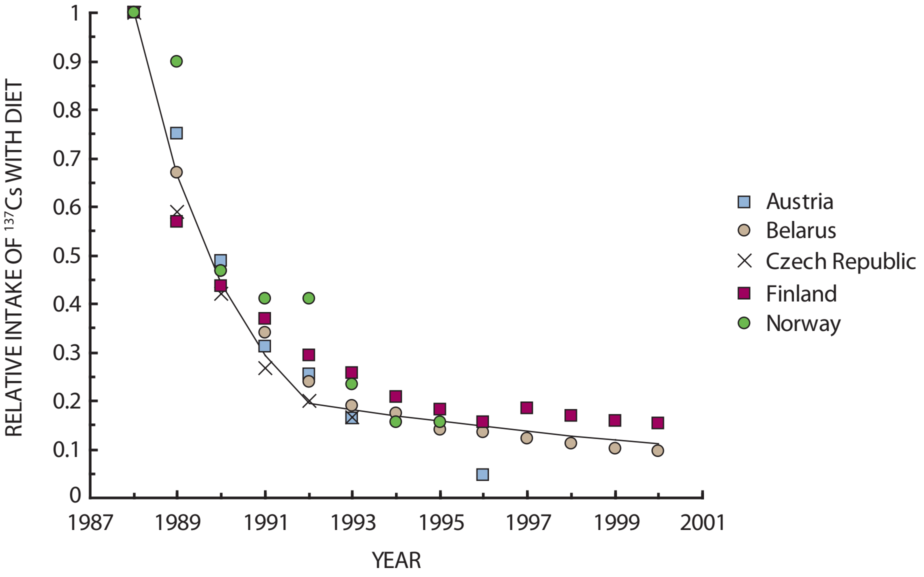
B76. Effective doses due to external and internal irradiation for 1986–2005 have been estimated for the populations of European countries using standard procedures [D13]. Doses due to external irradiation were based on the numerous measurements of deposition density of ^{137}Cs and other gamma emitters, using a model of radiation transport that took into account the decreasing dose rate in outdoor air with time due to radioactive decay and the migration of the deposited activity to deeper layers of soil [G4]. The effective doses delivered in 1986 were then derived from the outdoor dose rates in air using “behavioural” factors of 0.36 and 0.18 for the rural and urban populations, respectively. For the estimation of doses delivered in the following years, the values of the behavioural factors were taken to be 0.31 and 0.16 for the rural and urban populations, respectively [G3, U3, U7].

B77. The effective doses due to internal irradiation were estimated separately for the inhalation and the ingestion pathways. Consumption of milk and milk products, leafy vegetables, grain products, other fruits and vegetables, and meat was considered for the ingestion pathway. For most countries, the values of the time-integrated ^{137}Cs concentrations in foodstuffs for 1986 and of the consumption rates were taken from the UNSCEAR 1988 Report [U7]. The variation with time of the dietary intake of ^{137}Cs, normalized to the 1986 values, was found to be similar in a number of countries (figure B-IV). It was assessed using reduction factors of 0.65 and 0.25 for 1987 and 1988, respectively; for later years, exponential decreases with half-times of 1.7 years for 1989–1993 and 7.3 years for 1993–2005 were used [D13]. In addition, local experts from Bulgaria, the Czech Republic, Finland, Lithuania and Switzerland provided dose estimates for their respective countries [D13].

B78. As was the case for the estimates of the thyroid doses, internal effective doses for most of the distant European countries were estimated using models of the intake radionuclides in foodstuffs. However, internal doses could be substantially overestimated by this approach as shown by whole-body counting, which enables a direct assessment of the internal doses from incorporated radiocaesium to be made [I46, U7]. A detailed comparison of the two methods of dose assessment was performed in a contaminated area in the Russian Federation, revealing that internal doses assessed using intake modelling overestimated actual intakes by a factor of two to three [B2, I46]. As indicated in the UNSCEAR 1988 Report [U7] (paragraphs 88 and 142 of annex D), a possible explanation was that the results of the food sampling used in the models might have been biased towards areas of high deposition. In addition, such models often do not take account of the contribution to diet of foodstuffs imported from regions of the world that were not affected by the Chernobyl accident, or of culinary losses of radionuclides during the preparation of meals [D13, U7]. Nevertheless, this overestimation of effective internal doses to inhabitants of distant European countries should be taken into account in any risk assessment.

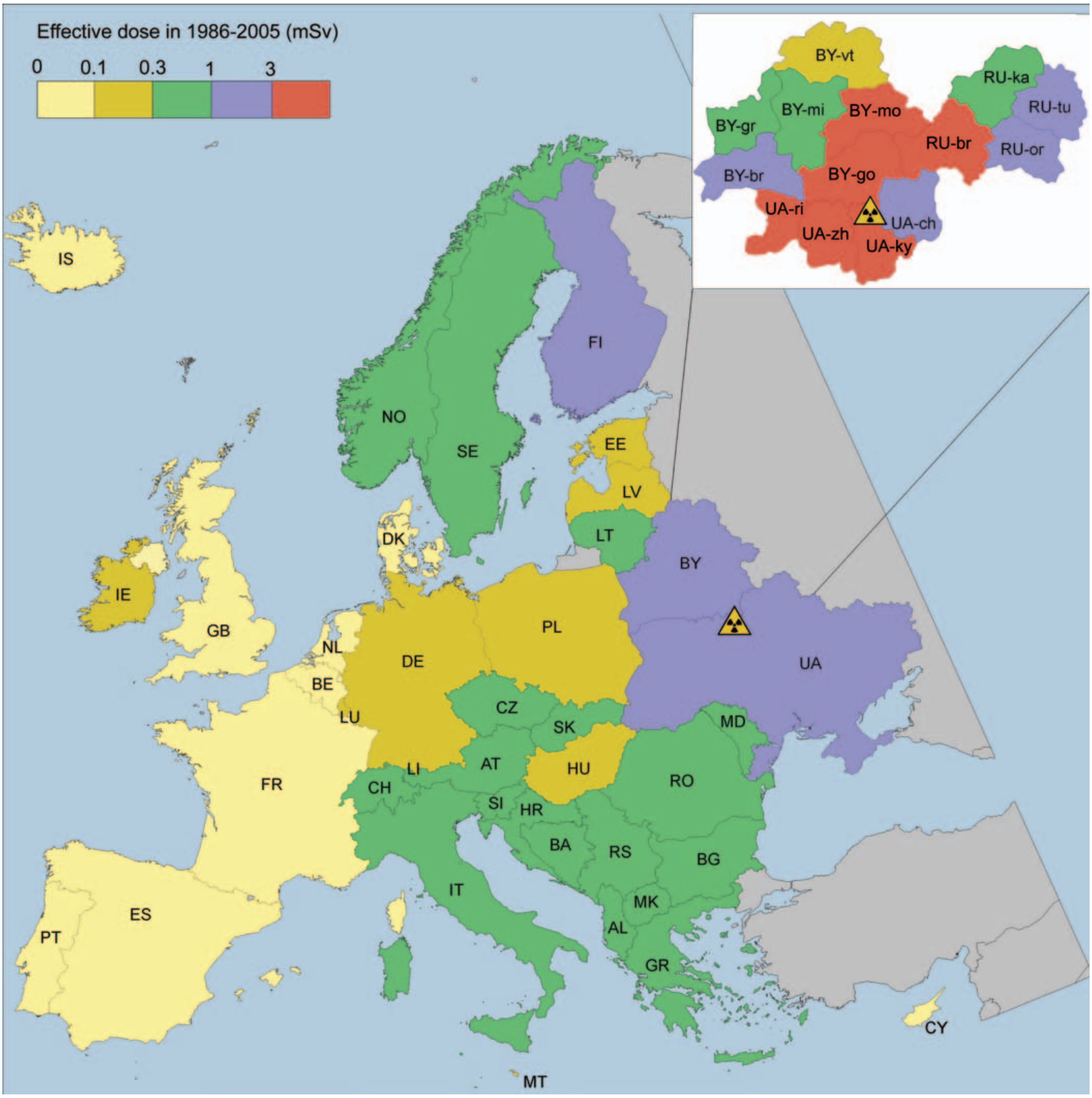
Figure B-IV. Time-dependence of dietary intake of ^{137}Cs activity

Based on measurements in Austria [M19, S25], Belarus [M16], the Czech Republic [M10], Finland [M18], and Norway [T10]



B79. The total effective doses estimated for the period 1986–2005 for most European countries are presented in figure B-V and in table B17. The estimates for Belarus, the Russian Federation and Ukraine are those previously presented in this appendix, whereas the estimates for all other countries were derived from Drozdovitch et al. [D13]. The effective doses (expressed in millisieverts, mSv) were generally much smaller numerically than the estimated absorbed doses to the thyroid of pre-school children (expressed in milligray, mGy). The ratios of the thyroid doses to the effective doses to pre-school children during 1986–2005 were about 50 in Belarus, the Russian Federation and Ukraine, about 10 for those in central and western Europe, and about 2 or less for those in Scandinavia. This variation was due in part to the countermeasures applied in Belarus, the Russian Federation and Ukraine to reduce the effective doses and, in the case of the Scandinavian countries, to the low thyroid doses owing to the late start of the grazing season.

Figure B-V. Spatial distribution of the effective doses to European populations for 1986–2005 [based on reference D13]
Abbreviations are the same as in figure B-III.



(c) Collective doses

B80. On the basis of the estimated thyroid and effective doses provided by Drozdovitch et al. [D13] and using the population data for 1986 (some 500 million people), the collective thyroid and effective doses, for 1986–2005, are estimated to be 660,000 man Gy and 130,000 man Sv, respectively, for the population of Europe (excluding Belarus, the Russian Federation, Ukraine, the countries of the Caucasus, Turkey, Andorra and San Marino) (table B18). The per caput doses for that same population were 1.3 mGy for the thyroid dose and 0.3 mSv for the effective dose (excluding the contribution from the thyroid dose) during 1986–2005.

B81. The collective thyroid and effective doses of 660,000 man Gy and 130,000 man Sv, respectively, for the populations of the distant countries, which are presented in table B19 can be compared with corresponding estimates of 760,000 man Gy and 260,000 man Sv that can be derived from information provided in the UNSCEAR 1988 Report [U7]. The two estimates of collective thyroid dose are very close because the information presented in the 1988 report was only updated for a few countries, because the thyroid doses had already been delivered by 1988, and it was felt that for most countries there was no need to re-evaluate them. In contrast, the present estimate for collective effective dose is approximately half that of the 1988 estimate, which is similar to the factor of 1.5 lower obtained for the populations of Belarus, Ukraine, and for the 19 regions of the Russian Federation deemed affected. As previously indicated, the 1988 assessment was actually completed in 1987, when the amount of data available varied greatly from country to country and most of the effective dose commitment had to be predicted using models for future environmental transfers. Also, because much of the then available data had been collected for radiation protection purposes, it is recognized that a bias existed in those data, which would have led to an overestimate of the actual exposures. Furthermore, while the original estimate of the UNSCEAR 1988 Report took account of countermeasures that had been imposed immediately, there was no attempt to consider the effects of possible long-term countermeasures.

III. SUMMARY

B82. In this appendix, in comparison with the UNSCEAR 2000 Report [U3]: *(a)* updated dose estimates are provided for the now larger number of recovery operation workers in Belarus, the Russian Federation, and Ukraine (510,000 instead of 380,000 in reference [U3]), and new information is presented giving the dose estimates for recovery operation workers in Estonia, Latvia and Lithuania; *(b)* updated thyroid dose estimates are provided for the Belarusian and Ukrainian evacuees, and new information is presented for the Russian evacuees; *(c)* the estimation of thyroid and effective doses for the inhabitants of Belarus, the Russian Federation and Ukraine has been expanded from five million to one hundred million people; and *(d)* thyroid and effective doses have been re-evaluated for the inhabitants of most other European countries.

B83. The updated average individual and collective doses estimated to have been received by the population groups in Europe exposed as a result of the Chernobyl accident are summarized in table B19. As far as possible, the dosimetric information is presented in a uniform manner for the evacuees, for the inhabitants of Belarus, the Russian Federation and Ukraine, and for the inhabitants of all other European countries (excluding those in Caucasus, Turkey, Andorra and San Marino). In addition, special attention has been given to the methods used to estimate individual doses for the purpose of epidemiological studies.

B84. The average effective dose received by the recovery operation workers, mainly due to external irradiation, between 1986 and 1990, was about 120 mSv. This is much higher than the average effective doses, due to both external and internal exposures, received by members of the general public during 1986–2005, that is, about 30 mSv for the evacuees, 1 mSv for the residents of the former Soviet Union, and 0.3 mSv for the populations of the rest of Europe. The recorded worker doses varied from less than 10 mGy to more than 1,000 mGy, but about 85% of the workers with recorded doses received doses in the interval from 20 mGy to 500 mGy.

B85. The average thyroid dose, due mainly to intakes of milk containing ^{131}I over the first few weeks following the accident, were highest for the evacuees—estimated to be about 500 mGy. It was much greater than the average thyroid doses received by the residents of the former Soviet Union who were not evacuated (about 20 mGy), those residing in the contaminated areas (about 100 mGy), and the residents of most other European countries (about 1 mGy). There was not enough information to make a reliable estimate of the average thyroid dose to the recovery operation workers.

B86. The distributions of the numbers of individuals in particular intervals of dose to the thyroid show a very large variability of individual doses for all population groups. For example, the thyroid doses to evacuees range from less than 50 mGy to more than 5,000 mGy; the dose interval with the largest number of pre-school children was 1,000–2,000 mGy, but, for all other age categories, the largest number was in the 200–500 mGy dose intervals. With respect to the non-evacuated population of 98 million people under consideration in Belarus, the Russian Federation and Ukraine, most of the people (93%) received thyroid doses of less than 50 mGy; only 1% received thyroid doses greater than 200 mGy. As expected, the average thyroid dose generally decreased with age at exposure; the dose to pre-school children was 2–4 times greater than the population average, with more than 4% of the pre-school children receiving thyroid doses greater than 200 mGy and 0.3% receiving doses greater than 1,000 mGy.

B87. The effective dose to members of the public, which by convention do not include the contributions of the thyroid doses, were much lower than the thyroid doses. For the 98 million people considered in the 3 countries, the average effective dose for 1986–2005 was 1.25 mSv, whereas the six million residents of the "contaminated areas" received average effective doses for the same period of about 9 mSv. Both values were about 3 times greater than the corresponding effective doses for 1986 alone; the same ratio of about 3 was observed for both the external and the internal doses. About 80% of the lifetime effective doses are estimated to have been delivered by 2005. Most of these people were residing in areas with ^{137}Cs deposition densities of less than 37 kBq/m^2, and therefore, about 70% of the population received doses of less than 1 mSv and 20% received doses in the range 1–2 mSv. However, about 150,000 people (0.1%) accumulated a dose of more than 50 mSv.

B88. The assessment of the uncertainties attached to the individual dose estimates is a topic of increasing interest, especially in the framework of epidemiological studies. When estimated from direct thyroid measurements, the uncertainties in the individual thyroid dose estimates have been found to vary among individuals and to range from 1.6 to more than 5.0 (in terms of geometric standard deviations). Uncertainties in the dose estimates for the recovery operation workers vary, according to the method of dose assessment, from less than 50% to up to a factor of 5. The bias is thought to be on the higher side for the military recovery operation workers.

B89. The collective effective dose to the recovery operation workers is estimated to be about 60,000 man Sv; this may, however, be an overestimate, as there is evidence that conservative assumptions were used in the calculation of some of the recorded doses. About 85% of the collective dose to the workers with recorded doses was in the individual dose interval 50–500 mGy.

B90. The highest collective dose to the thyroid is estimated to have been to the residents of the former Soviet Union and amounted to 1,600,000 man Gy. In the individual countries, the collective thyroid dose was highest in Ukraine, with 960,000 man Gy distributed over a population of 51 million people, even though the average thyroid dose in Ukraine was about 3 times lower than in Belarus. The highest collective thyroid dose in a region was in the Gomel oblast, where about 320,000 man Gy were distributed over a population of 1.6 million people, corresponding to an average thyroid dose of about 200 mGy.

B91. In terms of the collective effective dose to the populations of Belarus, the Russian Federation and Ukraine, 20% was contributed by individuals exposed to a dose of less than 5 mSv. The contribution of those exposed to more than 50 mSv was about 10%. As is the case for the thyroid doses, the average effective dose was greater in Belarus than in Ukraine, but the collective effective dose was greater in Ukraine than in the Russian Federation (19 regions deemed affected) and Belarus, principally because of the larger Ukrainian population.

B92. Finally, for the population of about 500 million people in the rest of Europe (excluding the countries of the Caucasus, Turkey, Andorra and San Marino), the per caput doses for 1986–2005 are estimated to have been 1.3 mGy for the absorbed dose to the thyroid and 0.3 mSv for the effective dose, while the collective effective dose is estimated to have been about the same value (130,000 man Sv) as that for the populations of Belarus, Ukraine and relevant parts of the Russian Federation.

Table B1. External doses[a] to recovery operation workers as officially recorded in national registries [K8, K23, K24, K31, N14, R7, R12, S10, S30, T9]

Period	*No. of recovery operation workers*		*Percentage of workers with recorded doses*	*External dose[b] (mGy)*				*Collective dose[b] (man Gy)*
	Absolute number	*%*		*Mean*	*Median*	*75th percentile*	*95th percentile*	
Belarus (as of 1996) [K8, K23]								
1986	68 000	74.7	8	60	53	93	138	4 080
1987	17 000	18.7	12	28	19	29	54	476
1988	4 000	4.4	20	20	11	31	93	80
1989	2 000	2.2	16	20	15	30	42	40
1990	0	0	—	—	—	—	—	0
1986–1990	91 000	100.0	9	51	—	—	—	4 676
Russian Federation (as of 2006) [R12]								
1986	87 772	46.6	62.0	149	175	220	250	13 078
1987	65 811	35.0	78.6	89	91	100	210	5 857
1988	24 160	12.8	83.4	35	27	46	96	845
1989	8 626	4.6	77.0	34	33	49	72	293
1990	1 805	1.0	72.2	39	43	49	66	70
1986–1990	188 174	100.0	71.3	107	94	188	244	20 143
Ukraine (as of 2005) [S30]								
1986	141 340	61.7	28.9	186	200	239	250	26 219
1987	49 365	21.5	60.1	127	93	100	230	6 259
1988	20 819	9.1	65.4	57	45	50	95	1 191
1989	12 979	5.7	70.8	49	48	49	50	635
1990	3 938	1.7	63.4	51	47	49	50	200
Unknown	778	0.3	—	—	—	—	—	
1986–1990	229 219	100	42.5	151	140	218	250	34 504
Estonia [N14, T9]								
1986	2 936	60.8	87.8	109	101	154	212	321
1987	1 089	22.6	84.7	111	89	162	207	121
1988	561	11.6	80.0	32	35	44	65	18
1989	108	2.2	91.7	45	44	45	94	5
1990	1	0.0	0.0	—	—	—	—	0
1991	1	0.0	0.0	—	—	—	—	0
Unknown	136	2.8	2.9	44	45	45	45	6
1986–1991	4 832	100.0	83.9	99	88	146	208	471
Latvia (as of 1998) [R7, S10]								
1986	3 338	55.0	78	146				487
1987	1 757	29.0	80	106				186
1988	732	12.1	71	31				23
1989	169	2.8	78	45				7
1990	19	0.3	68	55				1
1991	4	0.07	—	—				0
Unknown	46	0.8	—	—				0
1986–1991	6 065	100.0	77	117				704

Period	No. of recovery operation workers		Percentage of workers with recorded doses	External dose[b] (mGy)				Collective dose[b] (man Gy)
	Absolute number	%		Mean	Median	75th percentile	95th percentile	
Lithuania [K24, K31]								
1986	2 440	35.1	69	144	140	201	250	351
1987	3151	45.3	80	108	98	107	220	340
1988	1 006	14.5	64	43	42	50	100	43
1989	246	3.5	79	50	49	50	120	12
1990	3	0.04	67	28	28	40	40	0.08
Unknown	114	1.6	21	107	75	135	260	12
1986–1990	6 960	100.0	73	109	98	159	240	758
All countries								
1986	305 826	58.1	35	146				44 535
1987	138 173	26.3	64	96				13 240
1988	51 278	9.7	71	43				2 200
1989	24 128	4.6	69	41				993
1990	5 766	1.1	66	47				271
1991	5	<0.001	—	—				0
Unknown	1 074	0.2	—	—				18
1986–1991	526 250	100	48	117				61 256

[a] The external dose is expressed in milligray (mGy) for reasons of convenience. In fact, the quantity measured was, in many cases, exposure.

[b] The statistical parameters of dose distributions for particular years are given for workers with recorded doses (see percentiles in the 4th column). For 1986–1990, the statistical parameters and collective effective dose values are given assuming that dose distributions obtained for the workers with recorded doses apply to the entire population of workers. For some populations, this assumption might be rather questionable.

Table B2. Distribution of the number of Russian recovery operation workers and corresponding average doses according to the duration of their first mission to Chernobyl [I14, I25]

Duration of the first mission (months)	<1	1–2	2–3	3–6	6–12	>12	Total or average
Percentage of recovery operation workers	11.3	26.8	28.4	30.5	1.9	1.1	100
Average dose (mGy)	122	129	117	85	90	97	110

Table B3. Distribution of the number of recovery operation workers having recorded doses according to external dose [K8, K23, K24, K31, N14, R7, R12, S10, S30, T9]

Dose range (mGy[a])	Recovery operation workers having recorded doses			Percentage of collective dose
	Number	Rounded %	Average dose (mGy)	
Belarus [K8, K23]				
<10	2 196	25	4.7	2.7
10–20	1 791	20	16	7.7
20–50	1 858	21	33	15.9
50–100	1 865	21	75	36.8
100–200	1 032	12	120	33.1
200–500	48	1	260	3.3
500–1 000	3	0.03	630	0.5
>1 000	0	0	—	0
Rounded totals	8 793	100	43	100

Dose range (mGy[a])	*Recovery operation workers having recorded doses*			*Percentage of collective dose*
	Number	*Rounded %*	*Average dose (mGy)*	
Russian Federation [R12]				
<10	17 297	13	4.5	0.5
10–20	8 300	6	14	0.8
20–50	21 347	16	36	5.4
50–100	33 656	25	81	19.0
100–200	27 185	20	150	27.6
200–500	25 945	19	230	41.7
500–1 000	401	0.3	610	1.7
>1 000[b]	51	0.04	9 400	3.3
Rounded totals	134 182	100	107	100
Ukraine [S30]				
<10	3 426	3.6	5.0	0.1
10–20	2 164	2.4	16	0.3
20–50	23 796	26	43	8.5
50–100	23 592	26	86	17.0
100–200	16 357	18	160	22.4
200–500	20 755	23	240	41.1
500–1 000	129	0.1	710	0.8
>1 000[b]	168	0.2	6 900	9.7
Rounded totals	90 387	100	132	100
Estonia [N14, T9]				
<10	174	4.3	5.2	0.2
10–20	119	2.9	14	0.4
20–50	810	20	38	7.6
50–100	1 275	31	78	24.6
100–200	1 377	34	150	50.5
200–500	295	7.3	220	16.2
500–1 000	3	0.1	570	0.4
>1 000	0	0	—	0
Rounded totals	4 053	100	99	100
Latvia [R7, S10]				
<10	323	7.4	5	0.2
10–20	411	9.4	15	0.8
20–50	110	2.5	35	0.5
50–100	1 311	30	75	12.5
100–200	530	12	150	10.1
200–500	1 701	39	350	75.6
500–1 000	4	0.1	750	0.4
>1 000	0	0	—	0
Rounded totals	4 390	100	180	100

Dose range (mGy[a])	*Recovery operation workers having recorded doses*			*Percentage of collective dose*
	Number	*Rounded %*	*Average dose (mGy)*	
Lithuania [K24, K31]				
<10	144	2.8	4.9	0.1
10–20	178	3.5	12	0.4
20–50	634	13	35	4.0
50–100	1 699	34	76	23.4
100–200	1 525	30	130	35.6
200–500	886	17	230	36.2
500–1 000	3	0.06	600	0.3
>1 000	0	0	—	0
Rounded totals	5 069	100	109	100
All countries				
<10	23 560	9.5	4.6	0.4
10–20	12 963	5.3	14	0.7
20–50	48 555	20	39	6.7
50–100	63 398	26	82	18.4
100–200	48 006	19	150	25.5
200–500	49 630	20	240	41.4
500–1 000	543	0.2	630	1.2
>1 000[b]	219	0.1	7 500	5.7
Rounded totals	246 874	100	110	100

[a] The external dose is expressed in milligray (mGy) for convenience. In fact, the quantity measured was, in many cases, exposure.

[b] Doses above 1,000 mGy have been included in this table for the sake of completeness. It is believed that emergency workers or witnesses of the accident received such doses. The occurrence of clerical errors in these data cannot be completely excluded.

Table B4. Information on the population groups that were evacuated from the exclusion zone in 1986: numbers of persons, average thyroid doses and collective thyroid doses [B31, L4, S26]

Quantity	*Age group*				
	Pre-school children (0–6 y)	*School children (7–14 y)*	*Adolescents (15–17 y)*	*Adults (>17 y)*	*All ages*
Belarus (population evacuated in May 1986)					
Population, persons	1 126	1 049	478	8 705	11 358
Average thyroid dose (mGy)	4 616	1 967	1 518	918	1 407
Collective thyroid dose (man Gy)	5 198	2 064	725	7 991	15 978
Belarus (population evacuated in June–September 1986)					
Population, persons	1 199	1 328	645	10 195	13 367
Average thyroid dose (mGy)	3 024	1 192	735	487	797
Collective thyroid dose (man Gy)	3 626	1 583	474	4 965	10 648
Belarus (total population evacuated in 1986)					
Population (persons)	2 325	2 377	1 123	18 900	24 725
Average thyroid dose (mGy)	3 796	1 534	1 068	686	1 077
Collective thyroid dose (man Gy)	8 824	3 647	1 200	12 956	26 627

Quantity	*Age group*				
	Pre-school children (0–6 y)	*School children (7–14 y)*	*Adolescents (15–17 y)*	*Adults (>17 y)*	*All ages*
Russian Federation					
Population (persons)	19	22	10	135	186
Average thyroid dose (mGy)	1 280	500	450	310	440
Collective thyroid dose (man Gy)	24	11	4.5	42	82
Ukraine					
Population (persons)	9 587	10 721	4 692	64 610	89 600
Average thyroid dose (mGy)	1 004	278	230	250	333
Collective thyroid dose (man Gy)	9 622	2 985	1 077	16 175	29 859
Entire population evacuated in 1986					
Population (persons)	11 931	13 120	5 815	83 645	114 511
Average thyroid dose (mGy)	1 548	506	392	349	494
Collective thyroid dose (man Gy)	18 471	6 643	2 280	29 172	56 567

Table B5. Distribution of the thyroid doses to the Belarusian and Ukrainian evacuees [L4, S26]

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*All ages*	
	Number (persons)	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*
Belarus (population evacuated in May 1986)										
<0.05	8	0.7	5	0.5	11	2.3	333	3.8	357	3.1
0.05–0.1	31	2.8	36	3.4	15	3.1	637	7.3	719	6.3
0.1–0.2	34	3.0	61	5.8	40	8.4	998	11.5	1 133	10.0
0.2–0.5	126	11.2	142	13.5	102	21.3	2 159	24.8	2 529	22.3
0.5–1.0	146	13.0	200	19.1	93	19.5	2 135	24.5	2 574	22.7
1.0–2.0	213	18.9	242	23.1	95	19.9	1 537	17.7	2 087	18.4
2.0–5.0	275	24.4	277	26.4	98	20.5	782	9.0	1 432	12.6
>5.0	293	26.0	86	8.2	24	5.0	124	1.4	527	4.6
Total	1 126	100	1 049	100	478	100	8 705	100	11 358	100
Belarus (population evacuated in June–September 1986)										
<0.05	19	1.6	19	1.4	35	5.4	1 254	12.3	1 327	9.9
0.05–0.1	17	1.4	37	2.8	44	6.8	1 026	10.1	1 124	8.4
0.1–0.2	44	3.7	98	7.4	82	12.7	1 942	19.1	2 166	16.2
0.2–0.5	158	13.2	344	25.9	210	32.6	2 985	29.3	3 697	27.7
0.5–1.0	191	15.9	335	25.2	132	20.5	1 691	16.6	2 349	17.6
1.0–2.0	277	23.1	278	20.9	92	14.3	962	9.4	1 609	12.0
2.0–5.0	300	25.0	185	13.9	46	7.1	288	2.8	819	6.1
>5.0	193	16.1	32	2.4	4	0.6	47	0.5	276	2.1
Total	1 199	100	1 328	100	645	100	10 195	100	13 367	100

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*All ages*	
	Number (persons)	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*
Belarus (entire population evacuated in 1986)										
<0.05	27	1.2	24	1.0	46	4.1	1 587	8.4	1 684	6.8
0.05–0.1	48	2.1	73	3.1	59	5.3	1 663	8.8	1 843	7.5
0.1–0.2	78	3.4	159	6.7	122	10.9	2 940	15.6	3 299	13.3
0.2–0.5	284	12.2	486	20.5	312	27.8	5 144	27.2	6 226	25.2
0.5–1.0	337	14.5	535	22.5	225	20.0	3 826	20.2	4 923	19.9
1.0–2.0	490	21.1	520	21.9	187	16.7	2 499	13.2	3 696	15.0
2.0–5.0	575	24.7	462	19.4	144	12.8	1 070	5.7	2 251	9.1
>5.0	486	20.9	118	5.0	28	2.5	171	0.90	803	3.3
Total	2 325	100	2 377	100	1 123	100	18 900	100	24 725	100
Ukraine										
<0.05	—	—	143	1.3	97	2.1	2 617	4.1	2 857	3.2
0.05–0.1	4	0.04	1 504	14.0	985	21.0	10 306	16.0	12 799	14.3
0.1–0.2	458	4.8	1 234	11.5	1 384	29.6	7 090	11.0	10 166	11.4
0.2–0.5	1 813	18.9	7 011	65.4	2 071	44.2	42 469	65.7	53 364	59.6
0.5–1.0	3 400	35.5	631	5.9	74	1.6	674	1.0	4 779	5.3
1.0–2.0	3 525	36.8	133	1.2	51	1.1	1 067	1.7	4 776	5.3
2.0–5.0	306	3.2	65	0.6	20	0.4	387	0.6	778	0.9
>5.0	81	0.8	—	—	—	—	—	—	81	0.1
Total	9 587	100	10 721	100	4 682	100	64 610	100	89 600	100
Belarus and Ukraine combined										
<0.05	27	0.2	167	1.3	143	2.5	4 204	5.0	4 541	4.0
0.05–0.1	52	0.4	1 577	12.0	1 044	18.0	11 969	14.3	14 642	12.8
0.1–0.2	536	4.5	1 393	10.6	1 506	25.9	10 030	12.0	13 465	11.8
0.2–0.5	2 097	17.6	7 497	57.2	2 383	41.1	47 613	57.0	59 590	52.1
0.5–1.0	3 737	31.4	1 166	8.9	299	5.2	4 500	5.4	9 702	8.5
1.0–2.0	4 015	33.7	653	5.0	238	4.1	3 566	4.3	8 472	7.4
2.0–5.0	881	7.4	527	4.0	164	2.8	1 457	1.7	3 029	2.7
>5.0	567	4.8	118	0.9	28	0.5	171	0.2	884	0.8
Total	11 912	100	13 098	100	5 805	100	83 510	100	114 325	100

Table B6. Summary of estimated average and collective effective doses to the populations of areas evacuated in 1986 [B28, L4, S26, U3]

Country	*Population (persons)*	*Estimated mean[a] effective dose (mSv)*			*Collective effective dose (man Sv)*
		External	*Internal (excluding thyroid)*	*Total*	
Belarus	24 725	30	6	36	890
Russian Federation	186	25	10	35	7
Ukraine	89 600	20	10	30	2 688
Total	114 511	22	9	31	3 585

[a] Arithmetic mean.

Table B7. Distribution of the collective dose to the thyroid of the Belarusian and Ukrainian evacuated populations according to thyroid dose interval [L4, S26]

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*All ages*	
	man Gy	*%*	*man Gy*	*%*	*man Gy*	*%*	*man Gy*	*%*	*man Gy*	*%*
Belarus (population evacuated in May 1986)										
<0.05	0.3	0.01	0.2	0.01	0.4	0.05	11	0.1	12	0.1
0.05–0.1	2.3	0.04	3.0	0.2	1.2	0.2	47	0.6	54	0.3
0.1–0.2	5.4	0.1	8.9	0.4	5.9	0.8	155	1.9	175	1.1
0.2–0.5	41	0.8	50	2.4	32	4.4	728	9.1	851	5.3
0.5–1.0	108	2.1	145	7.0	68	9.4	1 539	19.3	1 860	11.6
1.0–2.0	306	5.9	346	16.8	127	17.5	2 188	27.4	2 967	18.6
2.0–5.0	906	17.4	848	41.1	280	38.6	2 347	29.4	4 381	27.4
>5.0	3 829	73.7	663	32.1	211	29.1	976	12.2	5 679	35.5
Total	5 198	100	2 064	100	726	100	7 991	100	15 979	100
Belarus (population evacuated in June–September 1986)										
<0.05	0.6	0.02	0.6	0.04	1.1	0.2	33	0.7	35	0.3
0.05–0.1	1.3	0.04	2.7	0.2	2.9	0.6	78	1.6	85	0.8
0.1–0.2	7.3	0.2	15	0.9	12	2.5	283	5.7	317	3.0
0.2–0.5	56	1.5	121	7.6	69	14.6	970	19.5	1 216	11.4
0.5–1.0	145	4.0	246	15.5	94	19.8	1 173	23.6	1 658	15.6
1.0–2.0	407	11.2	395	25.0	131	27.6	1 282	25.8	2 215	20.8
2.0–5.0	948	26.1	579	36.6	142	30.0	853	17.2	2 522	23.7
>5.0	2 061	56.8	224	14.2	22	4.6	293	5.9	2 600	24.4
Total	3 626	100	1 583	100	474	100	4 965	100	10 648	100
Belarus (entire population evacuated in 1986)										
<0.05	1.0	0.01	0.8	0.02	1.5	0.1	44	0.3	47	0.2
0.05–0.1	3.6	0.04	5.7	0.2	4.1	0.3	125	1.0	138	0.5
0.1–0.2	12.7	0.1	23.9	0.7	17.9	1.5	438	3.4	493	1.9
0.2–0.5	97	1.1	171	4.7	101	8.4	1 698	13.1	2 067	7.8
0.5–1.0	253	2.9	391	10.7	162	13.5	2 712	20.9	3 518	13.2
1.0–2.0	713	8.1	741	20.3	258	21.5	3 470	26.8	5 182	19.5
2.0–5.0	1 854	21.0	1 427	39.1	422	35.2	3 200	24.7	6 903	25.9
>5.0	5 890	66.8	887	24.3	233	19.4	1 269	9.8	8 279	31.1
Total	8 824	100	3 647	100	1 199	100	12 956	100	26 627	100
Ukraine										
<0.05	—	—	6.7	0.2	3.4	0.3	119	0.7	129	0.4
0.05–0.1	0.4	0.0	106	3.6	70	6.5	834	5.2	1 010	3.4
0.1–0.2	76	0.8	173	5.8	253	23.5	1 065	6.6	1 567	5.2
0.2–0.5	629	6.5	1 976	66.2	573	53.3	11 623	71.9	14 801	49.6
0.5–1.0	2 540	26.4	358	12.0	47	4.4	349	2.2	3 294	11.0
1.0–2.0	4 720	49.1	180	6.0	71	6.6	1 347	8.3	6 318	21.2
2.0–5.0	887	9.2	185	6.2	59	5.5	837	5.2	1 968	6.6
>5.0	770	8.0	—	—	—	—	—	—	770	2.6
Total	9 622	100	2 985	100	1 076	100	16 174	100	29 857	100

Dose interval (Gy)	Pre-school children		School children		Adolescents		Adults		All ages	
	man Gy	%	man Gy	%	man Gy	%	man Gy	%	man Gy	%
Belarus and Ukraine combined										
<0.05	1.0	0.01	7.5	0.1	4.9	0.2	163	0.6	176	0.3
0.05–0.1	4.0	0.02	112	1.7	74.1	3.3	959	3.3	1 149	2.0
0.1–0.2	88.7	0.5	197	3.0	271	11.9	1 503	5.2	2 060	3.6
0.2–0.5	726	3.9	2 147	32.4	674	29.6	13 321	45.7	16 868	29.9
0.5–1.0	2 793	15.1	749	11.3	209	9.2	3 061	10.5	6 812	12.1
1.0–2.0	5 433	29.5	921	13.9	329	14.5	4 817	16.5	11 500	20.4
2.0–5.0	2 741	14.9	1 612	24.3	481	21.1	4 037	13.9	8 871	15.7
>5.0	6 660	36.1	887	13.4	233	10.2	1 269	4.4	9 049	16.0
Total	18 447	100	6 632	100	2 276	100	29 130	100	56 485	100

Table B8. Distribution of the Ukrainian and Belarusian cohort subjects according to the geometric mean of their thyroid doses [L3]

Thyroid dose group (Gy)	Number of persons		
	Ukraine	Belarus	Total
<0.3	6 990	3 934	10 924
0.3–1.0	3 597	3 337	6 934
≥1.0	2 540	3 749	6 289
Total	13 127	11 020	24 147

Table B9. Characteristics of the thyroid dose distributions for the Ukrainian and Belarusian cohort subjects [M14, T3]

Thyroid dose (Gy)	Ukraine	Belarus
Arithmetic mean	0.78	1.38
Standard deviation	1.85	2.97
Median	0.26	0.54

Table B10. Average and collective doses to the thyroid for the populations of Belarus, the Russian Federation and Ukraine [K8, L4, Z4]

City or oblast	Average thyroid dose (mGy)					Population (persons)	Collective dose (man Gy)
	Pre-school children	School children	Adolescents	Adults	Total		
Belarus							
Minsk city	52.0	26.2	17.3	17.8	22.6	1 518 790	34 310
Brest	77.8	39.6	23.9	24.7	32.7	1 382 710	45 170
Vitebsk	5.5	2.6	1.6	1.7	2.1	1 269 530	2 720
Gomel	475.8	250.3	145.0	148.1	197.3	1 631 040	321 750
Grodno	16.7	8.7	5.2	5.4	6.9	1 126 230	7 780

City or oblast	*Average thyroid dose (mGy)*					*Population (persons)*	*Collective dose (man Gy)*
	Pre-school children	*School children*	*Adolescents*	*Adults*	*Total*		
Minsk	22.9	11.8	7.1	7.4	9.6	1 509 060	14 530
Mogilev	97.6	51.0	29.4	30.7	40.1	1 248 560	50 020
Rounded total or average for entire country	122	63	37	37	49	9 686 000	476 000
Rounded total or average for “contaminated areas”[a]	449	210	135	138	182	1 770 000	322 000
Russian Federation (19 affected regions[b])							
Bryansk	155	52	31	26	42	1 429 000	60 500
Tula	44	14	8	6	10	1 796 000	18 700
Orel	58	19	12	9	15	860 000	13 000
Kaluga	13	4	3	2	3	1 006 000	3 500
Other 15 “affected” regions[a]	10	3	2	2	3	32 134 000	94 000
Rounded total or average for entire 19 regions	18	6	4	3	5	37 225 000	190 000
Rounded total or average for “contaminated areas”[a]	107	35	20	17	27	2 474 000	68 000
Ukraine							
Vinnytsia	37	13	9.8	9.2	12	1 953 000	23 900
Volyn’	87	33	25	21	31	1 047 000	32 000
Luhans’k	12	4.0	3.1	3.1	4.1	2 832 000	11 600
Dnipropetrovs’k	13	4.4	3.4	3.4	4.5	3 810 000	17 200
Donets’k	24	8.0	6.0	6.1	8.1	5 328 000	42 900
Zhytomyr	231	87	67	60	81	1 549 000	126 200
Zakarpattia	7.6	2.8	2.1	1.8	2.7	1 203 000	3 200
Zaporizhzhia	26	8.8	6.2	6.5	8.8	2 045 000	17 900
Ivano-Frankivs’k	19	7.1	5.3	4.6	6.7	1 375 000	9 200
Kyiv	202	75	58	53	71	1 882 000	133 600
Kirovohrad	89	31	23	23	30	1 233 000	37 300
Crimea	34	12	8.8	8.4	12	2 005 000	23 200
L’viv	14	4.9	3.8	3.5	4.8	2 671 000	12 900
Mykolaiv	20	7.1	5.4	5.0	7.0	1 301 000	9 100
Odesa	15	5.2	3.8	3.7	5.1	2 656 000	13 600
Poltava	54	19	15	13	18	1 732 000	30 500
Rivne	177	64	49	42	62	1 162 000	71 700
Sumy	71	25	19	19	24	1 425 000	34 800
Ternopil’	18	6.4	4.8	4.5	6.2	1 150 000	7 100
Kharkiv	26	8.7	6.5	6.6	8.6	3 163 000	27 300
Kherson	30	11	7.8	7.3	10	1 222 000	12 500
Khmel’nyts’k	39	15	11	10	14	1 528 000	20 900
Cherkasy	142	52	39	37	49	1 522 000	74 300
Chernivtsi	40	14	10	9.3	13	914 000	12 200
Chernihiv	151	55	43	37	50	1 427 000	70 900

City or oblast	*Average thyroid dose (mGy)*					*Population (persons)*	*Collective dose (man Gy)*
	Pre-school children	*School children*	*Adolescents*	*Adults*	*Total*		
Kyiv city	94	30	23	24	32	2 469 000	80 000
Sevastopol' city	56	18	14	14	19	381 000	7 300
Rounded total or average for entire country	55	20	15	14	19	50 986 000	963 300
Rounded total or average for "contaminated areas"[a]	367	115	115	91	123	2 151 000	265 000
Belarus, Russian Federation and Ukraine combined							
Rounded total or average for three countries	48	19	13	12	16	97 900 000	1 630 000
Rounded total or average for "contaminated areas"[a]	289	110	84	75	102	6 395 000	655 000

[a] The "contaminated" areas were defined arbitrarily in the former Soviet Union as areas where the ^{137}Cs levels on soil were greater than 37 kBq/m^2.

[b] Belgorod, Kursk, Leningrad, Lipetsk, Nizhny Novgorod, Penza, Ryazan, Saratov, Smolensk, Tambov, Ulyanovsk and Voronezh oblasts, Chuvash, Mordoviya and Tatar autonomous republics.

Table B11. Distribution of the affected populations of Belarus, the Russian Federation and Ukraine according to age and thyroid dose interval [K8, L4, Z4]

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*Total population*	
	Number (persons)	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*
Belarus[a]										
<0.05	574 300	54.3	836 300	74.9	433 900	81.2	5 680 100	81.4	7 524 600	77.7
0.05–0.1	223 300	21.1	99 800	8.9	41 300	7.7	463 100	6.6	827 500	8.5
0.1–0.2	88 000	8.3	82 700	7.4	43 100	8.1	617 800	8.9	831 600	8.6
0.2–0.5	113 800	10.8	78 800	7.1	14 400	2.7	182 800	2.6	389 800	4.0
0.5–1.0	40 300	3.8	16 400	1.5	1 900	0.4	31 800	0.5	90 400	0.9
1.0–2.0	17 800	1.7	2 500	0.2	20	0.004	300	0.004	20 620	0.2
2.0–5.0	1 000	0.1	100	0.01	—	—	—	—	1 100	0.01
≥ 5.0	50	0.01	5	4×10^{-4}	—	—	—	—	55	6×10^{-4}
Rounded total or average	1 058 550	100	1 116 605	100	534 620	100	6 975 900	100	9 686 000	100
Russian Federation (19 affected regions[b])										
< 0.05	3 483 000	92.0	3 921 000	98.7	1 860 000	99.5	27 515 000	99.7	36 779 000	98.8
0.05–0.1	206 000	5.4	36 000	0.9	5 800	0.3	50 000	0.2	297 800	0.8
0.1–0.2	68 000	1.8	10 000	0.3	2 300	0.1	28 000	0.1	108 300	0.3
0.2–0.5	23 000	0.6	4 000	0.1	500	0.03	5 500	0.02	33 000	0.1
0.5–1.0	4 000	0.1	400	0.01	100	0.005	1 100	0.004	5 600	0.02
1.0–2.0	1 200	0.03	20	0.001	—	—	—	—	1 220	0.003
2.0–5.0	100	0.003	—	—	—	—	—	—	100	3×10^{-4}
>5.0	20	5×10^{-4}	—	—	—	—	—	—	20	5×10^{-5}
Rounded total or average	3 785 320	100	3 971 420	100	1 868 700	100	27 599 600	100	37 225 040	100

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*Total population*	
	Number (persons)	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*	*Number (persons)*	*%*
Ukraine[a]										
< 0.05	3 768 000	71.9	5 495 000	92.5	2 660 000	94.7	35 124 000	94.9	47 048 000	92.3
0.05–0.1	794 000	15.1	263 000	4.4	98 000	3.5	1 372 000	3.7	2 527 000	5.0
0.1–0.2	429 000	8.2	129 000	2.2	37 000	1.3	407 000	1.1	1 002 000	2.0
0.2–0.5	196 000	3.7	45 000	0.8	11 000	0.4	78 000	0.2	330 000	0.6
0.5–1.0	40 000	0.8	4 600	0.08	1 300	0.05	15 000	0.04	60 900	0.1
1.0–2.0	8 000	0.2	1 600	0.03	510	0.02	3 500	0.01	13 610	0.03
2.0–5.0	2 100	0.04	420	0.007	150	0.005	1 300	0.004	3 990	0.008
>5.0	470	0.01	30	5×10^{-4}	—	—	—	—	500	0.001
Rounded total or average	5 237 570	100	5 938 650	100	2 807 960	100	37 000 800	100	50 986 000	100
Belarus, Russian Federation and Ukraine combined										
< 0.05	7 825 300	77.6	10 252 300	93.0	4 953 900	95.1	68 319 100	95.4	91 350 600	93.3
0.05–0.1	1 223 300	12.1	398 800	3.6	145 100	2.8	1 885 100	2.6	3 652 300	3.7
0.1–0.2	585 000	5.8	221 700	2.0	82 400	1.6	1 052 800	1.5	1 941 900	2.0
0.2–0.5	332 800	3.3	127 800	1.2	25 900	0.5	266 300	0.4	752 800	0.8
0.5–1.0	84 300	0.8	21 400	0.2	3 300	0.06	47 900	0.07	156 900	0.2
1.0–2.0	27 000	0.3	4 120	0.04	530	0.01	3 800	0.005	35 450	0.04
2.0–5.0	3 200	0.03	520	0.005	150	0.003	1 300	0.002	5 170	0.005
>5.0	540	0.005	35	3×10^{-4}	0	0	0	0	575	6×10^{-4}
Rounded total or average	10 081 440	100	11 026 675	100	5 211 280	100	71 576 300	100	97 895 695	100

[a] Evacuees not included.

[b] Belgorod, Bryansk, Kaluga, Kursk, Leningrad, Lipetsk, Nizhny Novgorod, Orel, Penza, Ryazan, Saratov, Smolensk, Tambov, Tula, Ulyanovsk and Voronezh oblasts, Chuvash, Mordoviya and Tatar autonomous republics.

Table B12. Distribution of the collective dose to the thyroid of the affected populations of Belarus, the Russian Federation and Ukraine according to age and thyroid dose interval [K8, L4, Z4]

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*Total population*	
	man Gy	*%*	*man Gy*	*%*	*man Gy*	*%*	*man Gy*	*%*	*man Gy*	*%*
Belarus[a]										
<0.05	10 692	8.3	13 523	19.2	5 188	26.3	67 355	26.2	96 758	20.3
0.05–0.1	14 992	11.6	7 087	10.1	3 067	15.5	32 835	12.8	57 981	12.2
0.1–0.2	12 322	9.6	12 379	17.6	5 664	28.7	78 571	30.6	108 936	22.9
0.2–0.5	37 628	29.2	23 065	32.8	4 778	24.2	60 822	23.7	126 293	26.6
0.5–1.0	26 619	20.6	11 041	15.7	1 023	5.2	17 094	6.7	55 777	11.7
1.0–2.0	24 285	18.8	2 833	4.0	31	0.2	375	0.1	27 524	5.8

Dose interval (Gy)	*Pre-school children*		*School children*		*Adolescents*		*Adults*		*Total population*	
	man Gy	*%*	*man Gy*	*%*	*man Gy*	*%*	*man Gy*	*%*	*man Gy*	*%*
2.0–5.0	2 254	1.7	420	0.6	—	—	—	—	2 674	0.6
>5.0	302	0.2	38	0.05	—	—	—	—	340	0.07
Rounded total or average	129 094	100	70 386	100	19 751	100	257 052	100	476 283	100
Russian Federation (19 affected regions[b])										
<0.05	34 300	50.1	18 500	76.7	6 600	87.5	80 100	89.1	139 500	73.4
0.05–0.1	13 500	19.7	2 500	10.4	400	5.3	3 400	3.8	19 800	10.4
0.1–0.2	9 200	13.4	1 500	6.2	300	4.0	4 000	4.4	15 000	7.9
0.2–0.5	6 400	9.3	1 300	5.4	150	2.0	1 700	1.9	9 550	5.0
0.5–1.0	2 900	4.2	300	1.2	90	1.2	700	0.8	3 990	2.1
1.0–2.0	1 700	2.5	35	0.1	—	—	—	—	1 735	0.9
2.0–5.0	400	0.6	—	—	—	—	—	—	400	0.2
>5.0	120	0.2	—	—	—	—	—	—	120	0.1
Rounded total or average	68 520	100	24 135	100	7 540	100	89 900	100	190 095	100
Ukraine[a]										
<0.05	67 280	23.4	60 890	52.3	23 780	58.4	328 390	63.3	480 340	49.9
0.05–0.1	55 250	19.2	18 730	16.1	6 800	16.7	93 600	18.0	174 380	18.1
0.1–0.2	57 600	20.1	17 600	15.1	5 000	12.3	55 540	10.7	135 740	14.1
0.2–0.5	59 630	20.8	12 580	10.8	3 120	7.7	22 530	4.3	97 860	10.1
0.5–1.0	26 630	9.3	3 030	2.6	900	2.2	11 460	2.2	42 020	4.4
1.0–2.0	10 520	3.7	2 260	1.9	680	1.7	4 150	0.8	17 610	1.8
2.0–5.0	6 550	2.3	1 200	1.0	440	1.1	3 400	0.7	11 590	1.2
>5.0	3 570	1.2	170	0.1	5	0.01	—	—	3 745	0.4
Rounded total or average	287 030	100	116 460	100	40 725	100	519 070	100	963 285	100
Belarus, Russian Federation and Ukraine combined										
<0.05	112 272	23.2	92 913	44.0	35 568	52.3	475 845	55.9	716 598	44.0
0.05–0.1	83 742	17.3	28 317	13.4	10 267	15.1	129 835	15.0	252 161	15.5
0.1–0.2	79 122	16.3	31 479	14.9	10 964	16.3	138 111	16.0	259 676	15.9
0.2–0.5	103 658	21.4	36 945	17.5	8 048	11.8	85 052	9.8	233 703	14.3
0.5–1.0	56 149	11.6	14 371	6.8	2 013	3.0	29 254	3.4	101 787	6.2
1.0–2.0	36 505	7.5	5 128	2.4	711	1.0	4 525	0.5	46 869	2.9
2.0–5.0	9 204	1.9	1 620	0.8	440	0.6	3 400	0.4	14 664	0.9
>5.0	3 992	0.8	208	0.1	5	0.007	0	0	4 205	0.3
Rounded total or average	484 644	100	210 981	100	68 016	100	866 022	100	1 629 663	100

[a] Evacuees not included.

[b] Belgorod, Bryansk, Kaluga, Kursk, Leningrad, Lipetsk, Nizhny Novgorod, Orel, Penza, Ryazan, Saratov, Smolensk, Tambov, Tula, Ulyanovsk and Voronezh oblasts, Chuvash, Mordoviya and Tatar autonomous republics.

Table B13. Estimates of average effective doses[a] for oblasts and cities and corresponding collective doses due to external and internal exposure [B29, L4, M14]

Oblast	*^{137}Cs soil deposition (kBq/m^2)*	*External dose (mSv)*		*Internal dose (mSv)*		*Total dose (mSv)*		*Population (persons)*	*Collective dose in 1986–2005 (man Sv)*
		1986	*1986–2005*	*1986*	*1986–2005*	*1986*	*1986–2005*		
Belarus [M14]									
Gomel	<37	0.72	1.56	0.15	0.51	0.87	2.07	251 000	520
	37–185	1.90	4.13	0.32	1.04	2.22	5.17	1 202 000	6 220
	185–555	8.68	21.62	2.48	8.50	11.16	30.12	139 000	4 200
	555–1 480	14.87	40.75	5.20	17.82	20.08	58.57	66 400	3 890
	>1 480	31.54	49.00	3.66	12.54	35.20	61.53	8 730	540
Vitebsk	<37	0.02	0.09	0.01	0.05	0.04	0.14	1 410 000	200
	37–185	0.56	2.10	0.33	1.12	0.88	3.22	93	0.3
Minsk	<37	0.09	0.26	0.03	0.10	0.12	0.36	1 540 000	550
	37–185	1.45	4.23	0.57	1.96	2.02	6.18	35 900	220
	185–555	4.75	13.85	1.88	6.42	6.63	20.27	2 150	40
Minsk city	<37	0.03	0.12	0.01	0.04	0.04	0.15	1 610 000	250
Grodno	<37	0.09	0.27	0.03	0.10	0.12	0.37	1 110 000	410
	37–185	1.17	3.41	0.46	1.58	1.63	4.99	52 200	260
	185–555	5.35	15.58	2.11	7.22	7.46	22.81	295	7
Brest	<37	0.11	0.33	0.04	0.13	0.15	0.46	1 290 000	590
	37–185	1.47	4.24	0.55	1.86	2.02	6.10	154 000	940
	185–555	5.01	14.38	1.94	6.63	6.94	21.01	7 600	160
Mogilev	<37	0.15	0.54	0.06	0.21	0.21	0.75	1 070 000	800
	37–185	1.36	4.99	0.77	2.62	2.13	7.61	97 700	740
	185–555	3.53	12.93	1.90	6.43	5.42	19.36	84 700	1 640
	555–1 480	12.84	47.00	7.20	24.65	20.04	71.65	18 600	1 330
	>1 480	29.09	80.21	16.32	46.08	45.41	126.29	5 200	660
Rounded total/ weighted mean	<37	0.10	0.29	0.03	0.11	0.13	0.40	8 280 000	3 330
	37–185	1.79	4.18	0.38	1.26	2.17	5.44	1 540 000	8 380
	185–555	6.65	18.16	2.25	7.67	8.90	25.83	230 000	6 050
	555–1 480	14.43	42.12	5.64	19.31	20.07	61.43	85 000	5 220
	>1 480	30.62	60.65	8.39	25.06	39.01	85.71	13 900	1 190
	<37–>1 480	0.67	1.73	0.20	0.65	0.87	2.38	10 150 000	24 180
Russian Federation (19 affected regions[b]) [B29]									
Bryansk	<37	0.2	0.5	0.6	1.1	0.8	1.6	1 006 000	1 600
	37–185	1.0	3.0	2.5	5.0	3.5	8.0	183 000	1 500
	185–555	4.1	11.6	3.3	8.4	7.4	20.0	148 000	3 000
	555–1 480	10.0	28.2	3.0	11.4	13.0	39.6	85 000	3 400
	>1 480	40.1	120.0	6.7	24.6	46.8	144.6	7 000	1 000

Oblast	*^{137}Cs soil deposition (kBq/m^2)*	*External dose (mSv)*		*Internal dose (mSv)*		*Total dose (mSv)*		*Population (persons)*	*Collective dose in 1986–2005 (man Sv)*
		1986	*1986–2005*	*1986*	*1986–2005*	*1986*	*1986–2005*		
Kaluga	<37	0.1	0.2	0.1	0.2	0.2	0.4	893 000	400
	37–185	0.9	2.7	0.4	0.9	1.3	3.6	103 000	400
	185–555	3.5	10.2	1.5	3.8	5.0	14.0	11 000	200
Orel	<37	0.3	0.9	0.2	0.3	0.5	1.2	678 000	800
	37–185	0.9	2.8	0.7	1.2	1.6	4.0	168 000	700
	185–555	2.2	6.1	1.1	2.6	3.3	8.7	14 000	100
Tula	<37	0.2	0.6	0.2	0.3	0.4	0.9	1 017 000	900
	37–185	1.2	3.4	0.7	1.1	1.9	4.5	710 000	3 200
	185–555	3.4	9.7	1.1	2.1	4.5	11.8	69 000	800
Other 15 "affected" regions[b]	<37	0.1	0.4	0.1	0.2	0.2	0.6	31 167 000	19 500
	37–185	0.7	2.1	0.2	0.6	0.9	2.7	967 000	2 600
Total (19 regions)	<37	0.1	0.4	0.1	0.2	0.2	0.6	34 760 000	23 200
	37–185	0.9	2.7	0.7	1.3	1.6	4.0	2 131 000	8 400
	185–555	3.7	10.6	2.5	6.0	6.2	16.6	243 000	4 100
	555–1 480	10.0	28.2	3.0	11.4	13.0	39.6	85 000	3 400
	>1 480	40.1	120.0	6.7	24.6	46.8	144.6	7 000	1 000
	<37–>1 480	0.2	0.7	0.2	0.4	0.4	1.1	37 226 000	40 100
Ukraine [L4]									
Vinnytsia	<37	0.24	0.65	0.12	0.24	0.36	0.89	1 831 000	1 600
	37–185	1.7	4.6	1.1	1.4	2.8	6.0	123 000	730
Volyns	<37	0.19	0.52	0.12	2.0	0.31	2.5	1 019 000	2 500
	37–185	1.4	3.9	0.9	11	2.4	15	28 000	410
Luhans'k	<37	0.34	0.93	0.10	0.22	0.44	1.2	2 812 000	3 200
	37–185	1.0	2.9	0.6	0.8	1.6	3.7	20 000	70
Dnipro-petrovs'k	<37	0.10	0.26	0.05	0.15	0.15	0.41	3 810 000	1 600
	37–185	1.3	3.5	0.9	1.2	2.2	4.7	580	3
Donets'k	<37	0.20	0.54	0.07	0.18	0.27	0.72	5 028 000	3 600
	37–185	1.1	3.0	0.2	0.4	1.3	3.4	301 000	1 000
Zhytomyr	<37	0.20	0.54	0.09	0.46	0.29	1.0	1 165 000	1 200
	37–185	2.6	6.9	0.5	5.1	3.0	12	262 000	3 100
	185–555	6.8	19	0.7	3.5	7.6	22	111 000	2 500
	555–1 480	20	54	3	12	22	66	11 000	700
	>1 480	52	140	7	32	58	172	870	150
Zakarpattia	<37	0.12	0.33	0.08	0.21	0.20	0.55	1 203 000	660
Zaporizhzhia	<37	0.07	0.20	0.05	0.13	0.12	0.33	2 045 000	670
Ivano-Frankivs'k	<37	0.26	0.71	0.15	0.38	0.41	1.1	1 311 000	1 400
	37–185	1.7	4.6	1.1	1.5	2.8	6.1	64 000	390

Oblast	*^{137}Cs soil deposition (kBq/m^2)*	*External dose (mSv)*		*Internal dose (mSv)*		*Total dose (mSv)*		*Population (persons)*	*Collective dose in 1986–2005 (man Sv)*
		1986	*1986–2005*	*1986*	*1986–2005*	*1986*	*1986–2005*		
Kyiv	<37	0.45	1.2	0.14	0.45	0.59	1.7	1 411 000	2 300
	37–185	1.9	5.1	0.5	1.4	2.4	6.5	405 000	2 600
	185–555	8.2	22	2.1	4.2	10	26	21 000	540
	555–1 480	26	71	3	4	29	75	12 000	910
	>1 480	92	252	13	58	106	309	1 500	450
Kirovoh-rad	<37	0.20	0.55	0.10	0.19	0.30	0.74	1 224 000	910
	37–185	1.6	4.4	1.1	1.4	2.7	5.8	8 300	50
Crimea	<37	0.12	0.32	0.06	0.16	0.17	0.47	2 005 000	950
L'viv	<37	0.09	0.24	0.05	0.14	0.13	0.37	2 670 000	1 000
	37–185	1.2	3.3	0.8	2.1	2.0	5.4	220	1
Mykolaiv	<37	0.12	0.33	0.06	0.14	0.18	0.47	1 300 000	610
	37–185	2.4	6.6	1.7	2.1	4.1	8.7	740	10
Odesa	<37	0.19	0.52	0.06	0.15	0.25	0.66	2 651 000	1 800
	37–185	1.3	3.7	0.9	2.2	2.3	5.9	5 100	30
Poltava	<37	0.17	0.45	0.09	0.24	0.26	0.70	1 732 000	1 200
Rivne	<37	0.28	0.76	0.11	0.85	0.39	1.6	910 000	1 500
	37–185	2.2	5.9	0.6	11	2.8	17	247 000	4 300
	185–555	7.2	20	1.9	13	9.1	33	4 500	150
Sumy	<37	0.21	0.57	0.10	0.26	0.31	0.83	1 411 000	1 200
	37–185	1.9	5.2	1.3	2.3	3.2	7.4	14 000	100
Ternopil'	<37	0.15	0.42	0.10	032	0.25	0.74	1 116 000	820
	37–185	1.6	4.2	1.0	1.7	2.6	5.9	35 000	210
Kharkiv	<37	0.18	0.49	0.08	0.19	0.26	0.67	3 162 000	2 100
	37–185	1.1	3.0	0.8	1.2	1.9	4.3	160	1
Kherson	<37	0.07	0.19	0.05	0.12	0.12	0.32	1 222 000	390
Sumy	<37	0.16	0.44	0.09	0.23	0.26	0.67	1 502 000	1 010
	37–185	1.6	4.5	1.1	1.4	2.8	5.8	26 000	150
Ternopil'	185–555	6.7	18	4.6	4.7	11	23	50	1
Cherkasy	<37	0.30	0.81	0.14	0.27	0.44	1.1	1 281 000	1 400
	37–185	1.9	5.1	1.0	1.5	2.8	6.6	236 000	1 600
	185–555	7.3	20	5.0	5.1	12	25	5 700	140
Chernivtsi	<37	0.36	0.98	0.15	0.32	0.51	1.3	842 000	1 100
	37–185	1.7	4.6	1.0	1.4	2.7	6.0	70 000	420
	185–555	5.9	16	4.1	4.3	10	20	2 800	60
Chernihiv	<37	0.23	0.62	0.09	0.40	0.31	1.02	1 380 000	1 400
	37–185	1.8	4.9	0.8	2.5	2.5	7.4	46 000	340
	185–555	7.4	20	2.6	5.7	10.0	26	1 200	30
	555–1 480	18	48	11	21	29	68	140	10

Oblast	*^{137}Cs soil deposition (kBq/m^2)*	*External dose (mSv)*		*Internal dose (mSv)*		*Total dose (mSv)*		*Population (persons)*	*Collective dose in 1986–2005 (man Sv)*
		1986	*1986–2005*	*1986*	*1986–2005*	*1986*	*1986–2005*		
Kyiv city	<37	0.48	1.3	0.03	0.08	0.51	1.4	2 469 000	3 400
Sevasto-pol' city	<37	0.20	0,54	0.03	0.09	0.23	0.63	381 000	240
Rounded total or average	<37	0.21	0.56	0.08	0.26	0.29	0.82	48 893 000	39 800
	37–185	1.9	5.0	0.6	3.2	2.5	8.2	1 876 100	15 600
	185–555	7.0	19.3	0.9	3.6	8.0	22.9	132 000	3 100
	555–1 480	23.1	62.8	2.6	7.7	25.7	70.3	23 000	1 600
	>1 480	77.3	210.9	10.8	48.5	88.1	259.4	2 370	600
	<37–>1 480	0.30	0.81	0.11	0.39	0.41	1.2	51 000 000	61 000
Belarus, Russian Federation (19 regions) and Ukraine combined									
Rounded total or average	<37	0.16	0.48	0.08	0.22	0.24	0.70	91 930 000	66 600
	37–185	1.5	3.9	0.59	1.9	2.1	5.8	5 565 000	32 300
	185–555	5.6	15.4	2.1	6.2	7.7	21.6	624 000	13 500
	555–1 480	13.5	38.5	4.1	14.5	17.6	53.0	193 000	10 300
	>1 480	38.2	93.7	8.2	27.3	46.4	121.0	23 000	2 800
	<37–>1 480	0.30	0.86	0.13	0.39	0.43	1.25	98 000 000	125 000

[a] Population-weighted average doses assessed as doses of adults (≥18 years old).

[b] Belgorod, Kursk, Leningrad, Lipetsk, Nizhny Novgorod, Penza, Ryazan, Saratov, Smolensk, Tambov, Ulyanovsk and Voronezh oblasts, Chuvash, Mordoviya and Tatar autonomous republics.

Table B14. Distribution of the affected populations of Belarus, the Russian Federation and Ukraine according to time period and effective dose[a] interval [B29, L4, M14]

Dose interval (mSv)	*1986*		*1986–2005*	
	Number of persons	*%*	*Number of persons*	*%*
Belarus [M14]				
<1	8 268 000	81.4	7 679 000	75.6
1–2	631 000	6.2	410 000	4.0
2–5	919 000	9.0	1 261 000	12.4
5–10	179 000	1.8	345 000	3.4
10–20	91 000	0.9	219 000	2.2
20–50	61 000	0.6	147 000	1.4
50–100	3 400	0.03	77 000	0.7
>100	500	0.005	16 000	0.2
Rounded total or average	10 150 000	100	10 150 000	100
Russian Federation (19 affected regions[b]) [B29]				
<1	35 282 000	94.8	25 842 000	69.4
1–2	993 000	2.8	8 028 000	21.6
2–5	557 000	1.5	2 518 000	6.8
5–10	262 000	0.70	390 000	1.0
10–20	110 000	0.30	276 000	0.74
20–50	18 000	0.05	140 000	0.38
50–100	3 000	0.008	27 000	0.07
>100	0	0	5 000	0.01
Rounded total or average	37 000 000	100	37 000 000	100
Ukraine [L4]				
<1	48 072 000	94.3	36 096 000	70.8
1–2	1 694 000	3.3	10 322 000	20.3
2–5	912 000	1.8	2 948 000	5.8
5–10	213 000	0.42	850 000	1.7
10–20	43 000	0.08	532 000	1.0
20–50	17 000	0.03	182 000	0.36
50–100	1 400	0.003	18 000	0.04
>100	980	0.002	5 200	0.01
Rounded total or average	51 000 000	100	51 000 000	100
Belarus, Russian Federation (19 regions) and Ukraine combined				
<1	91 622 000	93.2	69 617 000	70.8
1–2	3 318 000	3.4	18 760 000	19.1
2–5	2 388 000	2.4	6 727 000	6.8
5–10	654 000	0.7	1 585 000	1.6
10–20	243 000	0.2	1 027 000	1.0
20–50	96 000	0.1	469 000	0.5
50–100	7 800	0.008	121 000	0.1
>100	1 500	0.002	26 000	0.03
Rounded total or average	98 000 000	100	98 000 000	100

[a] Effective doses assessed as doses of adults (≥18 years old).

[b] Belgorod, Bryansk, Kaluga, Kursk, Leningrad, Lipetsk, Nizhny Novgorod, Orel, Penza, Ryazan, Saratov, Smolensk, Tambov, Tula Ulyanovsk and Voronezh oblasts, Chuvash, Mordoviya and Tatar autonomous republics.

Table B15. Distribution of the collective effective dose to the relevant populations of Belarus, the Russian Federation and Ukraine according to time period and effective dose[a] interval [B29, L4, M14]

Dose interval (mSv)	*1986*		*1986–2005*	
	Collective effective dose (man Sv)	*%*	*Collective effective dose (man Sv)*	*%*
Belarus [M14]				
<1	1 040	11.9	2 180	9.0
1–2	860	9.8	630	2.6
2–5	2 360	26.9	4 570	18.9
5–10	1 240	14.1	2 490	10.3
10–20	1 280	14.6	3 110	12.9
20–50	1 720	19.6	4 320	17.9
50–100	210	2.4	5 000	20.7
>100	60	0.7	1 870	7.7
Rounded total or average	8 800	100	24 000	100
Russian Federation (19 affected regions[b]) [B29]				
<1	9 000	57.7	9 800	24.4
1–2	1 200	7.7	10 400	25.9
2–5	1 500	9.6	7 100	17.7
5–10	1 700	10.9	2 300	5.7
10–20	1 500	9.6	3 800	9.5
20–50	500	3.2	4 100	10.2
50–100	200	1.3	1 800	4.5
>100	0	0	800	2.0
Rounded total or average	15 600	100	40 000	100
Ukraine [L4]				
<1	12 850	62.4	17 230	28.3
1–2	2 390	11.6	14 260	23.4
2–5	2 730	13.3	8 380	13.7
5–10	1 390	6.7	5 960	9.8
10–20	530	2.6	7 710	12.6
20–50	500	2.4	5 180	8.5
50–100	90	0.4	1 320	2.2
>100	120	0.6	930	1.5
Rounded total or average	20 600	100	61 000	100
Belarus, Russian Federation (19 regions) and Ukraine combined				
<1	22 890	50.9	29 210	23.3
1–2	4 450	9.9	25 290	20.2
2–5	6 590	14.7	20 050	16.0
5–10	4 330	9.6	10 750	8.6
10–20	3 310	7.4	14 620	11.7
20–50	2 720	6.0	13 600	10.9
50–100	500	1.1	8 120	6.5
>100	180	0.4	3 600	2.9
Rounded total or average	45 000	100	125 000	100

[a] Effective doses assessed as doses of adults (≥18 years old).

[b] Belgorod, Bryansk, Kaluga, Kursk, Leningrad, Lipetsk, Nizhny Novgorod, Orel, Penza, Ryazan, Saratov, Smolensk, Tambov, Tula Ulyanovsk and Voronezh oblasts, Chuvash, Mordoviya and Tatar autonomous republics.

Table B16. Estimated average deposition densities of ^{137}Cs resulting from the Chernobyl accident and ratios of deposition densities of selected radionuclides to ^{137}Cs in European countries [D13, E5, U7]

Country or region	*Estimate of average ^{137}Cs deposition density (kBq/m^2)*	*Estimate for the ratio of deposition density of various radionuclides to that of ^{137}Cs at the time of deposition*						
		^{95}Zr	*^{103}Ru*	*^{106}Ru*	*^{131}I*	*^{132}Te*	*^{134}Cs*	*^{140}Ba*
Albania	7.2	0.1	2.5	0.6	3.8	7	0.5	1.5
Austria	18.7	—	1.3	0.46	5	4.8	0.57	—
Belarus, Brest Oblast	18.2	0.5–0.8	2.2–2.8	0.7–0.9	19–23	7.6–12	0.5	1.5–2.1
Belarus, Vitebsk Oblast	1.1	0.2	1.8	0.4	24	4.8	0.5	0.8
Belarus, Gomel Oblast	154	0.17–4	1.6–3.7	0.42–1	8.3–21	4.2–11	0.5	0.76–7.6
Belarus, Grodno Oblast	8	0.5	2.8	0.7	23	12	0.5	1.5
Belarus, Minsk Oblast	5.8	0.5	2.8	0.7	23	12	0.5	1.5
Belarus, Minsk City	6.2	0.3	1.5	0.45	14	2.8	0.5	1
Belarus, Mogilev Oblast	61	0.17–4	1.6–2.4	0.3–0.9	8.3–21	4.2–11	0.5	0.76–7.6
Belgium	0.3	—	1.7	0.5	6.2	4	0.55	1.6
Bosnia and Herzegovina	6.4	—	1.4	0.3	5.9	7.2	0.4	0.7
Bulgaria	7	0.14	1.4	0.36	1.7	4	0.5	1.6
Croatia	3.7	0.14	2.6	1	3.3	6.1	0.4	0.7
Cyprus	0.6	—	—	—	3.3	—	0.55	—
Czech Republic	4.7	—	1.9	0.3	13.8	5.1	0.5	1.0
Denmark	0.36	—	1.5	0.5	4.7	4.3	0.55	—
Estonia	2	1.1	2.2	0.5	4.2	5.9	0.6	0.7
Finland	12.2	1.7	2.2	0.5	4.2	5.9	0.6	0.7
France	0.7	—	1.4	0.3	7.3	4.8	0.55	—
Germany	2.8	—	1.5	0.3	5.8	6.8	0.55	—
Greece	5.2	0.1	2.5	0.6	3.8	7	0.5	1.5
Hungary	1.9	—	2.5	0.6	6.2	6.7	0.55	—
Iceland	0.3	—	—	—	—	—	0.55	—
Ireland	3.1	—	1.5	0.4	3.1	3.4	0.55	0.8
Italy	2.1	—	2	0.55	4	7.8	0.55	—
Latvia	0.85	0.2	1.8	0.4	24	4.8	0.5	1.5
Liechtenstein	11.8	—	1.3	0.46	5	4.8	0.57	—
Lithuania	3.7	0.4	1.5	—	23	12	0.55	0.72
Luxembourg	1.2	—	1.7	0.5	7	4	0.55	—
Macedonia (Former Yugoslav Rep. of)	8.5	—	1.5	0.3	6	7.6	0.4	—
Malta	1.9	—	1.8	0.5	3.8	8.5	0.55	—
Netherlands	0.3	—	1.9	0.5	6.3	3.3	0.55	—
Norway	4.7	—	2	0.5	16	2.6	0.55	—
Poland	1.3	—	2.5	0.3	7.3	8.4	0.55	—
Portugal	0.02	—	2	0.6	3.5	0.2	0.55	—

Country or region	*Estimate of average ^{137}Cs deposition density (kBq/m^2)*	*Estimate for the ratio of deposition density of various radionuclides to that of ^{137}Cs at the time of deposition*						
		^{95}Zr	*^{103}Ru*	*^{106}Ru*	*^{131}I*	*^{132}Te*	*^{134}Cs*	*^{140}Ba*
Republic of Moldova	10.1	—	2.9	0.7	5.2	6.4	0.55	—
Romania	6.5	—	2.9	0.7	5.2	6.4	0.55	—
Russia, Bryansk Oblast	110	0.07–0.14	1.6	0.45	7.6–11	6.7–10	0.54	0.41–0.63
Russia, Kaluga Oblast	14.2	0.07	1.5	0.42	7.7	6.3	0.5	0.48
Russia, Orel Oblast	41	0.07	1.6	0.43	8.1	7.1	0.5	0.49
Russia, Tula Oblast	67	0.07	1.6	0.46	7.9	6.5	0.5	0.5
Serbia and Montenegro	9	—	1.5	0.3	6	7.6	0.55	—
Slovakia	3.6	—	1.8	0.3	11	7.3	0.50	—
Slovenia	16.3	—	1.4	0.3	5.9	7.2	0.4	—
Spain	0.06	—	1.5	0.3	3.9	-	0.55	—
Sweden	4.6	—	2	0.78	15.9	1.1	0.55	—
Switzerland	5.6	—	1.9	0.6	7	8.6	0.55	—
Ukraine, Chernihiv Oblast	~15	2	8	2	13	20	0.5	2
Ukraine, Kyiv Oblast	~30	2	8	2	13	20	0.5	2
Ukraine, Kyiv-City	~15	2	8	2	13	20	0.5	2
Ukraine, Rivno Oblast	~40	2	8	2	13	20	0.5	2
Ukraine, Zhytomir Oblast	~50	2	8	2	13	20	0.5	2
Ukraine, remainder	~20	2	8	2	13	20	0.5	2
United Kingdom	0.9	—	1.8	0.6	7.1	12.9	0.55	—

Table B17. Average thyroid and effective doses to the populations of European countries[a] [based on D13]

Country or region	*Thyroid dose (mGy)*					*Effective dose (mSv) accrued in the period 1986–2005*
	Pre-school children (0–6 y)	*School children (7–14 y)*	*Adolescents (15–17 y)*	*Adults (>17 y)*	*All ages*	
Albania	7.9	4.7	3.3	2.8	3.5	0.52
Austria	6.0	2.3	1.1	0.9	1.5	0.98
Belgium	1.6	0.7	0.4	0.4	0.5	0.03
Bosnia and Herzegovina	15.6	9.5	6.7	5.7	7.0	0.41
Bulgaria	13.6	6.7	3.8	3.1	4.5	0.64
Croatia	17.3	10.2	6.3	5.0	6.8	0.47
Cyprus	3.7	2.0	1.3	1.1	1.4	0.08
Czech Republic	8.5	3.8	2.2	1.7	2.6	0.37
Denmark	0.09	0.05	0.03	0.02	0.03	0.03
Estonia	1.9	1.3	0.8	0.7	0.9	0.14
Finland	0.9	0.7	0.4	0.3	0.4	1.36
France	1.5	0.6	0.3	0.3	0.4	0.07
Germany	1.6	0.7	0.4	0.3	0.5	0.17
Greece	12.5	4.9	2.6	2.0	3.3	0.72
Hungary	4.1	1.7	1.0	0.7	1.2	0.3
Iceland	—	—	—	—	—	0.01
Ireland	1.8	0.8	0.5	0.4	0.6	0.21
Italy	6	2.6	1.5	1.2	1.8	0.33
Latvia	4.2	2.4	1.7	1.5	1.8	0.1
Liechtenstein	6.2	2.3	1.2	0.9	1.6	0.91
Lithuania	18.4	8.8	5.3	4.3	6.2	0.33
Luxembourg	1.8	0.9	0.5	0.4	0.6	0.11
Macedonia (Former Yugoslav Rep. of)	7.9	4.8	3.4	2.8	3.5	0.47
Malta	5.3	1.9	0.9	0.7	1.2	0.29
Netherlands	0.8	0.5	0.4	0.3	0.4	0.05
Norway	0.7	0.4	0.3	0.2	0.3	0.38
Poland	5.5	2.1	1.1	0.8	1.4	0.25
Portugal	0.007	0.004	0.003	0.002	0.003	0.003
Republic of Moldova	15.9	7.0	4.5	3.9	5.4	0.97
Romania	12.3	4.9	2.6	2.0	3.3	0.61
Serbia and Montenegro	7.8	4.7	3.3	2.8	3.5	0.55
Slovakia	12.3	5.0	2.7	2.1	3.4	0.41
Slovenia	17.3	10.6	7.5	6.3	7.8	0.98
Spain	0.08	0.04	0.02	0.02	0.03	0.009
Sweden	0.6	0.3	0.2	0.2	0.2	0.31
Switzerland	3.9	4.0	2.6	2.0	2.4	0.46
United Kingdom	0.5	0.2	0.1	0.08	0.1	0.05

[a] The values quoted in [D13] have not necessarily been endorsed by the individual countries concerned.

Table B18. Collective thyroid and effective doses to the populations of European countries[a] [based on D13]

Country	*Population in 1986 (millions)*	*Collective thyroid dose (man Gy)*	*Collective effective dose accrued in 1986–2005 (man Sv)*
Albania	3.02	11 000	1 600
Austria	7.56	11 000	7 400
Belgium	9.86	5 100	300
Bosnia and Herzegovina	4.4	31 000	1 800
Bulgaria	8.89	40 000	5 700
Croatia	4.72	32 000	2 200
Cyprus	0.64	900	50
Czech Republic	10.34	2 700	3 800
Denmark	5.12	200	150
Estonia	1.53	1 300	200
Finland	4.92	1 900	6 700
France	53.6	23 000	3 800
Germany	77.66	37 000	13 000
Greece	9.83	33 000	7 100
Hungary	10.62	12 000	3 200
Iceland	0.24	—	2
Ireland	3.54	2 100	700
Italy	56.91	100 000	19 000
Latvia	2.6	4 800	300
Liechtenstein	0.03	50	30
Lithuania	3.58	22 000	1 200
Luxembourg	0.37	200	40
Macedonia (Former Yugoslav Rep. of)	1.92	6 800	900
Malta	0.34	200	100
Netherlands	14.49	5 300	700
Norway	4.17	1 200	1 600
Poland	37.46	54 000	9 400
Portugal	10.01	30	30
Republic of Moldova	4.25	23 000	4 100
Romania	22.73	75 000	14 000
Serbia and Montenegro	10.5	37 000	6 000
Slovakia	5.19	18 000	2 000
Slovenia	1.99	16 000	2 000
Spain	37.3	1 000	300
Sweden	8.35	1 800	2 600
Switzerland	6.49	15 000	3 000
United Kingdom	55.87	7 400	2 800
Total (rounded)	~500	660 000	130 000

[a] The values quoted in [D13] have not necessarily been endorsed by the individual countries concerned.

Table B19. Summary of doses (rounded) to the main population groups exposed to radiation as a result of the Chernobyl accident

Country	*Population size (thousands)*	*Average thyroid dose (mGy)*	*Average effective dose in 1986-2005 [a,b] (mSv)*	*Collective thyroid dose (man Gy)*	*Collective effective dose in 1986–2005 (man Sv)*
Recovery operation workers[c,d] [K8, K23, K24, K31, N14, R7, R12, S10, S30, T9]					
Belarus	91	—	51	—	4 700
Russian Federation	190	—	107	—	20 100
Ukraine	230	—	151	—	34 500
Estonia	4.8	—	99	—	460
Latvia	6.1	—	117	—	700
Lithuania	7.0	—	109	—	750
All	530	—	117	—	61 200
Evacuees [B28, B31, L4, S26, U3]					
Belarus	25	1 100	36	27 000	900
Russian Federation	0.19	440	35	82	7
Ukraine	90	330	30	30 000	2 700
All	115	490	31	57 000	3 600
Inhabitants of contaminated areas of Belarus, Russian Federation and Ukraine[e] [B29, K8, L4, M14, Z4]					
Belarus	1 800	182	12	320 000	20 800
Russian Federation	2 500	27	7	70 000	16 900
Ukraine	2 100	123	10	260 000	21 200
All	6 400	102	9	650 000	58 900
Inhabitants of Belarus, Russian Federation and Ukraine [B29, K8, L4, M14, Z4]					
Belarus	10 000	49	2.4	480 000	24 000
Russian Federation (19 "affected" regions)	37 000	5	1.1	190 000	40 000
Ukraine	51 000	19	1.2	960 000	61 000
All	98 000	16	1.3	1 600 000	125 000
Inhabitants of distant countries[f] [D13]					
All	500 000	1.3	0.3	660 000	130 000

[a] The effective dose to workers includes only the dose due to external irradiation, which was delivered essentially from the accident in 1986 to the end of 1990. The effective dose was assumed to be numerically equivalent to the dose recorded in the national registry.

[b] The effective dose to the general population is the sum of the effective doses due to external and internal irradiation, excluding the contributions from the thyroid dose. The external dose was calculated for 1986–2005. The internal dose is the committed dose from intakes during 1986–2005.

[c] The average and collective effective dose have been calculated using the assumption that the dose distribution obtained for the workers with recorded doses applies to the entire population of workers.

[d] The thyroid doses are not summarized in this table, as they are only available for a very small number of workers.

[e] The contaminated areas were defined arbitrarily in the former Soviet Union as areas where the ^{137}Cs levels on soil were greater than 37 kBq/m^2.

[f] The distant countries that have been considered are all the European countries, with the exception of Belarus, Russian Federation, Ukraine, Turkey, countries of the Caucasus, Andorra, and San Marino.

APPENDIX C.
EARLY HEALTH EFFECTS

I. SUMMARY FROM PREVIOUS UNSCEAR REPORTS

C1. The first information on the early manifestations and outcomes of acute radiation syndrome (ARS) in persons who were exposed to ionizing radiation in the early phase of the Chernobyl accident was provided to the international community in Vienna in August 1986 [I31]. The analytical data derived from clinical observations of the victims of the accident at the Chernobyl nuclear power plant (ChNPP) were presented in the appendix, “Acute radiation effects in victims of the Chernobyl nuclear power plant accident”, and annex G, “Early effects in man of high doses of radiation”, of the UNSCEAR 1988 Report [U7]. Updated information on the early health effects, some longer term effects and the causes of death among emergency workers was provided in section III of annex J, “Exposures and effects of the Chernobyl accident”, of the UNSCEAR 2000 Report [U3].

C2. The simultaneous treatment of a large group of patients (134) for ARS with varying degrees of severity clarified many aspects of the early effects in man of acute irradiation, especially of the bone-marrow syndrome, which was the principal clinical syndrome. For many patients, the bone-marrow syndrome was combined with radiation damage to the skin; for some, it was combined with damage to the cornea (keratitis) and the lungs (pneumonitis), and with intestinal and oropharyngeal injuries.

C3. The average bone-marrow doses and the prognoses regarding the further course of the ARS were determined using biological criteria. During the early period, most of the information was obtained from chromosome analysis, lymphocyte counts and the primary reaction periods; later, most of the information was obtained from the granulocyte counts. Other indications were of a supplementary nature. For three cases, the estimated dose agreed closely with that obtained from an electron spin resonance study of dental enamel after death.

C4. There was a need for further analysis of the evolution of the early effects, for a more accurate understanding of the nature of the lung and neurological injuries, and for more detailed data on the relevance of biological dose indicators and the reasons for disparities between them.

C5. Both the UNSCEAR 1988 and 2000 Reports contained detailed information on the acute health effects from the Chernobyl accident. There are no substantive new data regarding the acute effects and therefore the material presented in the following section is a summary of that presented previously.

II. UPDATE

A. Acute radiation syndrome

C6. There are several publications that have described the acute health effects of the Chernobyl accident in detail [A8, B1, G12, G13, G14, I34, M13, R11, V3]. During the first few hours after the accident, a number of ChNPP personnel and firemen were admitted to the local hospital with symptoms of possible radiation injury. Emergency dosimetry was virtually non-existent. Based on the expected radiation effects, there appeared to be about 150 victims identified within 4.5 hours of the explosion who would probably need advanced treatment at the Radiation Medicine Department of the Institute of Biophysics (currently Burnasyan Federal Medical Biophysical Center) in Moscow.

C7. The possible diagnosis of acute radiation syndrome was initially considered for 237 persons. From this group, 115 were transported to the Radiation Medicine Department of the Institute of Biophysics, Moscow. Within several days, ARS was verified in 104 of these persons. Later, 30 additional patients were also verified retrospectively to have ARS, making a total of 134. The estimated doses to these patients and the clinical outcomes are shown in table C1 [A8].

Table C1. Data for the 134 patients with acute radiation syndrome [U3]

Degree of ARS	*Absored dose range (Gy)*	*Number of patients*[a]	*Number of early deaths*[b]	*Number of survivors*
Mild (I)	0.8–2.1	41	0 (0%)	41
Moderate (II)	2.2–4.1	50	1 (2%)	49
Severe (III)	4.2–6.4	22	7 (32%)	15
Very severe (IV)	6.5–16	21	20 (95%)	1
Total	0.8–16	134	28	106

[a] Acute radiation syndrome was not confirmed in a further 103 treated workers.
[b] Percentage of treated patients in parentheses.

C8. During the first two days, analyses were conducted to ascertain the degree of radioactive contamination of the skin and the activity of the radionuclides (including radioiodine and radiocaesium) taken into the body. These analyses were carried out on 75% of the total number of patients. The majority of patients did not show radionuclide body burdens above 1.5–2.0 MBq (40–50 µCi). Some 6% of the patients had internal burdens approximately 2–4 times higher than this. The patients were also analysed for the presence of ^{24}Na, to ascertain the neutron exposure. Neutron exposure, however, was found to contribute only a very small part of the total exposure of the patients. Data on internal and external exposures are presented in table C2.

Table C2. Doses of external and internal exposure of the lungs and thyroid to 23 patients who died shortly after the Chernobyl accident[a] [U3]

Personal code	*Internal absorbed dose*[a] *(mGy)*		*External absorbed dose (Gy)*
	Thyroid	*Lungs*	
25	21	0.26	8.2
18	24	2.8	6.4
22	54	0.47	4.3
5	62	0.57	6.2
9	71	0.77	5.6
21	77	0.68	6.4
8	130	1.5	3.8
2	130	2.2	2.9
19	210	3.5	4.5
23	310	2.3	7.5
1	340	8.7	11.1
15	320	27	6.4
16	470	4.1	4.2
3	540	6.8	7.2
17	600	120	5.5
4	640	34	6.5
7	780	4.7	10.2
10	890	9.4	8.6

Personal code	Internal absorbed dose[a] (mGy)		External absorbed dose (Gy)
	Thyroid	Lungs	
11	740	29	9.1
14	950	20	7.2
20	1 900	19	5.6
24	2 200	21	3.5
13	4 100	40	4.2

[a] Internal doses were accumulated to the moment of death and doses of external exposure evaluated using chromosomal analysis of peripheral blood lymphocytes. The relative errors in the internal organ doses are estimated to be less than 30%.

C9. Serial blood samples were obtained during the first three days for analysis of a number of factors, particularly the presence and severity of lymphopenia. This, combined with information on the time when symptoms such as nausea, vomiting and diarrhoea occurred, was of the greatest value for medical prognosis [B33, K18]. Cytogenetic dosimetry was also conducted using blood samples [P17, S24]. During the first 7–10 days, the depth and persistence of bone-marrow depression became more evident, as well as the presence or absence of gastrointestinal symptoms. Less informative and more difficult to evaluate for the purposes of prognosis were radiation dermatitis due to beta irradiation, and epithelial radiation damage of the upper digestive and pulmonary tracts. Based on the clinical and laboratory data, bone-marrow allogenic transplantation was considered and criteria for patient selection were developed. These criteria were later found to be too lax. Allogenic bone-marrow transplantation was subsequently performed on 13 patients, and implantation of human foetal liver cells was performed on only 6 other patients owing to the absence of appropriate donors [G13, I31].

C10. All of the expected major clinical symptoms of ARS, either singly or in combination, were observed in patients with whole-body gamma exposures of more than 1 Gy. As mentioned earlier, bone-marrow depression was seen in all 134 ARS patients. Gastrointestinal syndrome was observed in 15 patients and radiation pneumonitis in 8 patients. Combinations of these syndromes with severe widespread radiation dermatitis occurred in 19 patients (table C3) [B38]. Skin doses exceeded bone-marrow doses by a factor of 10–30 in some patients and a number of these patients had estimated skin doses in the range of 400–500 Gy. This local radiation damage to the skin resulted in significant aggravation of existing pulmonary and hepatic or renal abnormalities. Burns due to beta irradiation were the primary cause of death in a number of patients and significantly increased the severity of the ARS. In particular, when skin burns extended over more than 50% of the surface area of the body, this was a major contributing cause of morbidity and mortality.

Table C3. Relationship of ARS severity grade and percentage of skin burns and skin dose in Chernobyl patients [A8, B38]

Number of patients	ARS severity grade	Percentage of skin burn			Approximate absorbed skin dose (Gy)
		1–10%	10–50%	50–100%	
31	I	2	1	0	8–12
43	II	2	9	1	12–20
21	III	3	15	3	20–25
20	IV	1	10	9	>20

C11. In the early period (14–23 days post exposure), 15 patients died of skin or intestinal complications and 2 patients died of pneumonitis. In the period 24–48 days after exposure, there were six deaths from skin or lung injury and two from secondary infections following bone-marrow transplantation. A patient who had severe ARS developed acute diffuse interstitial pneumonia with rapid development of hypoxemia, which proved fatal. Bacterial and fungal pneumonia was not confirmed at autopsy, and it appeared that there was acute radiation pneumonitis with possible cytomegalovirus being present. There were two deaths at relatively late periods (86–96 days) related to infection complications due to local radiation injury of the skin and insufficient renal function. One female patient died at 112 days from a brain haemorrhage. Underlying bone-marrow failure was the major contributor to all of the deaths during the first two months.

C12. In addition to using blood counts for dose assessment, lymphocytes were also cultured for counting. The exact dose that patients had received was difficult to assess since estimates were based on a set of clinical symptoms; assessments based on marrow depression and on cytogenetics often yielded somewhat different results. Biochemical and haematological indices were determined twice daily for patients with ARS grades I-II; daily evaluations were carried out for the more severe patients. These serial counts were very important for the selection of supportive therapy and in order to assess its effectiveness. Bacteriological tests were also important for the effective management of antibiotic or antifungal therapy. In the absence of signs of active healing of the skin after 50–60 days, a number of patients received surgical grafts. The leg of one patient was amputated more than 200 days after the accident [B40].

B. Therapy and outcomes of patients with ARS

C13. The basic components of ARS therapy employed included:

- Prophylaxis and therapy for infectious complications;
- Detoxification;
- Parenteral nutrition;
- Transfusion therapy (allogenic transplantation of bone marrow and human hepatic foetal-cell infusion);
- Topical therapy of damaged skin areas; and
- Correction of secondary toxic metabolic disturbances.

C14. All patients who had grade II or more ARS were placed in single rooms, managed for delivering an aseptic regimen. Ultraviolet lamps were used for sterilization and medical staff were required to wash their hands thoroughly, wear laboratory coats and masks and wash their shoes with an aseptic solution. Patients’ clothes were changed daily. Microbial contamination indices were periodically monitored. Concentrations of micro-organisms in air were kept below 500 colonies per cubic metre.

C15. These same patients received prophylaxis against endogenous infections, using Biseptol and Nystatin in the event of fever. The patients were administered intravenously with a broad spectrum of antibiotics including aminoglycosides, cephalosporins and semi-synthetic penicillins. In more than half of the cases, this usually terminated any fever. However, if the fever had not gone within 24 to 48 hours, the patients were each given 4–5 intravenous injections of 6 g gamma globulin every 12 hours. Acyclovir was, for the first time, widely and successfully applied to acute ARS patients with herpes infections. About one third of the patients manifested herpes on the face, lips and oral mucosa.

C16. Many of the patients received multiple transfusions with fresh donor thrombocytes. The efficacy of these transfusions was confirmed, not only by the absence of life-threatening bleeding in the patients with prolonged (more than 2–4 weeks) thrombocytopenia (below 5,000–10,000 per microlitre), but also by the absence of any visible signs of increased bleeding in the majority of the patients. On average, 3–5 thrombocyte transfusions were necessary for the successful therapy of each patient with grade III ARS.

C17. Red cell transfusions were not necessary for the therapy of agranulocytic infectious complications. Red cell transfusions were however needed for a number of patients with grade II–III ARS who also had significant injury. All patients who had severe multiple organ damage were treated by modern detoxification techniques and anti-infectious and symptomatic therapies. Haemoabsorption, plasma absorption and plasmapheresis were applied. Direct anticoagulation was also used as a means to improve microcirculation. The major feature of intestinal syndrome therapy was total parenteral nutrition with correction of volume deficiency by means of nutritive liquids and electrolytes. This therapy was highly effective.

C18. Myelodepression and the potential need for additional measures were evaluated according to the scheme previously elaborated by Konchalovsky et al. [K18] and others [G14]. Additional data from blood lymphocyte counts indicating a dose over 6 Gy were also used. Bone marrow was sampled from relatives of patients who were identical (six cases), haploidentical (four cases), or haploidentical plus one common antigen in second haplotype (three cases). Typing was only conducted for A, B, and C loci because of the urgency of the situation. The cases of haploidentical bone-marrow transplantation were conducted with elimination of T-lymphocytes. Three deaths were considered to have occurred unnecessarily as a result of inappropriate bone-marrow transplantation. Bone-marrow transplantation for patients with doses below 9 Gy only worsened the ARS therapy results owing to the development of side effects [B40].

C19. Application of allogenic bone-marrow transplantation to these patients has demonstrated that:

- In radiation accidents, the percentage of victims for whom allogenic bone-marrow transplantation is absolutely indicated and who can obtain a clear benefit from such transplantation is very small;
- In the case of bone-marrow damage resulting from whole-body gamma exposure of 6–8 Gy, transplant survival is possible; however, the transplantation may be life threatening owing to the development of secondary disease and disease due to graft versus host; and
- Recovery of myelopoiesis and survival is possible following whole-body exposures of 6–8 Gy, and this was found after rejection of haploidentical transplants (three cases) as well as in patients who were not given transplants owing to the absence of an appropriate donor (four cases).

C20. Each patient who had grade III–IV bone-marrow syndrome usually also had radiation skin damage and required continuous nursing by highly qualified personnel. The effectiveness of therapy was judged as satisfactory since there were no fatalities with patients with ARS grade II (2–4 Gy doses), excluding the one female patient who later died from a brain haemorrhage. There were 27 patients in the clinic with ARS grade III–IV. The fatal outcomes in this group basically resulted from acute severe cutaneous injuries, from lung damage and from a combination of skin and intestinal damage combined with bone-marrow depression.

III. SUMMARY

C21. The Chernobyl accident resulted in many of the cases of acute radiation syndrome that have been reported worldwide. Cases occurred among the plant employees and first responders but not among the evacuated populations or the general population. The diagnosis of acute radiation syndrome was initially considered for 237 persons based on symptoms of nausea, vomiting and diarrhoea. Subsequently, the diagnosis of ARS was confirmed in 134 persons. There were 28 early deaths of which 95% occurred with people with whole-body doses in excess of 6.5 Gy. Underlying bone-marrow failure was the main contributor to all deaths during the first two months.

C22. Allogenic bone-marrow transplantation was performed on 13 patients and an additional 6 received human foetal liver cells. All of these died except one individual who later was discovered to have recovered his own marrow and rejected the transplant. Two or three patients were considered to have died as a result of transplant complications. Skin doses exceeded bone-marrow doses by a factor of between 10 and 30 and at least 19 of the deaths were considered to be primarily due to infection resulting from large area burns caused by beta irradiation. Internal contamination was of relatively minor importance.

APPENDIX D.
LATE HEALTH EFFECTS

I. LATE HEALTH EFFECTS IN WORKERS WHO SURVIVED ACUTE RADIATION SYNDROME

A. Summary from the UNSCEAR 2000 Report

D1. The early adverse health effects in emergency workers subjected to high levels of radiation mostly during the first night following the accident at the Chernobyl nuclear power plant (ChNPP) were presented in detail in the appendix, “Acute radiation effects in victims of the Chernobyl nuclear power plant accident”, of the UNSCEAR 1988 Report [U7]. Updated information on the early health effects in emergency workers, some long-term effects and the causes of death was provided in annex J, “Exposures and effects of the Chernobyl accident” of the UNSCEAR 2000 Report [U3]. A summary of that information and the experience in treating workers who developed acute radiation syndrome (ARS) is presented in appendix C, “Acute radiation health effects”, of this annex. The material presented in the following section is focused on the late health effects in emergency workers who survived ARS.

D2. Cataracts, scarring and ulceration were the most important causes of persistent disability in the ARS survivors. The consequence of severe skin ulceration was cutaneous fibrosis, which had been successfully treated with low-dose interferon. Surgical treatment was provided to 15 ARS survivors with extensive cutaneous radiation injuries, including ulcerations and fibrosis, between 1990 and 1996. Follow-up of these survivors had not shown a single case of skin cancer. The recovery of physical ability was related to the severity of the initial symptoms of ARS. To limit further occupational radiation exposure of the ARS survivors, legal measures were adopted in the Russian Federation and other countries of the former Soviet Union which restricted their activities or caused them to change their occupations.

D3. Sexual function and fertility among the ARS survivors were investigated up to 1996. In the majority of cases, functional sexual disturbances predominated, while 14 normal children were born to the ARS survivors within the first five years after the accident.

D4. Patients with ARS grades III and IV were severely immunosuppressed. Whereas haematopoietic recovery had occurred within a matter of weeks or, at most, months, full reconstitution of functional immunity may have taken at least half a year, and normalization may not have occurred for several years after exposure. This does not necessarily mean that after the acute phase (i.e. the first three months), recovering patients displayed major immunodeficiency, and it was not surprising that studies of immune status revealed a pattern of changes in blood cell concentrations without clinical manifestations of immunodeficiency. For higher doses of radiation, T-cell immunity may have shown protracted abnormalities; however, these abnormalities were not necessarily associated with clinically manifested immunodeficiency.

B. Update

D5. According to the data from retrospective analysis of case histories, the total number of verified cases of ARS was 134 out of the 237 cases that were initially registered [B41, U3]. During the acute phase, 28 fatalities were recorded; information on this phase was provided in the UNSCEAR 1988 Report [U7].

D6. From 1986 to 1990, 83 emergency workers diagnosed with ARS of different levels of severity were under clinical surveillance at the clinic of the Burnasyan Federal Medical Biophysical Center (FMBC)—formerly the Radiation Medicine Department at the Institute of Biophysics, Moscow. By 1996, the number of patients being followed up at the FMBC clinic had fallen to ten. The distribution of patients seen at FMBC according to the grade of ARS that they survived and to local radiation injuries that they incurred is presented in table D1.

D7. Since 1990, a large group of ARS survivors as well as a group of people initially suspected of having ARS, but later confirmed as not having ARS (hereafter expressed as people with “unconfirmed ARS” or “ARS grade 0”) were under surveillance at the Ukrainian Research Center of Radiation Medicine (URCRM), Kiev [B9, B39, B42]. The distribution of patients seen at the URCRM according to the grade of ARS is shown in table D2. The number of patients reported in different publications vary; this is because of different time periods of observation and because about 20% of the patients have been lost from the follow-up system. Early in 2008, there were 59 patients with ARS being followed up in Ukraine. The ARS grade 0 patients are sometimes used as a comparison group; however, they clearly do not represent a true unexposed control group and appear to have been exposed to absorbed doses in the range of about 0.1 Gy to about 1.0 Gy.

D8. In both clinics, the patients undergo annual examinations of the main systems of the body. As will be evident from the following sections, the follow-up data are difficult to analyse, compare and use because the data from the two clinics have been presented in different formats, have used different diagnostic criteria and only overlap for part of the time (partially in 1986–1990 and, to a lesser extent, in 1991–1995). For these reasons and also because of the small numbers of cases and the lack of analyses using formal epidemiological methods, it is generally not possible to infer trends in disease and mortality rates from these data.

D9. The data primarily refer to the following specific health outcomes: transient peripheral cytopenia, cataracts, thyroid disorders, local skin injuries, neuropsychological disorders, oncological diseases and deaths, and non-oncological diseases and death. Most of these topics are also discussed more extensively later in this appendix for the ARS survivors, other emergency workers, the recovery operation workers, and the general population.

1. Transient peripheral cytopenia

D10. Studies of peripheral blood indicators on patients at 1.5–2 years, 2–5 years, 5–10 and 10–20 years at FMBC, and 10–15 years at URCRM, after the accident produced generally similar results. During the first five years after the accident, the patients' peripheral blood indicators returned practically to normal although transient moderate cytopenia was observed in many patients. Granulocytopenia, thrombocytopenia, erythrocytopenia and lymphocytopenia were most frequently observed during the first 5 years after the accident, but from 5–15 years after the accident, the prevalence of cytopenia cases gradually declined.

D11. The frequency of haematological abnormalities in peripheral blood for the ARS survivors seen at FMBC over a 20-year period is shown in table D3. Reduction was seen mainly in thrombocytes and, to a lesser extent, in neutrophils and lymphocytes. There was little, if any, reduction in either haemoglobin or erythrocytes.

D12. For both the group of ARS survivors and the group of persons with unconfirmed ARS seen at URCRM, haematosis has generally recovered [B9, B39, B42]. Furthermore, recovery of the values of the blood parameters to minimum normal levels basically occurred during the first two months after exposure. The average levels of granulocytes, thrombocytes and lymphocytes in peripheral blood were within the normal range, although in some patients transient cytopenic conditions were noticed. Any dependence of haematological indices beyond two years post accident on the grade of ARS or on dose is ambiguous. The cytopenia frequency among the ARS survivors was higher than among persons with unconfirmed ARS (see figure D-I). The frequency of cytopenia in both groups decreased with time after exposure [B9, B39, B42] and was essentially equal by 2006.

D13. The URCRM has reported on the frequency of deviations of various peripheral blood values but these data are difficult to interpret without knowing the exact time period, criteria and values used to define the term "deviation". For example, deviations in erythrocytes were reported to occur in 67–91% of the ARS patients [B39], while the Moscow group reported abnormal values in erythrocytes in less than 17% of the ARS patients for the entire 20-year period after the accident.

2. Radiation-induced cataracts

D14. There are major differences in the data and conclusions of the FMBC and URCRM physicians and researchers regarding radiation-induced cataracts. According to the FMBC findings, the threshold for the development of radiation-induced cataracts due to beta and gamma irradiation was 3.2 Gy, while the researchers at URCRM indicated that radiation-induced cataracts have been found at absorbed doses of less than 1 Gy. This may be because of differences between the criteria used at URCRM and those used in previous studies [B39, K1, N2, N5].

D15. For the ARS survivors seen at the FMBC, the prevalence of eye disease was 15% versus 6% in the group with unconfirmed ARS, owing to a rise in the number of radiation-induced cataracts. Most of the radiation-induced cataracts in the patients who suffered moderate or severe ARS developed in the first few years after the accident. The latent period for cataract development was shorter for the patients who had received higher radiation doses [G9, N5, N6]. The relationship between the estimated dose and the latent period is shown in figure D-II. There was no relationship between the latent period and the age of the patient at the time of exposure. The cataractogenic effect appeared to have ceased after 200 months post exposure, and no new cases were diagnosed after 1999. The estimated doses due to beta and gamma irradiation of various parts of the eye, and the significant difference in depth–dose distribution, are shown in table D4 [G9] and in reference [G10].

D16. For the group of patients followed up at URCRM, numerous cases of radiation-induced (subcapsular posterior) cataract were reported, i.e. 23 cases among the ARS survivors and 3 cases among the persons with unconfirmed ARS [B44, G9]. A strong dependence of cataract prevalence in the long term on the grade of the ARS, and therefore the dose, is shown in figure D-III [B9, B44]. The majority of cataract cases developed during the first five years after exposure, and the dependence of the latent period on dose or on the ARS grade was not statistically significant. Furthermore, in contrast to the FMBC findings, a monograph by

Bebeshko et al. [B39] of URCRM does not account for the contribution of beta radiation to the dose to the lens of the eye, which may result in an underestimation of the total (beta + gamma) dose, and therefore of the value of the threshold dose.

3. Thyroid abnormalities

D17. Hypothyroidism among the ARS survivors is of interest owing to the high ambient levels of radioiodine during the accident. According to the results of the thyroid radiometry carried out on 81 patients during the acute period of ARS, the absorbed dose to the thyroid in only one patient reached 11 Gy.

D18. Among the patients monitored at the FMBC laboratory, signs of thyroid-function abnormalities were observed mainly during the first five years, with hypothyroidism found in 4 out of 83 patients (4.8%) and hyperthyroidism in one patient (1.2%). During the period 2001–2007, only 1 in 10 patients was hypothyroid. The number of cases of nodular goitre has increased from one during the first five years post accident and is now present in 4 out of 10 patients [G9].

D19. The URCRM researchers reported that 15 ARS patients suffered hypothyroidism in 1986 with 12 of them returning to normal in 1987. Three cases of moderately pronounced hypothyroidism were observed in subsequent years [B39].

4. Local radiation-induced skin injuries

D20. The major health consequences observed among the ARS survivors were related to local radiation-induced injuries (skin burns and radiation-induced cataracts) that often required surgery, sometimes repeated [N5]. In contrast to ARS, the local radiation injuries were a function of the dose due to beta and, to a lesser extent, gamma irradiation. The nature and severity of the skin injuries incurred during the late stage were a consequence of the severity of the injuries incurred during the acute phase. At the late-sequelae stage, the patients who suffered first-degree local radiation injuries displayed various levels of skin atrophy, ranging from slight smoothing of the skin surface to more pronounced changes. Over longer periods, the slight atrophic changes of the skin disappeared almost completely. With second-degree local radiation injuries, there was pronounced atrophy of the skin—areas of hypo- and hyperpigmentation, hyperkeratosis and telangiectasia, scarring, radiation-induced fibrosis, and late radiation-induced ulcers [G9].

D21. With third- and fourth-degree local radiation injuries, there were areas of fibrous scarring, contractures, non-healing primary radiation-induced ulcers and persistently recurring late radiation-induced ulcers. With the introduction in the 1990s of skin autoplasty using microsurgery techniques, it became possible to significantly reduce the problems of treating recurring radiation-induced ulcers—at least in the case of five patients suffering from the consequences of local radiation injuries sustained at the ChNPP who were under observation at the FMBC. Repeat operations necessitated by the recurrence of late radiation-induced ulcers at the same site, have not been reported [G9].

D22. Up to 2005, 38 patients suffering from the consequences of local radiation injuries were under observation (5 at FMBC and 33 at the URCRM). These included 18 persons with skin injuries of grades 2 and 3. Amputations (a lower leg, a finger and part of a finger) were performed on 3 patients [G9]. In the long term, telangiectasia was observed in 20 patients and repeated skin ulceration and fibrosis were observed in 6 patients. The remainder had moderate local skin atrophy and hyperkeratosis. There was a strong dependence of the frequency and intensity of the long-term effects on the grade of local skin injury incurred during the acute phase.

D23. Seven patients out of ten who were followed up in recent years at the FMBC clinic had local radiation injuries of the skin, i.e. radiation-induced fibrosis, relapsed ulcers and contraction. For the ARS survivors seen at the FMBC, the prevalence of dermatological diseases due to local radiation injury in 1986 was 7%. The data are shown in figure D-IV.

D24. The late effects of local radiation injuries to the skin were studied at the URCRM in 39 persons from both groups (the ARS survivors and persons with unconfirmed ARS). In 15 (39%) out of the 39 persons, no changes were found in the skin at the places of the former radiation injury. For the rest of the patients, local skin atrophy, skin hyper- and hypopigmentation, peeling and telangiectasia were observed. There was a strong dependence of the frequency and intensity of long-term effects on the grade of ARS and on the grade of the local skin injury in the acute phase [B39]. The data are shown in figure D-V.

5. Neuropsychological disorders

D25. Much attention was paid in the URCRM studies to a group of persons for whom a high prevalence (up to 100%) of nervous-system diseases (including functional abnormalities, such as vegetative and vascular dystonia) was registered during the first decade. The diagnostic criteria used were not always clear and the diagnoses were often based on subjective judgement. The URCRM also reported that during the second decade after the accident, there was a large contribution from organic diseases (cerebral atherosclerosis, and so on). There was no dependence of the frequency of disease on the grade of ARS and therefore, the dose. This indicates an aetiology other than radiation [B9, B39, B42].

D26. The majority of the ARS patients followed up were officially recognized as invalids with limited work ability. The small number of cases of people returning to work did not correlate with the severity of ARS that they survived or with their local radiation injury; their return was mostly determined by their personal motivation and the competence of the medical doctor [G9].

6. Oncological disease incidence and mortality

D27. According to Galstyan et al. [G9] the percentage of the ARS patients with cancer was 4.6% and included four cases of solid cancer (a kidney cancer, a colon cancer and two cases of thyroid cancer) with an average age of 45 years at diagnosis and an average latent period of about 11.5 years. There were also three cases of myelodysplastic syndrome, one case of acute myelomonoplastic leukaemia and one case of chronic myeloid leukaemia. The average age at diagnosis was 53 years with an average latent period of 11.8 years. No malignant thyroid neoplasms were detected in the 10 patients under observation in recent years at the FMBC, although multiple basal cell carcinomas have been detected in 2 patients who had suffered from grade III-IV ARS.

D28. Among 13 solid cancers diagnosed in the patients followed at the URCRM, 4 were in the ARS survivors and 9 in the persons with unconfirmed ARS (used as the control group) (table D5) [B44]. The mean latent period after exposure was 14 years for both groups. No statistically significant dependence of the disease frequency or severity on the grade of ARS and therefore the dose, has been observed. In fact, the crude incidence rate for solid cancers was higher for the group of unconfirmed ARS patients (9 out of 96), who had lower doses, compared to that for the ARS patients (4 out of 72).

D29. During 20 years (1987–2006), 19 ARS survivors and 14 persons with unconfirmed ARS died for various reasons [B10, B39, B41, B42, B44, G9, U3]. Among the ARS survivors, the most frequent cause of death (4 cases out of 19) was haematological malignancy with a mean latent period of 9 years [G9].

7. Non-oncological disease incidence and mortality

D30. Data on non-oncological diseases among the ARS survivors are complicated by the fact that often what is reported are either the number of patients suffering from a category of disease or the number of new diagnoses for a category of disease. Without specific diagnoses, meaningful conclusions regarding potential radiation effects are difficult to draw. For example, the category of respiratory disease would include infectious and neoplastic aetiologies as well as diseases resulting from smoking.

D31. The increasing age of the population with time is also an important factor influencing the increases in the numbers of disease cases and deaths. The long-term morbidity and mortality of the ARS survivors was analysed by the FMBC and by the URCRM. During the follow-up period 1986–2006, the mean age of the patients increased from 35.5 to 54 years, which, in itself, would imply an increased number of somatic diseases unrelated to radiation exposure.

D32. As for the other areas of medical follow-up of the ARS survivors, there appear to be significant differences between the prevalence of diseases reported by the FMBC and URCRM. Both groups however have generally been unable to link the prevalence of non-neoplastic diseases to the grade of ARS.

D33. The number of patients with diseases in four selected systems of the body followed up at the FMBC clinic is presented in table D6. It is reported that the general health condition of the ARS survivors is similar to that of the male population of the Russian Federation of corresponding age. An important exception is the increase in the percentage of patients with cardiovascular disease from 53% in 1986–1990 to 100% in 2001–2007; the increase correlates with their increase in age. The increase in the observed number of disease cases is largely attributable to the targeted diagnostics of the FMBC clinic. A comparison was made of the morbidity of the ARS survivors with that of the unconfirmed ARS group followed up at the FMBC clinic over the 15 years since the Chernobyl accident; it was concluded that, apart from dermatological and eye disease, the total disease prevalence and component disease prevalences are similar for both groups [G9].

D34. The percentage of the ARS survivors with cardiovascular diseases reported among the patients seen at the URCRM, in particular of essential hypertension and ischaemic heart disease, progressed with time and approached 90% in 2006. The prevalence of gastrointestinal disease was also reported to be high; it had grown from 80% in 1991 to almost 100% in 2006. The prevalence of hepatobiliary disease is similar to that of gastrointestinal tract disease [B9, B39, B42]. There was no dependence of the disease frequency on the grade of ARS and therefore the dose; this indicates that other risk factors than radiation are significant.

D35. The follow-up of the ARS survivors at the URCRM to the end of 2006, more than 20 years after exposure [B42], indicated a high prevalence of various groups of disease. Yet, no substantial difference between the ARS survivors and the persons with unconfirmed ARS (control group) regarding both the prevalence and morbidity structure was identified (e.g. see figure D-VI). The prevalence of reported respiratory and endocrine diseases seen in patients at the URCRM, has increased significantly with time, i.e. from 10–30% in 1991 to 70–80% in 2006, and from 5–15% in 1991 to 60–70% in 2006, respectively.

D36. An increase in the number of cases of cardiovascular disease was recorded later and correlated with the increasing age of the patients. The prevalence of this disease among the ARS patients was lower during the second and third five-year periods but increased during the fourth five-year period. Although there were considerable changes in the values of the biological parameters studied at the laboratory level, the majority of actual clinical manifestations took uncomplicated, compensated courses. Dependence of the disease frequency on the grade of ARS, and therefore the dose, has not been confirmed statistically [B39]. The use of the group with unconfirmed ARS as the internal control group is a methodological deficiency of the URCRM studies.

D37. By the beginning of 2007 (more than 20 years after the accident), 19 ARS survivors (6 with ARS grade I; 8 with ARS grade II; and 5 with ARS grade III) and 14 persons with unconfirmed ARS had died from various causes [B10, B39, B41, B42, B44, G8, U3]. The mean age of death, its standard error and range was: 45.5 ± 4.3 (26–53) years for persons with ARS grade I; 61.9 ± 4.9 (45–81) years for those with ARS grade II; 62.2 ± 7.7 (41–87) years for those with ARS grade III; and 57.0 ± 3.3 (32–73) years for those with unconfirmed ARS (ARS grade 0). The causes of death for the ARS survivors are presented in table D7. Among the causes of death were non-oncological diseases of internal organs (7, including 2 from pulmonary tuberculosis and 2 from cirrhosis of the liver), sudden cardiac death (6), oncological and onco-haematological diseases (5) and trauma (1).

D38. The numbers of deaths due to various somatic diseases during the 20 years since the accident along with the grade of ARS of the survivors are shown in table D8. Deaths from trauma and accidents are not included. In particular, the proportion of survivors who died from somatic diseases is substantially higher for those who survived ARS grade III than for those who suvived ARS grades 0 or I; however, the mortality coefficient is not age-standardized, the number of patients is small, and 4 cases of haematological death played a predominant role.

C. Summary

D39. The follow-up of the ARS survivors indicates that: the initial haemotological depression has decreased substantially in many patients; there remain significant local skin injury sequelae; there has been an increase in the number of cases of haematological malignancies; and an increase in the number of cases of non-haematological diseases is likely to have been a result of ageing and other factors unrelated to radiation exposure. However, the small numbers of cases and deaths, the lack of formal epidemiological analyses and the impact of some loss of patients from the follow-up, make inferences about disease or mortality rates problematic. While an increased number of cataracts has been documented, debate remains about the threshold dose for their induction and the criteria to be used in their diagnosis as well as their clinical importance and progression with time.

D40. The follow-up of the subjects who had ARS should be continued, especially because more than twenty years have passed since the accident and late carcinogenic effects may now be manifested. It would be very useful if the groups following these patients would use the same methodology and criteria for diagnosis and if these were carefully explained in any publication. Special attention should be given to the haematological proliferative diseases, tumours of the endocrine system and skin cancers. The control group could be composed of recovery operation workers exposed in 1986 to doses below the threshold for deterministic effects [N6]. Formal epidemiological methods should be used in analysing these data. Furthermore, the data on the ARS survivors of the Chernobyl accident should be analysed with reference to the ARS consequences in other accidental situations [N5, O2].

II. REGISTRATION AND HEALTH MONITORING PROGRAMMES

A. Summary from the UNSCEAR 2000 Report

D41. Following the Chernobyl accident, compulsory registration and continuous health monitoring of the recovery operation workers and residents of the most contaminated areas, including their offspring, had been initiated throughout the Soviet Union. Until the end of 1991, the All-Union Distributed Clinico-Dosimetric Registry had recorded information on 659,292 persons. After the dissolution of the Soviet Union into independent states, national Chernobyl registries had continued to operate, but independently of each other. Changes in national registration criteria, compensation laws, dose-reconstruction methods and follow-up mechanisms had increasingly limited the comparability of data from those different national sources. More detailed registries of exposed populations had existed in the Russian Federation (Registry of Professional Radiation Workers, Registry of Military Workers and the cohort of Helicopter Pilots and Crew). However, the quality and completeness of those registries remained largely unknown.

D42. The number of people registered in the national Chernobyl registries continued to increase, even in recent years, which raised questions about the completeness and accuracy of registration. Information on mortality and cancer incidence had been collected from many different sources and coded independently of international guidelines. Evidence from recent cohort studies suggested that the Chernobyl health outcome data could not be successfully compared with health data obtained from official statistical sources.

D43. Systematic linkage of the data from the Chernobyl registries with existing mortality and/or cancer incidence registries, and the subsequent comparison of the health outcome experience in the exposed cohorts with the corresponding national reference statistics were thought to be potentially valuable tools for epidemiological research. Internal comparisons, e.g. using a low-dose comparison group, were thought likely to provide information on the risks associated with ionizing radiation in subsequent years. However, complete information (e.g. on previous exposure to ionizing radiation in an occupational setting) would most probably only be available for small subcohorts.

D44. Health outcome registries were considered to be an important source of information for assessing the consequences of the Chernobyl accident. Their primary advantages were thought to be that the information had been collected in a systematic way before and after the accident and the criteria for data collection were the same in all countries of the former Soviet Union. However, most of these registries, whether related to mortality, cancer incidence or special diseases, continued to be operated largely manually, which seriously limited their use for epidemiological research purposes. The Chernobyl accident led to major international efforts to computerize the cancer incidence and special disease registries and to improve their registration methods so as to comply with international standards. However, mortality registration systems had received little attention. Information on the quality and completeness of these systems remained scarce.

D45. Compulsory cancer registration had been introduced throughout the former Soviet Union in 1953. The system relied on passive reporting of information on all newly diagnosed cancer cases to the regional cancer registry for the patient’s place of residence. Since the early 1990s, efforts had been made to computerize the existing systems and to gradually improve their quality in order to meet international standards. Belarus had been covered by a network of computerized cancer registries since 1991. Computerization had been well advanced in Ukraine, and full population coverage was expected soon. In the Russian Federation, efforts to develop computerized cancer registration had started only in the late 1990s and were to be focused on the areas deemed contaminated and control areas.

D46. Specialized population-based registries for haematological malignancies and thyroid cancer had been set up in the wake of the Chernobyl accident and in response to the unknown quality and lack of detail for these cancers in the general registries. Childhood cancer registries had also been developed for the same reasons. Assessments of the quality of these registries were underway. Other registries for hereditary disorders and malformations exist, but their quality and completeness had not been independently assessed.

D47. Shortly after the Chernobyl accident, efforts had been devoted mainly to developing adequate registration systems for future follow-up of those population groups most affected by radionuclide deposition. Later, international collaborations had helped to modernize the existing disease registration infrastructure. However, information on the quality and completeness of all these registries was still very scarce. The usefulness of the vast amount of data collected was expected to become clearer in the following decades as the long-term consequences of the accident were studied. In particular, matching the health outcomes with the dosimetric data was considered to be of great importance.

B. Update

1. Registration and monitoring of exposed populations

(a) The Chernobyl registries

D48. Since the dissolution of the former Soviet Union, registration practices in Belarus, the Russian Federation and Ukraine diverged. As a result, in many instances the data are no longer comparable for the four main groups of registrants, i.e. the recovery operation workers, the evacuees from the exclusion zone, the residents of the contaminated regions, and the children born to parents from the above three groups. For example, the Russian National Medical and Dosimetric Registry (RNMDR) only contains data on children born to recovery operation workers. Table D9 shows the most recent data on the nearly five million registrants in the three countries.

D49. Because registration is tied to social and economic benefits, concerns have been raised that this might have led to large numbers of people inappropriately being included in the registries in all three countries. These concerns are supported by the evidence of a continued rise in the number of people registered, even in recent years.

D50. Systematic medical follow-up of those registered varies by country. These differences stem from recent changes in the health systems in the three countries. The Russian Federation, in particular, has undergone a major change connected with a shift to private medical insurance. While Ukraine maintains the system of universal medical coverage, very limited funds are available for medical care, and, in particular, for the specialized care for those exposed to radiation resulting from the Chernobyl accident. Of the three countries, Belarus is the only one that maintains the regime of systematic examinations for the four main categories of registrants. Table D10 summarizes the information on the medical follow-up of those included in the Chernobyl registries for 2001–2005.

D51. Accurate and precise information on the state of the registries in the three countries is not readily available. Only one country (the Russian Federation) has a publicly accessible website for its registry [N1] that contains regulatory documents for and general information on the operation and structure of the registry, the number for those registered, their categorization and places of residence as well as basic results of radiation epidemiology studies. In recent years, many papers have appeared analysing subcohorts of registrants. These provide more detailed information on the rising number of people registered in the RNMDR [I41, M11].

D52. Since 1998, efforts have been underway to establish a “United Registry” for those exposed to radiation resulting from the Chernobyl accident in Belarus and the Russian Federation in order to facilitate joint epidemiological studies and thereby increase their statistical power. During 1998–2006, information on 256,000 emergency and recovery operation workers and 43,000 of their children was included in the United Registry. The registry also contains information on 23,000 cases of thyroid cancer, more than 5,000 cases of leukaemia and 18,000 cases of breast cancer diagnosed in the populations of the most radioactively contaminated areas of both countries [J8].

(b) Specialized registries

D53. In recent years, several initiatives to register and follow-up particular groups of those exposed to radiation resulting from the accident were started. In Belarus, a register of those exposed to radiation from nuclear accidents other than at Chernobyl was recently established. It mainly includes former professional nuclear workers who were exposed to high doses of radiation at various civilian and military nuclear facilities of the former Soviet Union. The number of registrants, however, is relatively small (772) and it is not clear what information and dosimetric records are available on these subjects [S14].

D54. The RNMDR continues to register and follow-up a number of special groups, including current and former professional nuclear workers, military clean-up workers and helicopter pilots who participated in the clean-up work at Chernobyl. In addition, it maintains ties with the five recently established professional registries of the Ministries of Defence, Interior, Atomic Power and Industry, Federal Security Service and Transportation, where the majority of clean-up workers were or are still employed and receive medical care [N1]. Currently, no information is available on the completeness and utility of these registries for epidemiological research. However, some of them (e.g. the Russian specialized registry of nuclear workers maintained at the Institute of Biophysics, Moscow) are used for epidemiological studies [I47].

2. Registration of mortality and disease in the general population

(a) Mortality

D55. Several major changes in the registration of vital statistics occurred in the three republics in recent years. In particular, the Russian Federation and then Ukraine began to introduce a universal taxation identification number for all citizens and legal residents after 2000. This could prove instrumental in tracing those registered in the Chernobyl registries through local birth/marriage and death registration offices. However, until computerized national death indexes are created, epidemiological research using passive follow-up methods would be very cumbersome and impractical.

(b) Cancer incidence

D56. The Belarusian Cancer Registry has been in existence in computerized form since 1973. Individual patient records, however, have only been available since 1985. The registry routinely contributes data to *Cancer Incidence on Five Continents* (volumes VI, VII and VIII) and is considered to be of very good quality [P13, P14, P15]. Very high proportions of all cancer cases have verified pathology and morphology. For example, while in 1980–1986, only 71% of all thyroid cancer cases had confirmed pathology, in 1997–2001, 95% were pathologically verified. Very low rates (less than 0.4%) of registrations by death certificate alone also attest to the high quality of the registry [M15]. The high quality of the data means that they are often used for comparison of cancer incidence from before and after the accident not just in Belarus, but also for the geographically close populations of the Russian Federation and Ukraine. However, caution in interpretation of time trends is recommended because, since 1990, there have been improvements in the completeness and accuracy of cancer registration related in part to early detection and treatment of various cancers in the most contaminated areas [C11].

D57. The Ukrainian Cancer Registry (UCR) was established in 1996 and now effectively covers 93% of the population (up to 97% in the six oblasts surrounding the site of the Chernobyl accident). The UCR is a population-based registry containing information about all malignant diseases diagnosed in Ukraine. Data are collected from hospital databases and combined at the oblast level, and then transferred in electronic format to the central office. Individual patient records include information on patient demographics, primary tumour site, tumour morphology and stage at diagnosis, treatments and follow-up for vital status, as well as the place and date of diagnosis and death. The majority of diagnoses come from specialized oncology hospitals and are generally of high quality. In 2004, for example, 98.5% and 50.6% of all leukaemia diagnoses had confirmed morphology and histology, respectively. Only 2.0% of all cases were based on death certificates alone, again suggesting high quality of the data. The majority of cancers are registered within the same year they were diagnosed, with complete coverage achieved by two years after diagnosis. Detailed reports are issued annually and the UCR data are accessible to researchers.

D58. The National Cancer Registry in the Russian Federation is only beginning to emerge after its founding in 1999. While some regions, such as St. Petersburg, could be considered to have complete population-based registries, coverage in other areas is patchy and frequently not in a computerized form [S27]. Reliability of information from other regional cancer registries varies widely. Thus, currently, these data cannot be used for epidemiological research.

(c) Specialized cancer registries

D59. Several specialized cancer registries were established in the 1990s and are currently in use. All three countries have registries of leukaemia, but while in Belarus, it is population-based, in the Russian Federation and Ukraine, they are attached to the Chernobyl registries and only seek information on those exposed to radiation resulting from the accident. The quality of these registries has not been evaluated despite the fact that their data have been used in several publications. In particular, the leukaemia registry operating under the RNMDR was a source for several quantitative studies of leukaemia among the recovery operation workers [I11, I12, I13, K11]. These multiple analyses from the same registry provide some evidence of increased risks of leukaemia from the exposures received during the clean-up work. The utility of the registry for epidemiological research has significantly improved due to the established system of case identification and verification procedures. Thus, in one of the studies, 92% of the leukaemia cases were said to be morphologically verified [I12].

D60. Other specialized registries include the Belarusian Thyroid Surgery Registry and Childhood Cancer Subregistry of Belarus, the Registry of Non-Cancer Diseases within the RNMDR, the Clinical and Morphological Registry of Thyroid Cancer of Ukraine. At present their computerization, standardization and, ultimately, aptness for epidemiological research need further attention.

C. Summary

D61. Chernobyl registries have a good possibility of becoming reliable sources of information on the long-term health effects of radiation exposure after the accident. Standardization of procedures across the three registries would greatly improve their utility for epidemiological research.

D62. The following special issues that are substantial for the successful use of the Chernobyl registries in epidemiological studies require further attention:

For the Chernobyl registries:

- Clarification of the eligibility criteria for registration;
- Collection and verification of retrospective data;
- Assessment of doses received after the accident;
- Standardization of government policies across countries governing the medical follow-up of those deemed affected by the accident;
- Flow of information from the local medical facilities conducting medical follow-up of those exposed, to the central offices of the Chernobyl registries; and
- Computerization of the data and their accessibility to researchers;

For specialized registries:

- Sharing of information with the Chernobyl Registries; and
- Utilization of collected data;

For cancer registries:

- Complete coverage at the national level;
- Verification of diagnoses; and
- Inclusion of follow-up information in individual patient records;

For death indexes:

- Complete coverage at the national level;
- Computerization of the data and their accessibility to researchers; and
- Utilization of the international classification of diseases on all death certificates.

III. LATE HEALTH EFFECTS OF THE CHERNOBYL ACCIDENT IN WORKERS AND THE GENERAL PUBLIC

D63. Apart from the economic, social and psychological effects of the Chernobyl accident, a major concern is the potential long-term health effects due to radiation exposure. The Committee decided in this annex to focus on the incidence of thyroid cancer, leukaemia, all solid cancers as a whole, cardiovascular mortality, cataract development and autoimmune thyroiditis. This decision was based on the potential sensitivity of these outcomes to radiation and because the Committee considered that there were insufficient new data in other areas to modify the conclusions of the UNSCEAR 2000 Report.

A. Summary from the UNSCEAR 2000 Report

D64. The majority of the studies completed before the UNSCEAR 2000 Report on the health effects of the Chernobyl accident were of the geographical correlation type (often called “ecological studies”). These studies compared average population exposure with the average rate of health effects or cancer incidence in time periods before and after the accident, or between different periods after the accident. As long as individual dosimetry was not performed, no reliable quantitative estimates could be made.

The reconstruction of valid individual doses would be a key element in future research on the health effects related to the Chernobyl accident.

D65. The number of thyroid cancers in groups of individuals who had been exposed in childhood, particularly in the contaminated areas of Belarus, the Russian Federation and Ukraine, increased dramatically during the previous 15 years. The high incidence and the short induction period had not been experienced in other exposed populations, and factors other than ionizing radiation were thought almost certainly to have influenced the risk. Some such factors that were considered included age at exposure, iodine intake and metabolic status, endemic goitre, screening, short-lived isotopes other than ^{131}I, higher doses having been received than had been estimated, and, possibly, genetic predisposition. Approximately 1,800 thyroid cancer cases had been reported in Belarus, the Russian Federation and Ukraine in children and adolescents for the period 1990–1998. Age at exposure seemed to be an important modifier of risk. The influence of screening was difficult to estimate. Approximately 40–70% of the cases had been found through screening programmes, and it was unclear how many of these cancers would otherwise have gone undetected. Taking the advanced stage of the tumours at the time of diagnosis into consideration, it was thought likely that most of the tumours would have been detected eventually.

D66. Results from some studies had indicated that the majority of the post-accident thyroid carcinomas in children showed the intrachromosomal rearrangements characterized as *RET/PTC1* and *RET/PTC3*. There were, however, several questions left unanswered, e.g. the influence of age at exposure and time since exposure on the rate of chromosome rearrangements.

D67. The risk of leukaemia had been shown clearly to be increased by radiation exposure in epidemiological studies on other exposed populations. Up till the time of the UNSCEAR 2000 Report, no increased risk of leukaemia linked to ionizing radiation had been confirmed in children, in the recovery operation workers, or in the general population of the former Soviet Union or other areas with measurable levels of radioactivity due to the Chernobyl accident.

D68. Increases had been reported in a number of non-specific detrimental health effects other than cancer among the recovery operation workers and among the residents of contaminated areas. It was difficult to interpret these findings without referring to a known baseline or background incidence. Because health data obtained from official statistical sources, such as mortality or cancer incidence statistics, were often passively recorded and were not always complete, it was not appropriate to compare them with data on the exposed populations, which underwent much more intensive and active health follow-up than the general population.

D69. Some investigators had interpreted a temporary loss of ability to work among individuals living in contaminated areas as an increase in general morbidity. High levels of chronic diseases of the digestive, neurological, skeletal, muscular and circulatory systems had been reported. However, most investigators related these observations to changes in the age structure, the worsening quality of life and the post-accident countermeasures such as relocation.

D70. Many papers had been published on the immunological effects of exposure to radiation due to the Chernobyl accident. Since it was unclear, however, whether possible confounding factors had been taken into account (including, in particular, infections and diet), it was difficult to interpret these results.

B. Methodological approaches

1. Types of studies

D71. Two approaches are commonly used to assess the long-term health effects of the accident. The first approach is to use risk models derived from other populations exposed to radiation exposure, for example, the survivors of the atomic bombings of Hiroshima and Nagasaki, and then apply these models to the estimated doses received by the relevant population after the accident and thus project the subsequent risks to that population. The second approach is to conduct empirical studies of the populations exposed as a result of the accident in order to assess the health effects directly in these populations.

D72. The approaches have different advantages and disadvantages. The first approach, often called the risk-projection approach, is based on studies of populations with higher doses than those experienced by populations after the Chernobyl accident. But, the main disadvantage is that it involves extrapolation of the risk observed in one exposed population, with its own specific characteristics, to another one, for which the levels of dose and dose rate or the mixture of types of radiation are different. In the populations exposed as a consequence of the accident, internal exposure to radioiodine played a major role in the induction of thyroid cancer; this specific type of exposure could not be studied through follow-up of the survivors of the atomic bombings.

D73. On the other hand, the empirical approach suffers from low statistical power because of the relatively low doses, and the need for a long-term follow-up; however it has the advantage of considering the directly affected populations. This appendix focuses mainly on the empirical studies, i.e. those carried out directly on the relevant populations, and considers preferentially those populations for which there are precise estimates of individual dose. These studies, called “analytical studies”, provide the most direct and convincing evidence of the long-term health effects in humans [I1]. Disciplines such as dosimetry, clinical medicine and anatomopathology are part of these analytical studies and contribute to a valid interpretation of the observations.

D74. When an empirical epidemiological study provides evidence of an increase in incidence of or mortality due to a potentially radiogenic disease, it is still necessary to consider the issue of the attributability of that effect to radiation. Epidemiological studies are observational in nature and, as such, any observed associations may not necessarily indicate causality. It is necessary to take detailed account of factors that may confound or bias the results, such as industrial pollution, environmental features (e.g. stable iodine levels in soil), lifestyle (e.g. smoking habits, alcohol consumption or reproductive history), improvement of diagnostic tools, and increased medical attention to affected populations (e.g. special screening). In combination, confounding factors can simulate an apparent radiation effect or mask a true effect, and lead to incorrect conclusions, if they are not properly taken into account.

D75. Currently published studies may be divided into the so-called geographical correlation studies (“ecological studies”) and analytical studies. In most ecological studies, exposure is reconstructed at the group level, whereas in analytical studies, exposure is assessed at the individual level. It should be noted, however, that ecological studies have been published that are based on a large number of individual dose measurements, and case-control studies have been published that are based on radioecological models. Examples of geographical correlation studies include those that monitor cancer incidence as a function of time and/or geography, e.g. rates before and after the Chernobyl accident, or rates in oblasts with varying levels of radionuclide deposition. Geographical correlation studies have the disadvantage that potential confounding or biasing factors, such as screening (see below), can only be studied at the group level and may thus be subject to residual individual confounding. This concern regarding the attributability of geographical correlation study results to radiation has already been discussed in the UNSCEAR 2000 Report [U3] and annex A, “Epidemiological studies of radiation and cancer”, of the UNSCEAR 2006 Report [U1].

D76. Analytical epidemiological studies are typified by case-control and cohort studies. In this case, adjustments for confounding factors (if known and available) can be made at the individual level. Biases, such as in selection of subjects or in information acquisition, however, are inherent flaws in study design and cannot be readily accounted for in analyses. Generally, analytical studies are regarded as providing stronger evidence of possible attribution to radiation exposure than geographical correlation studies.

D77. In addition to the fundamental consideration of the study design, the criteria that should be used to determine the potential quality of the study include:

- Availability of accurate and precise dose estimates, at either the individual or group level (appendix B);
- Well-defined study population;
- Confirmation of disease diagnoses, preferably made independently;
- Complete ascertainment of disease cases, with an ascertainment mechanism that is independent of dose. The existence of high quality and independent cancer registers on a regional or national basis are important;
- Reporting of appropriate dose–response analyses, taking into account appropriate time factors such as minimal latent period, age at exposure and age attained;
- Sources of data and methods being clearly reported.

D78. Studies vary in their concordance with these criteria, and may provide useful information even if one or more of them is not satisfied. Nevertheless, each study should be considered in terms of its concordance with these criteria for an appropriate evaluation to be made.

D79. A number of epidemiological studies have been reported that have been conducted in the three republics. In general, these studies have considered one or more of the following groups: the evacuees; the residents of contaminated territories; and the recovery operation workers. The third group is of particular interest because, on average, their doses were generally higher than those to the people in the other two groups. However, caution must be exercised in considering the studies of the recovery operation workers based only on “official” doses and/or diagnoses recorded in the state registries. The official doses are known to be incomplete and possibly biased in some cases (appendix B). Diagnoses made without independent confirmation may also be of inadequate quality. In addition, more intensive and frequent medical examinations were carried out on the recovery operation workers, which may have led to the earlier detection of disease and provided more specific diagnosis than would have been the case for the general population covered by the normal health care system. Comparison of the data for the recovery operation workers with different exposure levels but the same level of medical attention may avoid these problems.

D80. Generally then, two types of study are considered when evaluating the incidence of cancer and non-cancer diseases in populations exposed as a result of the accident:

i. *Geographical correlation studies* (often termed “ecological studies”) describe incidence rates of disease characterized by age attained or place of residence at diagnosis. A description in relation to the place at exposure should be considered carefully, as it presupposes either that this information (the place of residence in April 1986) has been registered systematically in the cancer register or that the place of diagnosis is equivalent to the place of residence. The latter has to be verified as it presupposes no migration of this population. This may be true if the follow-up is limited in time, but after more than 15 years, it may no longer be true if people, exposed in one oblast, are now living in the city of another oblast. In some geographical correlation studies, the average doses have been reconstructed at group level (village, settlement or oblast). Quantitative estimates of measures of risk derived from these data have to be considered with caution, because uncertainties linked to individual behaviour could not be taken into account in this type of dose reconstruction. A special type of geographical correlation study resulting in more reliable risk estimates has been introduced to analyse thyroid cancer risk after the Chernobyl accident. The cases were related to the place of residence at the time of exposure (and not at the time of diagnosis) and based on dose estimates in settlements, for which more than 10 individual dose measurements had been performed.

ii. *Analytical studies* (with two subtypes: case-control or cohort) use individual-specific information, and are considered to be more reliable and valid for examining the dose–response relationship. Any resulting dose–response relationship has at least two interpretations:

- If the risk of a specific disease like thyroid cancer increases with increasing exposure, and other confounding factors are accounted for, then the radiation exposure should be considered as playing a role in the development of this cancer;
- The possibility to legitimately compare the risk for this population with the risk observed in other situations of human exposure, even when the exposure in those situations was at higher levels (radiotherapy patients) or of different nature (survivors of the atomic bombings).

2. Diagnostic and screening issues

D81. In epidemiological studies, it is necessary that the frequency of detection of a disease and the quality of diagnosis are independent of the degree of exposure. In the case of studies related to the Chernobyl accident, three issues are of particular concern.

D82. The first is improvement in diagnostic techniques. Specifically in relation to the Chernobyl situation, this refers to the introduction of ultrasonography for the detection of thyroid cancer. Since the accident, there has been a substantial increase in the number of ultrasound examinations used to detect thyroid cancer. Figure D-VII shows, for example, the number of ultrasound examinations performed per 10^5 inhabitants in the three most contaminated oblasts in Ukraine in 1990, 1995 and 2002 [L5]. During the same period, an increasing incidence of thyroid cancer was reported in these oblasts [L5]. Thus, part of the increase in the observed thyroid cancer incidence may be attributable to the improved detection of cancers because of the greater use of ultrasonography.

D83. The second issue is that these screening programmes make it possible to detect smaller tumours that may have been latent for many years. Screening refers to examining individuals who do not have clinically manifest disease in an attempt to diagnose any disease earlier in its natural history and, hopefully, to improve the prognosis and treatment for that disease. A number of formal screening programmes have been introduced in the three republics since the Chernobyl accident, again with thyroid cancer being the target disease, particularly in those exposed as children, e.g. the Sasakawa project [S8, S9]. This type of surveillance inevitably increases the apparent incidence of thyroid cancer either by detecting thyroid cancers at an earlier stage than would otherwise have been the case or possibly by detecting thyroid cancers that otherwise would never have come to clinical attention (the so-called “occult cancers”). However, only 174 of about 4,000 thyroid cancer cases were detected by such formal screening programmes [J7].

D84. Apart from these formal ultrasound screening programmes, the response to the Chernobyl accident led to informal screening, i.e. examination of individuals who were under medical care for other reasons, to determine whether or not there is evidence of thyroid disease. Thus, if a physician knew that a person had been exposed to radiation as a result of the Chernobyl accident and considered that thyroid disease was a possible consequence, he or she may have been inclined to look for it more thoroughly than would otherwise be the case. This is termed here “diagnostic suspicion bias” and is the third issue of particular concern. The baseline thyroid cancer incidence did in fact increase due to the intensified surveillance of the thyroid during regular medical examinations and an improved reporting system, from 1988 to 1999, by a factor of 3 in Belarus and the more contaminated regions of Ukraine, and by a factor of 2 in the less contaminated regions of Ukraine [J7].

D85. The above issues are closely related. Thus, if the cancer incidence in the residents of areas with high levels of radioactive contamination is compared to that in the residents of areas with low levels, part of the observed excess probably relates to better detection methods. Similarly, comparisons of thyroid cancer rates before and after the Chernobyl accident, which do not take into account the use of ultrasonography, cannot sensibly be used to quantify the thyroid cancer risks due to radiation exposure.

D86. Both screening and diagnostic suspicion bias may operate in the studies of the recovery operation workers, who are examined every year for various diseases and consequently for whom there is a higher likelihood of detection of small tumours. Comparison of disease rates between groups of recovery operation workers is only informative if the same detection methods used in diagnosis were applied over the whole period and regardless of the individual exposure level.

D87. Overall, interpretation of the results from studies of the populations exposed as a consequence of the Chernobyl accident must take into account the variation in detection methods with time, and the likelihood of detection for the different frequencies of screening between the populations exposed to high levels of radiation and those exposed to low levels.

C. Empirical studies on specific diseases

1. Thyroid cancer in groups exposed as children and adolescents

(a) Introduction

D88. The thyroid gland of children is one of the organs most susceptible to the carcinogenic effect of ionizing radiation [U1]. There have been a number of studies of children whose thyroids had been exposed to external low-LET radiation (i.e. gamma and X-rays). These include studies of children exposed as a result of the atomic bombings of Hiroshima and Nagasaki and those exposed for therapeutic reasons, like in the treatment of *tinea capitis* or enlarged tonsils and adenoids. A combined analysis of the data from these studies was reported by Ron et al. [R1]; this demonstrated an excess relative risk (ERR) of 7.7 (95% CI: 2.1, 28.7) Gy^{-1} and an excess absolute risk (EAR) of 4.4 (95% CI: 1.9, 10.1) $(10^4 \text{ PY Gy})^{-1}$ in children under age 15 at exposure. This analysis also showed a marked effect of the age at exposure, with the highest risks being seen in the youngest ages. The analysis also showed an effect of the time since exposure, with the risk dropping substantially 30 years after the first exposure. The ERR estimates were also dependent on the sex ($p = 0.07$), but the findings from individual studies were not consistent.

D89. There have been fewer studies specifically of children exposed to ^{131}I and other shorter-lived iodine isotopes. There have been studies of those who had received ^{131}I for diagnostic purposes [D12, H1, H2], those who were exposed to weapons testing fallout in the Marshall Islands [C4, H3, R2], those who were exposed to fallout from the atomic bomb tests conducted in Nevada, USA [K2] and those who were exposed to ^{131}I from the Hanford Nuclear Site in the state of Washington, USA [C2, D9].

D90. Except for the studies of the Marshall Islanders, these studies of exposure to iodine isotopes have not provided convincing evidence of any measurable increase in the risk of thyroid cancer. However, all these studies have considerable limitations in terms of their statistical power, and the results are generally consistent with both a null effect and an increased risk. An analysis by Shore [S1] suggested that any effect of ^{131}I exposure would be lower than that predicted by applying the risks observed with exposure to external low-LET radiation, primarily due to the differences in dose rate. Some animal data, however, are consistent with an effect that is equal for both ^{131}I exposure and exposure to external low-LET radiation. It has also been shown that the radiation risk coefficients observed after the Chernobyl accident are consistent with observations made in the studies involving external exposure [J2]. Thus, this remains an important and unresolved issue.

D91. Releases of ^{131}I and other shorter-lived isotopes of iodine from the Chernobyl accident led to the exposure of the thyroid gland to substantial doses of radiation in many areas of Belarus, the Russian Federation and Ukraine mainly through drinking contaminated milk. Therefore, the potential risk of thyroid cancer, particularly among those exposed at very young ages, is one of the major concerns and needs to be discussed carefully in regard to all available approaches (registers, geographical correlation studies and analytical studies). The observed large excess of thyroid cancer in children is clearly the major public health problem associated with radiation exposure encountered in the three republics.

D92. In view of the higher radiosensitivity of children and adolescents than of adults, the former group is discussed in the present section and the latter in the following section.

(b) Assessment of current evidence

D93. Since the Chernobyl accident, there has been a striking increase in the reported incidence of thyroid cancer in children and adolescents residing in Belarus, Bryansk and Orel oblasts of the Russian Federation and Ukraine. The increase started some four to five years after the accident and has continued to manifest itself. As the underlying incidence rate of thyroid cancer in young children is very low (few cases per million children per year) [D10, I38], many of the cases diagnosed before age 15 years have been attributed to the releases from the Chernobyl accident. For thyroid cancers diagnosed at ages 20–30 years, the underlying incidence rate is close to some tens of cases per million persons per year, and hence any apparent excess has to be interpreted more cautiously; screening techniques may have been responsible for a substantial part of the apparent excess (this also suggests that screening may have played a role in the excess incidence rate reported among children under age 15 years). For these age groups, analytical studies using accurate individual dose estimates need to be used.

D94. The thyroid cancer incidence rates for both sexes and various ages at exposure for children and adolescents are shown for the whole of Belarus, the four most affected oblasts of the Russian Federation and the whole of Ukraine in table D11. These data are for periods between 1982 and 2005 and were obtained from the corresponding national cancer registries and the specific Chernobyl registries for the particular areas, see section II of this appendix. Amongst those under age 14 years in 1986, 5,127 cases (under age 18 years in 1986, 6,848 cases) of thyroid cancer were reported between 1991 and 2005 [I8]. There is no evidence of a decrease in the excess incidence of thyroid cancer up to 2005. Part of the increase is related to the normal age pattern of disease occurrence but the majority of the increase is attributed to the radiation exposure.

D95. It has been estimated that 60% of the Belarusian thyroid cancer cases and 30% of the Ukrainian cases among those who were children or adolescents at the time of the accident may be related to the radiation exposure [J7]. The remaining increase in the incidence rate of thyroid cancer is related to enhanced surveillance, improved diagnostic technology and other non-radiation factors. Risk estimates that are relatively independent of such factors need to be developed from studies with identical screening of all cohort members.

D96. The thyroid cancer incidence rates for both sexes and various ages at diagnosis in the three countries are shown in tables D12 to D14. These data were also obtained from the national cancer registries and the specific Chernobyl registries for the particular areas. To provide a better appreciation of the information, figures D-VIII to D-XIII were constructed using the incidence rates for various ages at diagnosis separately for males and females. For all age groups, the rates are higher for females than for males.

D97. Annual incidence rates of thyroid cancer are presented in figures D-VIII to D-XIII for the period from 1990 to 2005. Data from before 1990 are omitted from the figures, because the data in several registries for some age groups seem to be incomplete. Indeed for Belarus and Ukraine, for the period before 1990, the average incidence rate for the age group 20–29 years old at diagnosis was very low in comparison to the expected average rates (derived from European and/or Russian sources). The major reason is that because thyroid cancer is a rare disease (and especially so for young age groups), at the period before or close to 1986, thyroid cancers were included in a common group of "other solid tumours"; they were not recorded separately in the national registries. Following the Chernobyl accident, major efforts were made to collect this information and, since 1990–1992, the data can be considered as largely complete. Moreover, if a minimum of 4–5 years were necessary before an excess risk linked to the Chernobyl accident might be expressed, then data for the period before 1990 would in any case be less informative.

D98. For each country, the incidence rates in the three diagnosis age groups follow parallel trend lines, but with some discrepancies. These discrepancies reflect fluctuations in the annual incidence rates between countries, as thyroid cancer is a rare disease and the number of cases is low. However, they may also reflect different practices for the detection of the disease (see the discussion in section III.B.2 above on the screening effect) that may affect the results for different age groups at different times; and they also reflect the fact that the average thyroid doses to the populations of the three countries were not the same. At the national level, the Belarusian population experienced higher exposure levels than the population of Ukraine. For the Russian data, because they are limited to the oblasts with high radioiodine levels, the incidence rate is also relatively high, but with large annual fluctuations.

D99. The observations may be considered as expressing different time trends for the different age groups, and may suggest that for the near future, any increased incidence rate will continue in groups exposed at young ages. Those groups exposed as very young children expressed their risk at the beginning of 1990s in the age group 0–9 years. They then entered the age group 10–19 years. During recent years, their thyroid cancer risk will be expressed in the age group 20–29 years. The different "waves" of increase in the incidence rate for each age group, followed by a decrease, reflect the movement of people from the young exposed cohort through the other two age groups over the last 20 years. These waves are illustrated clearly by the Belarusian data for females, but can be observed also in the data for the other countries.

D100. An increased incidence rate of thyroid cancer is evident in the age group 0–9 years at diagnosis for both sexes and each country during the first part of the 1990s compared with that in the second part of that decade. The children in this group were under 5 years old at the time of the Chernobyl accident; since 1996, all of those exposed before the age of 10 years became members of the age group 10–19 years. These data indicate that the risk to those children born since 1986 is close to that observed before the accident, even though they could have been subject to increased medical surveillance (i.e. possible post-accident screening effects).

D101. For the category of people aged 10–19 years at diagnosis of thyroid cancer, an increased incidence rate is evident in each country from about 1991–1992 until about 2000. For some countries, a decrease in incidence rate since 2002 also can be seen. The beginning of the increase relates to those children who were 5–10 years old at the time of the accident.

D102. For the category of people 20–29 years old at diagnosis of thyroid cancer, an increased incidence rate is evident in each country from 1991, which persists up to the years 2000–2005. The underlying incidence rate in 1990 (i.e. in the absence of a radiation effect), would be expected to lie between 10 and 50 per million persons (see e.g. [J7]); however it seems to be lower for some countries. For the age group 20–29 years, the increase in incidence rate reflects better screening, but also the fact that 15 years after the accident, the risk continues to increase for those exposed at ages less than 10 years.

D103. Since the Committee's evaluation in the UNSCEAR 2000 Report [U3], several "ecological studies" have been published in the literature.

D104. Shibata et al. [S4], in a screening-based study of school children in the Gomel oblast of Belarus, reported a significant relationship between exposure to radioactive deposition and the frequency of thyroid cancer, comparing those born after the accident to those born before the accident, after adjustment for sex and age ($p = 0.006$).

D105. Tronko et al. [T2] reported a total of 1,876 cases of thyroid cancer occurring in Ukraine between 1986 and 2000 among those aged 0–18 years at the time of the accident. There was a statistically significant increase in thyroid cancer incidence with time since the accident.

D106. In a study conducted in the Bryansk oblast of the Russian Federation, Shakhtarin et al. [S6] focused on the relationship between iodine deficiency and the risk of radiation-induced thyroid cancer. A sample of 3,070 individuals resident in 1996 in the 75 most heavily contaminated settlements of the oblast was used to estimate the mean urinary excretion of iodine and the level of iodine deficiency in those settlements. The sample was heavily weighted towards children and adolescents. Based on these data and 34 histologically confirmed cases of thyroid cancer that occurred in those aged 0–18 years in 1986 in the oblast, excess risks were calculated using estimates of the average radiation dose in the various areas. A statistically significant relationship of excess relative risk with radiation dose was observed. The risk values were twice as great in the areas where there was iodine deficiency compared to those areas where there was adequate iodine nutrition; this seemed to suggest that iodine deficiency may enhance the risk of thyroid cancer following radiation exposure. However, several limitations of this study have to be mentioned. There were no individual measurements (e.g. of radiation doses and of iodine deficiency) but rather approximations based on aggregated data (e.g. mean urinary excretion of iodine based on averaging measurements on a limited number of persons). Any migration of the population since 1986 could not be taken into account and the expected number of thyroid cancer cases calculated from the Russian national incidence rates was possibly underestimated, when considering the effect of screening for thyroid cancer in these contaminated areas.

D107. Another study by Ivanov et al. investigated the thyroid cancer incidence between 1991 and 2001 in persons from the Bryansk oblast who were exposed at ages between 0 and 17 years [I22]. Dosimetric information was evaluated using data on their place of residence and age at exposure. The analysis revealed statistically significant radiation risk only for those exposed as children at an age of 0–9 years. In this group, the standardized incidence ratio (the national incidence rate was used as a reference) in the considered time period is estimated to be 6.7 (95% CI: 5.1, 8.6) and 14.6 (95% CI: 10.3, 20.2) for girls and boys, respectively. The same limitations as mentioned above apply to this study.

D108. An ecological study of the thyroid cancer incidence in the whole population of Belarus was undertaken. The results were presented separately for those who were exposed as children and adolescents (0–18 years old in 1986 [K10, K22]) and adults (older than 18 years in 1986 [K22]). The sources of information on thyroid cancer were the medical records of the patients treated in the national Scientific and Practical Center and the Belarusian cancer registry. The incidence rate attributable to radiation was estimated by subtraction from the total incidence rate of the relatively small baseline rate estimated from the data for 1986–1990 (assumed to be minimum latent period for thyroid cancer induction), with account being taken of the time trend in incidence rate during that period. Average thyroid doses to residents of the administrative districts and dose uncertainties were estimated by means of a radioecological model [K10, K22, K28] and were verified using available radiation measurements on the thyroids of the residents of a number of Belarusian settlements. The relationship between thyroid cancer incidence rate in five selected dose groups and the average thyroid dose, which was in the range of 0.1–2.7 Gy, was found to be close to linear. The calculated value of the excess absolute risk (EAR) in 1990–1998 for children and adolescents (table D16) was about half of that obtained from the studies involving external exposure of the thyroid of children [R1], but the ERR was a factor of five higher than that obtained in reference [R1]. The EAR for girls was twice as high as that for boys. The EAR values for children aged 0–6 years and 7–14 years were close to each other, but for adolescents, no significant dose–response relationship was found.

D109. Heidenreich et al. [H4], using the 1986–1998 data from the Ukrainian thyroid cancer register for patients born after 1968, reported that the EAR coefficient increased with time after exposure and demonstrated no statistically significant dependence on age at exposure, up to age 15 years. This was a relatively small study where thyroid doses were averaged over large areas; it was later replaced by the study reported in reference [J4].

D110. A more recently published formal dose–response analysis by Jacob et al. [J4] covered a larger population (Belarus and Ukraine) but was partly overlapping with the Ukrainian population studied in reference [H4]. This study focused on the more detailed dose estimates for the 1,034 settlements in Ukraine and Belarus in which more than 10 measurements of the ^{131}I activity in the human thyroid had been performed. Thyroid doses were assessed for the birth years 1968–1985 and related to the incidence of thyroid cancers that were surgically removed during the period 1990–2001 (data obtained from registries). The central estimate for the linear coefficient of the dose response was estimated as an ERR of 18.9 (95% CI: 11.1, 26.7) per Gy. The ERR was found to be smaller for females than for males and decreased strongly with age at exposure. In contrast, the EAR increased with time after exposure; this was explained by a faster increase over age and over the period of observation in the underlying thyroid cancer incidence than in the radiation-induced excess incidence. The best estimate of the ERR per unit dose is higher than that expected from the studies involving exposure to external radiation. However, the difference is not significant and the authors noted that uncertainties in underlying rates may have made the estimate for the ERR less stable than the EAR per unit dose, which was estimated to be 2.66 (96% CI: 2.19; 3.13) per 10^4 PY Gy. It should be noted that the present follow-up period is shorter than that for the pooled study of populations exposed to external radiation.

D111. The incidence of thyroid cancer for children (up to age 18 years in 1986) in the settlements within the three northernmost oblasts of Ukraine, which received the highest concentrations of radioactive deposition, has been compared by Likhtarov et al. [L5] to the corresponding estimated average doses to the populations of these settlements. The individual doses were estimated using direct thyroid measurements on about 25% of the study population. For the people without direct measurements, group average doses were reconstructed. The corresponding thyroid cancer rates were modelled as a function of age at exposure, sex and oblast. The degree of screening operating in an oblast in a particular calendar year was taken into account and was found to be significantly associated with an increased thyroid cancer incidence ($p < 0.0001$). A strong dose–response relationship was observed, with an overall estimated ERR of 8 (95% CI: 4.6, 15) per Gy and an estimated EAR of 1.5 (95% CI: 1.2, 1.9) per 10^4 PY Gy. The risk estimates were modified both by sex (males had a higher estimated risk than females), age at exposure (those older at exposure had lower corresponding radiation risk estimates) and calendar year (the risk increased in recent years). The estimates for the ERR and EAR differed significantly for those people with doses derived from direct thyroid measurements and those people with reconstructed doses, the risk being lower in the former group.

D112. To date, few analytical studies of thyroid cancer occurring in those exposed as children or adolescents have been reported. Most of them are case-control studies, and one is a cohort study.

D113. A case-control study of 107 children diagnosed with thyroid cancer in 1987–1992 has been conducted in Belarus [A1]. The primary objective was to assess the relationship between the dose to the thyroid and the incidence of thyroid cancer. Individual doses were estimated based on ground deposition of ^{137}Cs, ground deposition of ^{131}I, a data bank of measurements made in 1986 of radiation exposure of the thyroid, questionnaires and interviews. Although no formal dose–response analysis was presented (because the dose estimates were considered to be too imprecise for such an analysis), the risk nevertheless increased monotonically with the estimated group dose, with the odds ratio (OR) for the highest (>1.0 Gy) versus the lowest (<0.3 Gy) dose group being generally of the order of 5, (OR) = 5.04 (95% CI: 1.5, 16.7).

D114. The second reported analytical study is that conducted by Davis et al. [D1] in the contaminated areas of the Bryansk oblast (Russian Federation) with high levels of radioactive deposition. Cases were those identified before October 1997 ($n = 26$) and who were aged 0–19 years at the time of the accident; two controls were selected for each case and matched by sex, birth year, district (raion) of residence and type of settlement (rural or urban). A semi-empirical dose model was used to estimate individual thyroid doses for all cases and controls, with data provided by interview of the participants' mothers. Based on fitting a log-linear model to the data, there was a statistically significant increase in risk with increasing dose ($p = 0.009$), with an estimated ERR of 1.65 (95% CI: 0.10, 3.20) per Gy. This study is however based on a small number of cases.

D115. A later study, which extended the Bryansk study to include all of the Bryansk oblast and an additional year of thyroid cancer diagnoses [K17], included 66 confirmed cases of primary thyroid cancer diagnosed between 1986 and 1998 in people who were age 0–19 years at the time of the accident. Two controls were identified for each case. Individual doses were estimated as outlined above. According to a log-linear model, the estimated ERR was 1.54 (95% CI: 0.50, 4.50) per Gy, increasing to 3.84 (95% CI: 1.19, 13.9) per Gy after adjusting for uncertainty in the dose estimation. The various linear models gave extremely broad ranges of risk which are essentially not interpretable. Estimates of the ERR reported here must be viewed with caution because of the extremely wide confidence intervals related in part to the relatively small number of cases in the study and to the models used.

D116. The results of a population-based case-control study conducted in the most heavily contaminated areas of Belarus and the Russian Federation have recently been reported by Cardis et al. [C8]. The number of cases was large: $n = 276$; they represent all those thyroid cancer patients identified between 1992 and 1998 among those whose thyroids had been exposed to radiation resulting from the accident at age 0–14 years in Belarus or 0–18 years in the Russian Federation. The study period did not overlap with a previous case-control study in Belarus [A1]. A total of 1,300 controls were used. The aim of the study was to estimate the radiation-related thyroid cancer risk, and possible interactions of other factors, such as iodine status at the time close to exposure. Individual doses for all study subjects were estimated based on their whereabouts and dietary habits at the time of the accident. Their stable iodine intake was also evaluated and their iodine deficiency approximated from the area-specific mean iodine content in the soil since 1986. A strong dose–response relationship was observed between the radiation dose received by the thyroid during childhood and the thyroid cancer risk ($p < 0.01$). The OR at the dose of 1 Gy varied from 5.5 (95% CI: 3.1, 9.5) to 8.4 (95% CI: 4.1, 17.3), depending on the risk model used (table D15).

D117. In this study, the excess risk was three times higher in iodine-deficient areas than elsewhere. If potassium iodide had been administered, the risk of radiated-related cancer was lower by a factor of 3, even if the administration had been delayed after the accident. This observation is important and could be explained not only because stable iodine given shortly after exposure reduces the uptake of radioiodine by the thyroid, but also because long-term use of iodine as a dietary supplement reduces the size and growth of the thyroid in iodine-deficient areas and could be expected to be associated with a reduced incidence of cancer.

D118. A cohort study of the relationship between the exposure to radiation resulting from the accident and the increased risk of thyroid cancer in those exposed as children or adolescents has been designed and is being conducted in parallel in Belarus and Ukraine [S7]. Results of the follow-up of the Ukrainian part of the cohort have been reported by Tronko et al. [T3]. In total, a cohort of approximately 32,000 individuals younger than 18 years of age and resident in the most heavily contaminated areas in Ukraine at the time of the accident was followed by biennial screening examinations using ultrasonography, palpation and blood assays. An important feature of this study was the availability, for all study subjects, of thyroid activity measurements made in 1986, shortly after the accident. These activity measurements, in combination with personal data obtained from questionnaires and radioecological models, have been used to estimate the individual thyroid doses for each study subject (see appendix B). The thyroid cancer risk based on the first round of screening, from 1998 to 2000, showed a strong approximately linear relationship with the individual thyroid dose estimate ($p < 0.01$); the ERR was estimated to be 5.25 (95% CI: 1.70, 27.5) per Gy. This study provides quantitative risk estimates that appear to be minimally confounded by any screening effects. However, only 44% of the cohort had actually been screened.

D119. The results of geographical correlation and analytical studies that have led to quantitative estimates of risk are summarized in table D16. It is notable that the geographical correlation studies give EARs very similar to each other, i.e. EAR ~2 per 10^4 PY Sv. These EARs are about a half of the corresponding value reported for populations followed after external X- or gamma-ray exposure [R1]. It should be mentioned that the EAR is increasing with time after exposure [J4], and consequently, as the time after exposure is shorter in the currently published Chernobyl studies than in the analysis of populations exposed exclusively to external radiation [R1], the EAR shown in table D16 may continue to increase in the future. Consequently, these EAR values may differ if not based on the same age groups and durations of follow-up.

D120. The ERR shows large variation, both in the case-control and in geographical correlation studies. Whereas in the former, this variation probably reflects the large dose uncertainties, in the latter, it probably reflects the influence of the underlying disease rates, which may change as a function of the quality of the follow-up, completeness of registration, and the degree to which account has been taken of any screening programmes and migration of the population. The ERR is strongly influenced by the age attained in the population considered, which may differ from one study to another. In view of the uncertainties involved, the values of ERR that are estimated here from analytical studies can be considered as close to that expected from studies of other populations exposed to external radiation. The studies reported in references [C8, T3] are the most informative; they have a larger statistical power and an individual approach to dosimetry; they indicate quite comparable results for the ERR.

D121. Nonetheless, the effect of iodine deficiency in enhancing the risk of radioiodine-induced thyroid cancer and the protective effect of stable iodine supplements months or even years after exposure would caution against generalizing the Chernobyl findings to other exposed populations of children whose diets are not deficient in iodine.

(c) Conclusions

D122. The substantial increase in thyroid cancer incidence seen among those exposed as children or adolescents in Belarus, the Russian Federation and Ukraine since the Chernobyl accident shows no signs of diminishing up to 20 years after exposure. On the contrary, the EAR has been observed to increase with time after exposure [J4], indicating that the number of annual excess cases may also continue to increase. The data from the national and regional registers show clearly that the main increased incidence for future years will be in those who were children or adolescents in 1986. Systematic follow-up of these populations would need to be continued in order to detect any benign or malignant tumour as soon as possible and consequently provide adequate medical treatment.

D123. There is no doubt that there is a substantial contribution to this excess incidence from exposure to radioiodine due to the Chernobyl accident. The magnitude of the dose response remains uncertain but the recent results from published analytical studies show some agreement in estimates of the ERR at 1 Gy. The results from the geographical correlation studies, which are summarized in table D16, show that the EAR associated with exposure of the thyroid to radioiodine is somewhat smaller than the corresponding risk associated with external exposure by a factor of about one-half or two-thirds, but nevertheless, still indicate a significant health hazard to those exposed [R1]. This difference can be partially explained by the shorter follow-up period in the Chernobyl studies.

D124. Evidence has also emerged since the UNSCEAR 2000 Report [U3] that iodine deficiency may well increase the risk of thyroid cancer due to radioiodine released in the accident. Two studies so far have provided support for this [C8, S6]; both suggest that iodine deficiency sometime between exposure and diagnosis may double the radiation risk. Nevertheless, individual measurements of iodine status at the time of the accident are not available and approximations derived in these studies from iodine concentrations in soil or urine 10 years after the accident, have to be considered with caution. In another analytical study [T3], it was noted that neither stable iodine excretion in 1998–2000 nor the presence of diffuse goitre was associated with the risk of radiation-induced thyroid cancer. Future study of this effect will be important in terms of extrapolating the results from the experience of the Chernobyl accident to other scenarios where iodine deficiency may be different from that in the study area.

D125. Strengths and limitations of epidemiological studies have to be taken into consideration in interpreting the results regarding the risk of thyroid cancer. Uncertainty in the estimated average dose is a main concern in geographical correlation studies. Some studies have made more reliable estimates of the average dose by considering those settlements in which a large number of individual ^{131}I thyroid measurements were made in 1986. Analytical studies provide more informative quantitative estimates of the risk of thyroid cancer associated with radiation exposure, but are also not free of bias. For example, the reliability of information from retrospective interviews on dietary habits at the time of the accident and some of the estimates of past exposure conditions depend on the quality of the memory of the interviewed cases and controls. Studies that are not based on measurements of thyroid doses suffer particularly from very large uncertainties in the estimates of individual thyroid doses. Nevertheless, these studies have contributed significantly to a better understanding of how iodine status and radioiodine may play a role in the development of thyroid cancer.

D126. Estimates of increased incidence of thyroid cancer cannot be considered reliable unless account has been taken of the increasing use of ultrasonography, and the introduction of mass screening programmes after the accident. However, the similarity of risk estimates between the cohort study where screening apparently was “matched out” and those of other studies suggests that the potential confounding effects of screening may not have seriously affected those relative risk estimates.

D127. The other issue in extrapolation is the mixture of radioactive isotopes of iodine released in the accident. The most significant of these as far as irradiation of the thyroid is concerned was ^{131}I (contributing more than 90% of the thyroid dose). The possibility has been suggested that the shorter-lived isotopes are more effective in inducing thyroid cancer than ^{131}I. However, so far, little empirical evidence has emerged to permit an evaluation to be made to determine whether the carcinogenic effect of the various isotopes differ. The contributions of other radioactive isotopes of iodine than ^{131}I to the thyroid dose were relatively small and therefore their influence cannot be evaluated in epidemiological studies of groups exposed to radiation from the accident.

2. Thyroid cancer in those exposed as adults

(a) Introduction

D128. As far as induction of thyroid cancer in those who were exposed as adults is concerned, there are two groups of interest. The first group is the general population (the evacuees and residents of the contaminated areas), for whom the main source of radiation exposure of the thyroid was radioiodine shortly after the accident. However, it should be noted that this group also was subjected to long-term exposure (both external and internal) from long-lived radionuclides such as ^{137}Cs (see appendix B).

D129. The second group of interest is that of the recovery operation workers. Apart from those who worked during the early days after the accident, for whom internal doses due to radioiodine may have been important, the recovery operation workers received doses to the thyroid essentially due to external radiation exposure that were much higher on average than the external doses received by the population.

D130. These two groups of individuals are now considered separately.

(b) Assessment of current evidence of risk for the general population

D131. In the Russian Federation, standardized incidence ratios (SIRs) have been reported for residents of the Bryansk oblast, the one most heavily contaminated with radionuclides [I3]. The data are shown in table D17. There is a statistically significant excess of thyroid cancers in the Bryansk oblast compared to the general population for the period 1991–1998.

D132. These data have been subject to a dose–response analysis. This yielded estimates for ERR of -1.3 (95% CI: -2.8, 0.1) Gy^{-1} for females and -0.4 (95% CI: -3.5, 2.7) Gy^{-1} for males. These negative dose–response trends, i.e. the higher the dose the lower the risk of thyroid cancer, suggest that the increased SIRs for adult thyroid cancers may be an effect of screening rather than of radiation exposure [I3]. In a more recent paper, the authors have expanded the study population to include the inhabitants of the Bryansk, Tula, Kaluga and Orel oblasts [I23].

D133. From an ecological study of post-accident thyroid cancer incidence in the total Belarusian population, a substantial increase in incidence among adults (older than 18 years in 1986) in 1992–2000 was reported, but the SIR values were not presented [K22]. The incidence rate attributable to radiation was separated from the total incidence rate by subtraction of the expected baseline rate estimated for the study period from the data for 1986–1990 (minimum latent period), accounting for the time trend in incidence during that period. Details of exactly how this was done were not provided. This methodological approach may have produced misleading results because medical attention to detecting thyroid cancer in the contaminated areas may have resulted in a substantial screening bias, particularly in the 1990s following the discovery of the excess thyroid cancer incidence in children related to radiation exposure [K32]. Average thyroid doses to the residents of administrative districts and the uncertainties in the dose estimates were analysed by means of a radioecological model [K10, K22, K28] and verified with the available radiation measurements on the thyroids of the residents. The relationship between the excess thyroid cancer incidence in three selected dose groups and average thyroid dose in the range from 0.01 to 0.3 Gy is apparently non-linear; although values for the uncertainties were not provided. For this period, the calculated EAR was 1.7 (0.3–3.2) per 10^4 PY Gy and ERR 3.8 (0.1–9.8) Gy^{-1}. The influence of screening practice and adjustment for age groups were not mentioned; these factors may have influenced the observed results.

D134. In Ukraine, the overall incidence of thyroid cancer approximately doubled during the post-accident period [S18]. Three major groups were considered in a recent follow-up study to 2004. The highest incidence was observed among the recovery operation workers. Among the general population, the most significant increase occurred with the evacuees (table D17). For residents of the contaminated areas, a statistically significant increase was also observed.

D135. However, no quantitative risk estimates from an analysis of the dose–response data have been reported for Ukraine. Therefore, distinguishing between a screening effect and a radiation effect in the data for Ukraine, which are shown in table D17, is not possible, and effects due to migration out of the contaminated areas cannot be excluded.

(c) Assessment of current evidence of risk for the emergency and recovery operation workers

D136. Two cohorts of Chernobyl recovery operation workers from Estonia (4,786 men) and Latvia (5,546 men) were followed from 1986 to 1998 [R7]. Cancers were ascertained by linkage with nationwide cancer registries. Overall, two thyroid cancer cases were identified in the Estonian cohort and five in the Latvian cohort. Statistically significant excess cases of thyroid cancer were observed: SIR = 7.08 (95% CI: 2.84, 14.55). However, there was no evidence of a dose–response relationship. Screening bias was likely because all thyroid cancers reported from Estonia had been detected during a special screening study so that comparison with the general population not undergoing such screening would be misleading. Further, the number of cases was small.

D137. Another cohort study conducted among 99,000 Russian recovery operation workers showed a significant excess of thyroid cancer (SIR = 4.33 (95% CI: 3.29, 5.6)) but no association with radiation dose [I9]. Data on thyroid cancer incidence are shown in table D18, which provides the SIRs for thyroid cancer in the different groups, analysed according to the period that they worked within the 30-km zone and whether the cancer appeared in the latent (1986–1991) or the post-latent (1992–1998) period. The values of SIR are with respect to the comparable age-, sex- and period-specific rates for the Russian Federation as a whole.

D138. Significantly elevated thyroid cancer SIRs were observed during both the latent period and the post-latent periods; the values were higher in the post-latent period. Within the post-latent period, the thyroid cancer SIRs were largest for the recovery operation workers who worked either from April–July or from August–December in 1986. The ratios also remained significantly elevated (SIR was ~4) for workers who started work in 1987 or in the period 1988–1990 when there was no radioiodine in the environment [I9].

D139. To address whether the elevated SIRs in table D18 might represent an association between excess thyroid cancer incidence and external radiation exposure received during the course of their work, values of the ERR per unit dose were calculated. The authors observed no significant ERR during any work period related to external radiation dose. Most of the point estimates indicated, in fact, a negative correlation with dose for the entire 1986–1990 work period. These results, taken together with those in table D18, argue strongly that the external radiation dose received by the recovery operation workers is, so far, not a significant factor for increased risk of thyroid cancer in this cohort, and that screening bias contributed to, at least, part of the excess incidence of thyroid cancer.

D140. In earlier studies of the Russian recovery operation workers, Ivanov et al. [I10, I11] did find a suggestion of an increased risk of thyroid cancer in the “early” workers, i.e. those exposed within several weeks of the accident to radioiodine in addition to the external radiation to which the “later” workers had been exposed. However, estimates of internal dose caused by inhalation of radioiodine for those who worked on site in April–June 1986 were not available.

D141. In Ukraine, the overall incidence of thyroid cancer up to 2004 was approximately eight times higher in the group of recovery operation workers than the reference rate [S18]. However, no quantitative risk estimates from an analysis of dose–response data have been reported for Ukraine, so the relatively high SIR reported for the recovery operation workers may partly reflect better screening of this population.

(d) Conclusions

D142. The evidence from studies of adults in Belarus, the Russian Federation and Ukraine is somewhat mixed, with some groups showing elevated SIRs and others showing substantially smaller effects. The Russian study [I3] shows that using internal comparisons instead of external comparisons (i.e. with the general population rates) produces no evidence of any association between the incidence of thyroid cancer in adults and the estimated thyroid dose. It remains unresolved whether the increase in thyroid cancer over the baseline rate in the Belarusian study is simply a result of changes in diagnosis and detection activities. This strongly suggests that increased screening of the exposed groups, as well as increased awareness of the general population, substantially complicates the detection of radiogenic thyroid cancers in adults. Thus, there is little suggestion in the various exposed population groups of increased thyroid cancer incidence among those exposed as adults in the general population.

D143. Elevated rates of thyroid cancer among the recovery operation workers compared to the general population were observed, but no clear association with external dose (among the Russian recovery operation workers) has been found. Estimates of the internal doses received by those who worked on site in April–June 1986 are not available. The complex follow-up of the recovery operation workers after the Chernobyl accident is discussed further in the later section on solid cancers.

3. Biological aspects of thyroid cancer following the Chernobyl accident

(a) The Chernobyl Tissue Bank

D144. Many research studies depend on the availability of high quality, pathologically verified, biological material. The Chernobyl Tissue Bank was established to provide material for molecular biological research into post-accident thyroid tumours. The Chernobyl Tissue Bank comprises two separate banks (one for Russian citizens and the other for Ukrainian citizens) of biological material and information consisting of: *(a)* samples from tumour and normal tissue, and where possible metastatic tissue from post-operative specimens; *(b)* nucleic acid extracted from these specimens; *(c)* vials of serum from patients whose thyroid tissue is held in the bank; *(d)* samples of blood; *(e)* DNA extracted from blood; and *(f)* a computerized database in which relevant information on the patient (date of birth, date of operation, sex, oblast of residence at the time of the accident and of the operation) is held, together with location coordinates for each sample of tissue, DNA or RNA extracted from tissue, and blood serum and DNA extracted from blood.

D145. It was a political imperative that biological specimens collected for the Chernobyl Tissue Bank be stored in the institutes in which the patients were operated on and where they continue to be treated. One bank of biological material is therefore situated in the Institute of Endocrinology and Metabolism in Kiev, Ukraine and a second in the Medical Radiological Research Centre of the Russian Academy of Medical Sciences in Obninsk, Russia. Each bank houses only material and information from its own national population. A back-up copy of all data is kept at the Coordinating Centre, Imperial College, London and a web-based database is currently being developed. The two banks of biological samples plus the databases in Ukraine and the Russian Federation together with the integrated database are collectively referred to as the Chernobyl Tissue Bank. The project builds on relationships that have been established between scientists in Ukraine and the Russian Federation and those based in Europe, Japan and the United States over a period of nearly 10 years.

D146. The Chernobyl Tissue Bank integrates a number of research projects in different countries and provides a pooled data set on the results of the various studies. The material held in the bank has been reviewed by an international panel of expert thyroid pathologists, and all extracted nucleic acid samples are subject to extensive quality control. Researchers are provided with a minimum data set (date of birth, date of operation, place of residence at the time of accident, sex and the consensus diagnosis from the pathology panel) together with samples of DNA extracted from blood, DNA/RNA from tissue, and/or serum or sections from formalin-fixed, paraffin-embedded material. Currently there are more than 2,137 reviewed cases of thyroid cancer and adenoma in the Chernobyl Tissue Bank, the majority of which will have DNA and RNA from frozen samples available. Most cases have paired samples of tumour and normal tissue. These 2,137 sets include a small number of cases of cancer and adenoma that occurred in children aged less than three months who were in utero at the time of the accident and can therefore be considered as unexposed to radioiodine resulting from the accident. Paraffin sections from tissue microarrays are also available. More detailed pathological and clinical information is held in the Ukrainian and Russian institutes that participate in this project. The studies supported so far encompass research groups from Japan, the United States and six European countries, and include single and multigene cDNA array and comparative genomic hybridization (CGH) studies. The results from each research project using the resource are returned on a case-by-case basis and entered into a database for later correlation. Many of the studies quoted below have utilized material from the resource.

(b) Pathology

D147. Thyroid cancers derived from the follicular cell can be divided into two main types: papillary and follicular cancers. Papillary cancer arises de novo from the follicular epithelial cell. Follicular cancers are morphologically similar to follicular adenomas, which are benign lesions. Evidence of invasion through the capsule into veins or extra-thyroid tissues distinguishes carcinoma from adenoma. Papillary and follicular cancers show different clinical and molecular biological features as well as characteristic morphological features. Diagnosis is made on using a number of features characteristic of papillary cancers (e.g. characteristic features of the cell nucleus include grooved pale nuclei that frequently show intranuclear cytoplasmic inclusions, and the tumours contain calcified structures called psammoma bodies) that are lacking in follicular tumours. The diagnosis of papillary cancer depends on the presence of a number of these features, although not all have to be present for a diagnosis of papillary cancer to be made.

D148. In addition to the two main types of cancer derived from the follicular cells, there are a number of subtypes of papillary cancer. These are named on the dominant structural component. The classic papillary cancer, most commonly found in adults, is composed of papillary structures. The follicular variant of papillary cancer is composed of follicular structures but has the nuclear features and psammoma bodies that are indicative of papillary cancer. The solid or solid follicular variant is composed of solid sheets of cells with or without a follicular component. The latter variant shows variable nuclear features but does contain psammoma bodies.

D149. The majority of thyroid cancers diagnosed in those who were children or adolescents at the time of the accident in Belarus and Ukraine are papillary thyroid cancers (90%). This is the most common of the two main types of thyroid cancer in unexposed populations. Early reports of the pathology of post-accident thyroid cancer suggested that there was a particularly high frequency of the solid and solid follicular variants of papillary cancer. This subtype of papillary cancer is also seen in young children who were not exposed to radiation. An international panel of expert thyroid pathologists has reviewed all cases of thyroid cancer in people (aged under 19 years at the time of the accident) living in the contaminated areas of the Russian Federation and Ukraine from October 1998 to the present that are included in the Chernobyl Tissue Bank and all those that had occurred in Belarus from October 1998 to February 2001. Whilst in the majority of cases it has been easy to distinguish papillary cancers from follicular cancers, there are a few cases where a definitive diagnosis has not been possible. This type of intermediate lesion is also seen in unexposed populations and has led to a suggested reclassification of thyroid tumours [W2]. Only 2% of the cancers diagnosed in this population are medullary carcinomas, and 0.3% are poorly differentiated carcinomas. The remainder are split evenly between follicular cancers and an entity termed well-differentiated carcinoma not otherwise specified by the Pathology Panel of the Chernobyl Tissue Bank.

D150. Annex J of the UNSCEAR 2000 Report [U3] suggested on the evidence then available that there might be a link between the morphological subtype (i.e. solid/follicular variant) of papillary cancer observed in children and exposure to radiation. More recent evidence raises questions as to whether there is a causal relationship between radiation exposure and the solid/follicular morphology of papillary cancer. The morphology and aggressiveness of papillary cancer groups were shown to be a function of the latency in groups of children exposed at different ages, and it was suggested that they were independent of age at exposure [W4]. The proportion of papillary cancers that are composed mainly of papillae increases with time after the accident, whilst the solid/follicular variant appears to be decreasing with time after the accident [B23]. This is illustrated in figure D-XIV with data from Ukraine. In addition, the percentage of small (≤1 cm) papillary cancers appears to be increasing with time [B23]. This could be a function of more sensitive screening or of a decrease in growth rate or aggressiveness.

(c) Molecular biology

D151. Earlier studies reported that there was a higher than expected frequency of *RET* rearrangement in post-accident thyroid cancer, suggesting some *RET* rearrangements might be regarded as a marker for radiation exposure [F2, K4]. More recent papers have suggested that there is no link between radiation exposure and *RET* rearrangements. The high prevalence of PTC3 versus PTC1 in post-accident PTC may reflect the association between the solid morphological subtype with *PTC3* rearrangement and the age of the patient at diagnosis, rather than the aetiology of the tumour [N3, T1]. There have been few statistically valid studies of *RET* rearrangement in paediatric thyroid cancers not associated with the accident [F1, W3], making substantiation of the association of *RET* rearrangements with age at diagnosis difficult. It is important to remember that the correlation between molecular biology and pathology is not absolute: in all of the series published so far, a substantial proportion (30–50%) of the papillary cancers do not harbour a *RET* rearrangement. A variety of different techniques have been used to assess the frequency of *RET* rearrangements and, although this may explain the variation in frequency of *RET* rearrangements among studies [Z3], there still remains a large proportion of papillary carcinomas for which alternative molecular pathways need to be identified. Moreover, a few studies have demonstrated *RET* rearrangements in benign tumours associated with radiation exposure [B8, E1, S19]; however, other studies have failed to substantiate these findings [T1], adding further uncertainty to the specific association of *RET* rearrangement with papillary thyroid cancer. A recent paper by Port el al. [P18], has suggested that radiation signatures do exist—however, caution is urged in the interpretation of this paper because the radiation-associated group was substantially younger than the control group and of a different ethnic origin, and detailed pathological information is lacking.

D152. Despite the evidence that *RET* is able to transform the follicular cell in vitro, the evidence from transgenic mice suggests that other oncogenic mutations must be required for the development of the tumour. The clinical relevance of *RET* rearrangements in post-accident papillary carcinoma still remains unclear. Some studies in adults have suggested that the presence of *RET* rearrangements may confer a better prognosis, but other studies suggest the opposite [B5, B7, M2, S3]. In addition, it has also been suggested that *RET* rearrangements are not found in all cells in post-accident papillary carcinomas, and that cells harbouring the rearrangement may be clustered [U17]. The degree of clustering appears to be related to the latency of the tumours, with shorter latency giving a more homogenous profile than longer latency [U18]. This suggests either a polyclonal origin for these tumours or that *RET* rearrangement is a later event in thyroid papillary carcinogenesis than had previously been thought [U17].

D153. In addition, the B-raf oncogene has recently emerged as the most commonly mutated oncogene in papillary carcinoma in adults. The frequency varies in a number of studies from 36% to 69% in adult *PTC* [C5, K3], including one study on Ukrainian tumours [P2]. The frequency of B-raf mutation in post-accident cases (aged under 18 years at operation) is much lower: less than 10% [N3]; and does not appear to be significantly different from that observed in sporadic cases of childhood thyroid papillary carcinoma [L6]. This finding is perhaps not surprising as B-raf and *RET* oncogenic alterations appear to be virtually mutually exclusive in the series published thus far. However, it is clear that all cases that are negative for B-raf in young onset papillary cancer are not necessarily positive for *RET* rearrangement, and that there are as yet unidentified oncogenic changes in these tumours. A novel rearrangement involving inversion of chromosome 7, resulting in fusion of part of the BRAF gene with the AKAP9 gene has also been described in three papillary carcinomas from young children in Belarus [C6]. However, further studies in age-matched cases will be needed to establish whether this is a radiation-specific event. BRAF gene reduplication has also been shown to be present in follicular tumours [C9], suggesting that activation of this pathway is critical in thyroid follicular cell tumourigenesis. To date, there have been no studies specifically related to the molecular biology of follicular rather than papillary tumours of the thyroid following radiation exposure.

D154. To further complicate matters, there is now evidence that the morphology of post-accident papillary cancer is changing with time [T7, W4]. This suggests that the molecular profile observed in the early cases may owe more to the age of the patient at diagnosis than to the aetiological agent. Although the rate of increase of papillary carcinomas appears to be slowing in those aged under 19 years at operation, it may be that, as with other types of radiation-induced cancers such as leukaemia, there are a number of different subtypes of the disease, which show different latencies. This may be further complicated by differential effects of radiation exposure, depending on the age of the patient at exposure.

D155. One recent publication highlights the change in proliferative activity of the thyroid during maturation. However, the authors were unable to relate the increased sensitivity of the young thyroid gland simply to proliferative rate, suggesting that a number of factors may also influence this sensitivity [S20].

D156. The evidence so far suggests that the molecular biology of post-accident childhood thyroid cancer is similar to that seen in age-matched series from non-irradiated populations. Post-accident papillary thyroid carcinomas, in common with childhood papillary carcinomas not associated with radiation exposure, do not harbour *RAS* [S2] or p53 mutations [S2, S5], or show specific microsatellite instability [S2]. However, two publications have indicated that post-accident thyroid cancers may show gains and losses of chromosomal material when DNA is analysed on a global scale [K19, R8].

D157. A number of studies have recently been published giving transcriptomic analyses demonstrating different expression profiles between normal follicular thyroid epithelium or follicular tumours and papillary carcinomas [B45, C21, H13, J6, M3]. Similar methods have not yet been shown to be able to differentiate between different types of papillary carcinomas; and in one recent paper analysed, it has been shown that the overall profile of post-accident papillary cancers was found to be similar to papillary carcinomas from Belgium and France [D2]. Taken together, these results suggest that DNA aberrations may not necessarily lead to differences in gene expression. However, similar studies need to be carried out on DNA and RNA from the same series of tumours before adequate conclusions can be drawn. The consensus opinion appears now to be that *RET* rearrangements are more frequent in childhood papillary carcinomas regardless of their aetiology.

D158. There has been little work carried out on the effect of single nucleotide polymorphisms in DNA and post-accident thyroid carcinoma. A number of studies are underway, but their results are too preliminary to be included in this annex. One published observation suggested that polymorphisms in the p53 gene may contribute to the risk of developing papillary thyroid cancer after radiation exposure [R9]. Further studies are clearly needed in this important area.

D159. There are a number of large studies of the molecular biology of post-accident thyroid cancer currently underway, with pathologically verified material supplied by the Chernobyl Tissue Bank. There is no doubt that these studies will enable the separation of those elements that are due to the effects of age from those that are truly due to radiation exposure.

4. Leukaemia

(a) Introduction

D160. Studies such as those of the survivors of the atomic bombings have demonstrated that leukaemia can be induced by ionizing radiation delivered at high doses and dose rates [U1]. Further, leukaemia is one of the cancers most sensitive to induction by ionizing radiation and has the shortest minimum induction period of any such cancer, of the order of two years. Detailed analysis of the latest data on the survivors of the atomic bombings, shows that in terms of relative risk, the risks are highest for those exposed at an early age, and follow a wave pattern with time after exposure. The fall in risk with time since exposure occurs more rapidly among those exposed at an early age than among those exposed at a later age. Therefore, studies relevant to the Chernobyl accident have to be reviewed according to age at the time of exposure.

D161. Analysis of pooled data from several studies of nuclear workers [C3, C10] have yielded estimates of leukaemia risk that are consistent with those from studies of the survivors of the atomic bombings. In this pooled analysis, the selected nuclear workers were monitored for exposure to external radiation on a monthly or yearly basis and, consequently, might be expected to provide a better estimate of any effect due to dose rate. However, despite the huge number of workers involved in this pooled analysis, the confidence intervals in relation to the estimated leukaemia risk remain very large; the ERR was 1.93 (95% CI: <0, 8.47) Sv^{-1} and was not statistically significant. So, the effect of protracted radiation exposure on leukaemia risk and, in particular, the magnitude of any dose and dose-rate effectiveness factor (DDREF) [U1, U3] are matters that still need to be resolved. The non-linear dose–response relationship for leukaemia, particularly that seen in the survivors of the atomic bombings, should be taken into account when discussing values for the DDREF.

D162. The population exposed as a result of the Chernobyl accident includes the recovery operation workers, some of whom were exposed at high or moderate dose rates (depending on when they worked on the industrial site), and members of the general population, who have been subject to exposures at low dose rates (primarily from ^{137}Cs) for a number of years and will continue to be exposed in this manner in the future. Thus, the risk of leukaemia in the exposed population is a matter both of public health concern and scientific interest. A number of studies have been reported in which the incidence of leukaemia in various subgroups of the population have been examined.

D163. Studies of leukaemia incidence in those exposed in utero or at an early age as a consequence of the accident have been reported specifically, in view of the increased susceptibility of such individuals to radiation-induced leukaemia. These studies are discussed first, followed by more general studies of those exposed as adults. Some of the more general studies presumably include those exposed as children or adolescents, since results with respect to age at exposure are not always presented separately in these studies.

(b) Assessment of current evidence for those exposed in utero

D164. Several geographical correlation studies were available in the UNSCEAR 2000 Report [U3] which compared leukaemia rates in those exposed in utero with those not so exposed. These studies did not provide any convincing evidence of a measurable association, with the possible exception of the study in Greece [P9]. Rates of leukaemia in those exposed in utero and those born either before the accident or a year after, differed by a factor of 3. However, the numbers of cases in each exposure category were small. Furthermore, a similar study design was applied to the inhabitants of other countries exposed to radioactive deposition, but the findings were negative [S8].

D165. Since then, a further study has been published by Noshchenko et al. [N9] comparing the cumulative incidence of leukaemia amongst those exposed in utero in a highly contaminated area of Ukraine with that in one with lower levels of radioactive deposition. This yielded a relative risk of 2.7 (95% CI: 1.9, 3.8) for all leukaemias. The number of cases available for analysis was not large (21 in the exposed area and 8 in the control area), and the descriptive nature of the study limits the interpretation that can be placed on this estimate.

D166. Information on infant leukaemia rates following the accident has been evaluated by the UK Committee Examining Radiation Risks of Internal Emitters (CERRIE) [C24]. Whilst the data from Great Britain were too sparse for firm conclusions to be drawn, CERRIE concluded that the findings on infant leukaemia in various countries after the Chernobyl accident do not provide sufficient persuasive evidence that the risk of internal exposure to radionuclides is seriously underestimated by using risk estimates obtained from studies of exposure in utero to sources of external radiation [C24].

(c) Assessment of current evidence for those exposed as children

D167. In the UNSCEAR 2000 Report [U3], a number of geographical correlation studies of leukaemia incidence occurring in populations exposed as children to radiation resulting from the Chernobyl accident were reviewed. These studies provided little or no evidence of any increase in leukaemia risk due to the radiation exposure.

D168. Since the UNSCEAR 2000 Report, similar geographical correlation studies, which compared rates of leukaemia before and after the accident among those exposed as children, have again provided no support for the hypothesis of a measurable increase in leukaemia risk in Belarus [G5], the Russian Federation [I24] or Hungary [T4].

D169. In addition to the geographical correlation studies, the results of two analytical studies of leukaemia occurring amongst those exposed in childhood have appeared [D5, N10]. In the first case-control study [N10], carried out in Ukraine, all cases of leukaemia among those aged 0–20 years at the time of the accident were diagnosed in the Rivne and Zhytomyr oblasts between 1987 and 1997. Controls were selected from the same two oblasts, but from districts other than those that provided the cases, and they were matched by age at exposure, sex and type of settlement. The mean cumulative bone marrow dose to all study subjects was very small (4.5 mSv). A total of 98 out of 272 potentially eligible cases were independently confirmed and interviewed; no explanation was given for the method of their selection. Statistically significant associations were found for acute leukaemia between 1993 and 1997 among males with doses of 10 mSv or more, and for acute myeloid leukaemia among those diagnosed between 1987 and 1992. Possible biases in the selection of cases and controls cast doubts about the findings of this study [D5, U1, W5].

D170. The larger case-control study reported in reference [D5] was conducted in the three republics, and included cases from the earlier study [N10] as a subset. This study showed mixed results: those from the Ukraine data showed a significant association of leukaemia risk with the radiation exposure; those from the Belarus data showed a non-significant association; and those from the Russian Federation data showed no association. The ERRs in the three countries were 78.8, 4.09 and -4.94 Gy^{-1}, respectively. Because radiation doses were very low (median dose was less than 10 mGy), the statistical power of the analyses was diminished [U1]. The authors concluded that "this study provides no convincing evidence of an increased risk of childhood leukaemia as a result of exposure to Chernobyl radiation" [D5].

D171. Thus, overall, so far there are few studies available and little convincing evidence to suggest a measurable increase in the risk of leukaemia among those exposed as children to the radiation resulting from the accident at Chernobyl. This conclusion is consistent with the earlier cancer registry studies of childhood cancer risk in Europe following the Chernobyl accident [P12].

(d) Assessment of current evidence for those exposed as adults

D172. *General population groups.* A few studies of leukaemia incidence in groups of people exposed as adults to radiation resulting from the Chernobyl accident were available in the preparation of the UNSCEAR 2000 Report [U3]. Again, none of these studies provided persuasive evidence of any measurable effect. The majority of the geographical correlation studies conducted in various countries relied on the data available from national registries and showed no convincing evidence of any trends of increasing incidence of leukaemia.

D173. *Emergency and recovery operation workers.* In 1996, a large cohort study of the Russian recovery operation workers (>142,000) was reported by Ivanov et al. [I11]. A total of 48 cases of leukaemia, including chronic lymphatic leukaemia (CLL), were diagnosed in the period 1986–1993 in the cohort. A statistically significant SIR of 1.77 (95% CI: 1.22, 2.47) was estimated comparing the rates of leukaemia in this cohort to the rates in the Russian population for 1990–1993. The value of the SIR estimated using population rates from before 1990 as a comparison was much lower and not statistically significant. A statistically significant ERR of 4.3 (95% CI: 0.83, 7.75) Gy^{-1} was estimated from the data. Risk estimation was based on a comparison of the observed incidence with the national incidence of leukaemia for males of the same age groups. This estimate appeared comparable in magnitude with the leukaemia risk estimate derived from data on the survivors of the atomic bombings who were older than 20 years of age at the time of the bombings (ERR = 3.70 Sv^{-1}, averaged over sexes) [U3]. However, it should be noted that the estimate in the Ivanov et al. study [I11] included cases of CLL (n = 10).

D174. In a further study of the Russian recovery operation workers, Ivanov et al. [I13] studied the occurrence of leukaemia in a cohort of 71,870 workers engaged in recovery operations within the 30-km zone between 1986 and 1990, and for whom estimates of individual external radiation doses were available from the Russian national dosimetric registry. They observed 58 cases of pathologically confirmed leukaemia between 1986 and 1998. After excluding CLL (n = 16), the type of leukaemia thought not to be induced by radiation, they obtained an SIR of 2.5 (90% CI: 1.3, 3.7) comparing those who incurred doses of 150–300 mGy with those who incurred doses below 150 mGy; they estimated an ERR of 6.7 (90% CI: 0.8, 23.5) Gy^{-1}.

D175. An earlier case-control analysis from the same registry initially showed no significant trend with dose for all leukaemias, or for leukaemia excluding CLL, among the recovery operation workers who worked in the 30-km zone in 1986–1987 [I10]; however a later analysis estimated significant ERRs ranging from 0.28 Gy^{-1} to 15.59 Gy^{-1} for essentially the same groups [K11]. In the latter study, a total of 36 non-CLL cases diagnosed between 1986 and 1993 were compared with controls (case : control ratio = 1:3). The mean doses for cases were lower than those for the corresponding controls, but nevertheless an elevated (but not statistically significant) relative risk was observed in the highest dose group.

D176. The results from these studies have been questioned, see reference [U3]. In discussing the discrepancy between the findings of the case-control and cohort studies, Boice and Holm [B46] suggested that the increased incidence observed in the cohort analyses reflected a difference in case ascertainment between the recovery operation workers and the general population and not an effect of radiation exposure. The magnitude of the risk is also questionable because of the large uncertainties in the "official" doses from the Russian State Chernobyl Registry and the procedures used to verify leukaemia cases were unknown.

D177. Buzunov et al. [B13] studied the incidence of leukaemia in 1987–1993 in a group of approximately 175,000 recovery operation workers in Ukraine. They compared the rates of leukaemia in those first employed in 1986 and those employed in 1987, when doses were lower. They found that the rate of leukaemia was approximately double in the first group, but dose dependence within the groups was not studied.

D178. Two other albeit smaller cohorts of recovery operation workers were followed. In the initial study, Rahu et al. reported no cases of leukaemia in the cohort of Estonian recovery operation workers who worked during 1986–1993 [R3]. In the second study, which involved follow-up of the Estonian and Latvian recovery operation workers until 1998 [R7], the incidence of leukaemia in the Estonian workers remained unchanged, but that in the Latvian workers was significantly higher compared to the age-matched general population (SIR = 2.59; 95% CI: 1.04, 5.34; n = 7 cases). The overall leukaemia excess, however, was not significantly increased (SIR = 1.53; 95% CI: 0.62, 3.17); and the authors were concerned that "ascertainment bias stemming from increased awareness and medical attention may increase false-positive diagnoses of leukaemia, and hence explain the excess number of cases in the Latvian cohort."

D179. Two case-control studies of recovery operation workers—one using data from Belarus, the Russian Federation and the Baltic countries, and the other data from Ukraine—were conducted [H11]. Both utilized the same questionnaire and had the same nested case-control design, with both cases and controls having been drawn from the cohorts of recovery operation workers in each country. The cohorts were assembled on the basis of the national Chernobyl State Registries. Both studies used the same method of dose reconstruction (RADRUE) based on interviews and various measurements of dose fields in the 30-km zone around Chernobyl [B11]. The Committee was informed that the unpublished results of both studies indicate similar non-significant increases in both non-CLL and CLL leukaemia. This is somewhat surprising in view of the lack of any significantly increased radiation risk for CLL observed in most other studies. The Committee has recently concluded that CLL is not established as being caused by ionizing radiation [U1].

(e) Conclusions

D180. The interest in leukaemia arises because of its known sensitivity to induction by ionizing radiation and also because of its short latent period. So far, no persuasive evidence has been found to suggest that there is a measurable increase in the risk of leukaemia among those exposed in utero and as children. This is not unreasonable given that the doses involved were generally very small, and therefore epidemiological studies would lack sufficient statistical power for an effect to be observed.

D181. Amongst adults, the most meaningful evidence comes from the studies of recovery operation workers. At present, there is some evidence of a detectable effect among a group of recovery operation workers from the Russian Federation, but this is far from conclusive. It would therefore be premature to make a direct comparison between the data obtained from these studies directly with the risk estimates obtained from studies involving high doses and dose-rate (such as of the survivors of the atomic bombings). The limitations discussed earlier of the studies of the recovery operation workers must be borne in mind. Nevertheless, future results from studies of the recovery operation workers will, hopefully, provide meaningful data that can be compared with those from other studies.

5. Other solid cancers

(a) Introduction

D182. A few studies have been reported on specific solid tumours following the Chernobyl accident, but evidence so far is extremely limited. Other studies have examined the risk of all solid cancers combined (i.e. excluding leukaemia and sometimes thyroid cancer). Although using such an aggregated endpoint could obviously mask an effect for any individual cancer, statistical power is increased as it provides greater numbers for analysis, even though any derived risk estimate would actually be lower than the risks of any individual cancers that are induced by radiation exposure.

(b) Assessment of current evidence in groups of the general population

D183. Table D19 shows the SIRs for all solid cancers combined occurring among various exposed groups in the Russian Federation and Ukraine. The data are shown for separate time periods, where available.

D184. For the Russian Federation, the SIRs in table D19 are for the seven contaminated districts of the Bryansk oblast with a total population of 316,000 persons in 1991 and of 291,000 in 2005. The incidence of solid cancer for the whole of the Russian Federation was used as a reference value. There is no evidence of any significant increase in the incidence of all solid cancers in the seven contaminated districts for any time period of observation within the period 1991–2005 [I25, I26]. The observed incidence of cancer among the residents of the worst affected areas of the Bryansk region did not differ significantly from the expected value. Although comparison with the national cancer registration rate creates a potential for bias, the SIR for the whole period is essentially equal to unity.

D185. The data for Ukraine in table D19 show that generally the rates of all solid cancers are lower both among evacuees and among permanent residents of the contaminated areas of the country compared to the rest of the country despite any potential bias caused by using national cancer registration rates as the basis for the comparison [P16, S18].

D186. A geographical correlation study conducted by Pukkala et al. [P10] investigated the potential relationship between radiation exposure and breast cancer incidence in Belarus and Ukraine. Cumulative dose estimates were based on average district-specific whole body doses accumulated since the accident due to external exposure and to ingestion of long-lived radionuclides. Values of breast cancer incidence were derived from information in the national registries. Analysis of the pooled Belarusian and Ukrainian data showed a significantly increased relative risk (RR) between 1999 and 2001 in districts with average cumulative dose of 40 mSv or more. This increase was seen in particular among women who were younger than 45 years old at the time of the accident. For Belarus, the RR in the group with an average dose of 40 mSv or more was 2.24 (95% CI: 1.51, 3.32). No significant excess was seen for earlier periods. The RR was higher for metastatic breast cancer (RR = 3; 95% CI: 1.70, 5.29) than for localized cancer (RR = 2.01; 95% CI: 1.16, 3.51). For Ukraine, the RR in the group with an average cumulative dose of 40 mSv or more was 1.78 (95% CI: 1.08, 2.93) in the period 1997–2001. A significant increase in the RR was also observed in the period 1992–1996 in areas with an average cumulative dose of 20–39.9 mSv. Risk values derived from this study are substantially higher than those determined from the other epidemiological studies that were reviewed in annex A of the UNSCEAR 2006 Report [U1] and need, therefore, to be interpreted cautiously.

D187. A publication by Dardynskaia et al. [D6] in contrast shows no clear increase in the incidence of breast cancer in Belarus, but it does not present breast cancer incidence with respect to dose, except in order to contrast the data for the Vitebsk oblast (with minimal deposition due to the accident) with those for the Gomel oblast (with much higher levels). It is a descriptive study comparing trends for all women from 1978 to 2003 and for those of age 30–49 years. In a separate analysis, the rates in the Gomel and Vitebsk oblasts were compared: there is a tendency for an increased incidence of breast cancer since 1976 in both oblasts and the authors concluded that "these data provide no convincing evidence for Chemobyl-induced breast cancer in Belarus".

D188. Other epidemiological studies have demonstrated a clear association between external radiation exposure and the risk of breast cancer, with the ERR per unit dose being greatest for exposure at young ages [U1]. Only very few studies on women exposed as a result of the Chernobyl accident have considered breast cancer. There are numerous weaknesses in these studies—they are unable to take into account some major cofactors that have to be considered, such as the age at first pregnancy, other hormonal factors, and nutrition. These factors could be studied through a future case-control study, but reconstruction of individual organ doses needs unbiased information on past exposures.

D189. Analyses were conducted of the trends in the data on cancer registry and cancer mortality in Europe [C11]. The incidence of most cancer groupings of interest increased in Europe after 1981. However, after 1991, the time slope of that increase for all cancers combined, breast cancer and leukaemia decreased. Only for thyroid cancer was there a statistically significant increase in the slope of the trend noted after 1991. The authors concluded that the "results of analyses of trends in cancer incidence and mortality do not appear to indicate (except for thyroid cancer) a measurable increase in cancer incidence in Europe to date, related to radiation from the Chernobyl accident". Furthermore, in discussing the concerns over surveillance and better diagnostic capabilities in areas with elevated deposition due to the Chernobyl accident, they stated, "The interpretation of trends in cancer incidence should be made with caution, as cancer registration data are subject to a number of potential biases".

(c) Assessment of current evidence among emergency and recovery operation workers

D190. Various studies of all solid cancers combined for Russian and Ukrainian emergency and recovery operation workers have been reported. Table D20 shows the SIRs for all solid cancers combined in various groups of workers, over various time periods following the accident.

D191. In two studies, Ivanov et al. [I47, I48] examined the data for the Russian emergency and recovery operation workers regarding the incidence of solid cancers. In the larger of them [I48], they studied a cohort of 55,718 workers who worked within the 30-km zone during 1986–1987, and for whom the documented estimates of external dose ranged from 0.001 Gy to 0.3 Gy (mean 0.13 Gy). A total of 1,370 solid cancer cases were diagnosed during 1991–2001. In the smaller study [I47], they examined 8,654 nuclear workers who participated in the recovery operations at Chernobyl and who had their external doses documented. In this smaller cohort, which had an average external dose of 0.05 Gy, 179 solid cancers had occurred during 1996–2001. In both cohorts, solid cancer incidence was lower than in the relevant age/gender groups of the Russian general population and although the value of the ERR per unit dose was positive, it was not significantly different from zero.

D192. Ivanov recently transmitted to the Committee updated information from the RNMDR system; it addressed the cohort of male recovery operation workers residing in six regions of the European part of the Russian Federation (39 jurisdictions). The information related to 104,466 persons as of 2005 (55.5% of the total number of recovery operation workers registered in the RNMDR). Figure D-XV summarizes the number of workers by year of entry into the 30-km zone. This cohort was established in 1991 when the number of its members was 76,229. Complete personalized medical information is available for this cohort: 4,220 solid cancer cases were registered from 1991 to 2005 [I26]. Official external dose records are available for 74% of the cohort members; the average dose was 107 mGy.

D193. The SIRs for the recovery operation workers were calculated using the age-specific incidence of all solid cancers combined in the male population of the Russian Federation as the external control (table D20). These updated data indicate an apparent excess of solid cancers among the emergency workers (16%), and a tendency for a decrease with time since exposure. However, the apparent excess observed may be explained by the more sophisticated medical screening of the population than for the Russian population in general [I25, I26]. Caution therefore needs to be exercised in interpreting these data.

D194. Ivanov et al. also studied mortality from solid cancer in a cohort of 61,000 Russian emergency and recovery operation workers with documented estimates of external dose (average dose 107 mGy) [I25, I40, I49]. In the first study covering 1991–1998, out of 4,995 recorded deaths, 515 were due to solid cancers [I25, I40]. Although neither the mortality rate due to all causes nor the mortality rate due to solid cancer exceeded the corresponding mortality rates for the relevant age/gender groups of the Russian population in general, the dependence of SMR on dose was statistically significant: ERR = 2.11 (95% CI: 1.31, 2.92) Gy^{-1}. In the second study [I49], the authors focused on the most exposed fraction of the cohort, i.e. on the 29,000 workers who entered the 30-km zone in the period April 1986 to April 1987. The average dose to this subcohort was 156 mGy. From the time of the accident to the end of 2002, some 4,719 deaths were registered in this subcohort and 651 of them were caused by solid cancers. Moreover the mortality rate for this subcohort from all causes did not exceed the corresponding mortality rates of the relevant age/gender groups of the Russian population in general. The only group of diseases for which the dependence of SMR on dose was statistically significant were solid cancers (ERR = 1.52 (95% CI: 0.20, 2.85) Gy^{-1}). The weakness of these studies is that most of the deaths from solid cancer would have been registered during the latent period for most solid cancers if they had been initiated by radiation exposure from the Chernobyl accident, i.e. many years before radiation-related fatal cancers would have occurred.

D195. The Ukrainian recovery operation workers showed a similar, statistically significant increase in the SIR for all cancers combined for the period 1991–2004 (table D20) [P16, S18]. This result suffers from the same weakness as that of the Russian studies.

(d) Conclusions

D196. There appears at present to be no persuasive evidence of any measurable increased incidence of all cancers combined or breast cancer alone among the general populations of the Russian Federation and Ukraine. There also appears to be no pattern of increased incidence of solid cancers among the inhabitants of the areas deemed contaminated compared to the inhabitants of the areas deemed uncontaminated, and no difference in the trends with time for areas with different levels of radioactive deposition.

D197. The evidence regarding any increased incidence of solid cancers among recovery operation workers is mixed. Although some groups showed elevated SIRs, statistically significant quantitative risks of increased cancer incidence per unit of additional dose have not been reported. In contrast, two Russian studies reported a dose dependence of the solid cancer mortality rate with a corresponding statistically significant ERR per unit dose.

D198. Several limitations need consideration when interpreting these results. First, for many cancers, a latent period of 10 years or more is to be expected between the time of exposure and the observation of an effect. If this applies to the incidence of all solid cancers combined, one would not expect to see any effect manifest itself until the mid- to late 1990s. Second, interpretion of the results of comparisons of the data on the recovery operation workers with those for the general population should take into account the fact that all of the workers are offered a regular annual medical examination. This has the possible effect of introducing a screening bias, as discussed earlier. Furthermore, the risk values derived from the various studies are substantially higher than those determined from other epidemiological studies reviewed in annex A of the UNSCEAR 2006 Report [U1] and need, therefore, to be interpreted cautiously.

D199. Assessments of statistical power, based on the follow-up to date and using findings from the study of the survivors of the atomic bombings and other studies summarized in annex A of [U1], would suggest that doses in the general population are too low to yield sufficient statistical power to detect any measurable increase in the risk of all solid cancers combined among such individuals exposed to radioactive deposition after the Chernobyl accident. Certainly, empirical studies to date do not suggest that risks are substantially greater than those predicted by risk projection models.

6. Autoimmune thyroiditis

D200. Autoimmune thyroiditis is a complicated phenomenon and almost certainly involves interaction between genetic predisposition and environmental factors, such as the level of dietary iodine intake [D7]. However, its association with radiation exposure is controversial [E3]. In addition, the underlying incidence of autoimmune thyroiditis increases with age [D8]. Therefore, dissecting out the effect of radiation exposure from the other elements that may or may not have a bearing on the incidence of autoimmune thyroid disease in the population requires extremely careful study.

D201. There have been few studies of significant size that have addressed the relationship between autoimmune thyroiditis and exposure to radiation resulting from the Chernobyl accident. The largest study to date involved 12,240 subjects who resided in an area of mild to moderate iodine deficiency in Ukraine [T7]. All subjects had estimates of thyroid dose due to the intake of ^{131}I based on individual radiation measurements on the thyroid performed in May–June 1986. Measurements of circulating antibodies and TSH levels together with ultrasonography of the thyroid gland were taken to determine whether the autoantibodies produced were significantly affecting thyroid function. The presence of thyroid autoantibodies is not considered on its own to be an indicator of clinically significant destruction of the thyroid by the immune response (i.e. true autoimmune thyroiditis), but to represent evidence of thyroid autoimmunity.

D202. This study, despite its size, did not provide any conclusive evidence of a relationship between thyroid dose and autoimmune thyroid disease, defined by both the presence of circulating autoantibodies and evidence of thyroid dysfunction by ultrasonography, and/or TSH elevation. This study therefore agrees with the findings of studies of exposed individuals from the Hanford nuclear site [D9] and from the Hiroshima and Nagasaki bombings [I27, N11].

D203. The clinical significance of elevated levels of thyroid autoantibodies in the absence of signs of destruction of thyroid cells by an autoimmune response remains unclear. Furthermore, caution is necessary when extrapolating from one study that comprises individuals studied at a single point in time (12–14 years) after the accident. However the findings are in general consistent with earlier, less robust studies [P11, V4].

7. Cardiovascular and cerebrovascular diseases

(a) Introduction

D204. High doses of radiation to the heart and blood vessels can cause a spectrum of cardiovascular diseases, including coronary heart disease. Recent reports have clearly demonstrated the direct association between high levels of radiation exposure (such as in radiation therapy for Hodgkin lymphoma [A2] or breast cancer [D4]) and cardiovascular disease during long-term follow-up. The risk of radiation-related cardiac disease is strongly related to age at irradiation and is especially high when exposure occurred during childhood or adolescence. Little information is available regarding the possible effects of smoking and other cardiovascular risk factors on the radiation-related risk of ischaemic heart disease. The biological mechanisms by which low-dose radiation exposure induces risks of cardiovascular disease are currently unclear. Although several plausible biological models have been suggested, more research is needed to explore possible models [U1].

D205. Studies of the survivors of the atomic bombings in Japan, who received single doses ranging from 0 to 4 Gy to the whole body, showed that the risk of death caused by non-cancer diseases, including cardiovascular and cerebrovascular diseases, is dose-related with an ERR of 0.14 Gy^{-1} [P3]. This evidence has been recently confirmed by the longer observation times in the Adult Health Study from 1958 to 1998 [Y1]. According to this study, a significant positive dose–response relationship has been confirmed for myocardial infarction among survivors exposed at ages younger than 40 years ($p = 0.049$). Analysis of the cause of death between 1968 and 1997 among the survivors of the atomic bombings led to an estimate of the ERR for heart disease of 0.17 (90% CI: 0.08, 0.26) Sv^{-1} and to that for stroke of 0.12 (95% CI: 0.02, 0.22) Sv^{-1} [P3, U1].

D206. In annex B of the UNSCEAR 2006 Report [U1], the Committee concluded that “to date, the evidence for an association between fatal cardiovascular disease and radiation exposure at doses in the range of less than about 1–2 gray (Gy) comes only from the analysis of the data on the survivors of the atomic bombings in Japan. Other studies have provided no clear or consistent evidence of a fatal cardiovascular disease risk at radiation doses of less than 1–2 Gy … the present scientific data are not sufficient to establish a causal relationship between ionizing radiation and cardiovascular disease at doses of less than about 1-2 Gy”.

(b) Assessment of current evidence

D207. Two studies conducted by Ivanov et al. [I12, I39] focused on cardiovascular and cerebrovascular incidence among the cohort of Russian recovery operation workers. About 60,000 men with an average dose of 109 mGy were followed from 1986 to 2000. The authors observed a statistically significant excess relative risk of ischaemic heart disease: ERR = 0.41 (95% CI: 0.05, 0.78) Gy^{-1}; of essential hypertension: ERR= 0.36 (95% CI: 0.005, 0.71) Gy^{-1}; and of cerebrovascular diseases: ERR= 0.45 (95% CI: 0.11, 0.80) Gy^{-1}. The authors focused on the 29,003 workers with an average dose of 162 mGy who worked in and around the Chernobyl site during the first year after the accident. The authors considered that the group at risk with respect to cerebrovascular diseases are those who received external radiation doses greater than 150 mGy over a short period (less than six weeks), with a relative risk equal to 1.18 (95% CI: 1, 1.4). Nevertheless, several weaknesses of the study have to be considered: the absence of information on the percentage of people lost from the follow-up process, the use of death certificates for assessing part of the disease incidence, and the absence of adjustment for the well-known risk factors of cerebrovascular diseases (i.e. smoking, obesity, hypercholesterolaemia and others).

D208. In a cohort of 60,910 emergency workers in the Russian Federation (basically the same cohort as in references [I12, I39]) followed for overall mortality, 4,995 deaths were reported in 1991–1998. Of these, 1,728 died of cardiovascular disease, which was indicative of a much higher rate than for the normal population [I40]. The estimate of the ERR for deaths from cardiovascular disease was 0.54 (95% CI: 0.18, 0.91) Sv^{-1}. The ERR for the incidence of cardiovascular disease was less, at 0.23 (95% CI: -0.03, 0.50) Sv^{1} [I25]. This latter value was driven primarily by hypertensive diagnoses and it appears paradoxical that the incidences of ischaemic heart disease and acute myocardial infarction (which might be expected to correlate with mortality) did not increase with dose.

D209. Another study conducted by Rahu et al. [R3] on a cohort of 4,742 emergency workers from Estonia followed from 1986 to 1993, found no association between the dose and the incidence of cardiovascular disease, based on an estimation of SMR by categories of dose.

D210. Recently, an analysis of non-cancer incidence and mortality rates in various groups registered in the Ukrainian State Chernobyl Registry (USCR)—including workers, evacuees and residents of contaminated areas—was published by Buzunov et al. [B43]. The authors attempted to evaluate total and disease-specific incidence and mortality rates from 1988 to 2004. The most surprising finding was a decrease in the incidence of non-cancer diseases among the recovery operation workers since 2000. However, since the paper lacks any presentation of the methodology used in estimating the rates, it is not possible to determine if the rates were age-adjusted or if the denominators of the rates were adjusted for the numbers of deaths that occurred, which, according to some sources, were more than 15% of this cohort. Another limitation is the absence of the underlying numbers of cases in the tables. Since only roughly 40% of those registered in the USCR have official doses, and in most instances these subjects had higher doses, any calculations based only on those with doses would be biased. In summary, this paper does not provide any new reliable information on non-cancer morbidity and mortality due to radiation exposure resulting from the Chernobyl accident.

D211. In Belarus, there have been studies of the incidence of coronary heart disease and mortality due to that disease in contaminated and uncontaminated districts [G6, G7]. The age-standardized incidence of coronary heart disease among 617 male agricultural workers residing in the Narovlyansky district of the Gomel oblast (one of the most contaminated districts of Belarus) was 5.0%, whereas that among 213 workers in an uncontaminated district of Minsk was 9.1% [G7]. Reference [G6] considered mortality caused by cardiovascular diseases among agricultural workers who lived in the same two districts. Correlations were found between cardiovascular mortality and the various non-radiation risk factors (arterial hypertension, smoking, etc.) known to cause heart disease. However, the cohorts described were very small and unlikely to be informative, and, as yet, there are no studies specifically devoted to analysing the possible associations between disease prevalence and mortality and radiation dose.

(c) Conclusions

D212. Little solid evidence exists of any demonstrable effect of radiation exposure due to the Chernobyl accident on cardiovascular and cerebrovascular disease incidence and mortality. One study of the recovery operation workers in the Russian Federation has provided evidence of a statistically significant association between radiation dose and both mortality rates due to cardiovascular disease and cerebrovascular disease incidence. The observed excess of cerebrovascular disease was linked to those having worked for less than six weeks and having received a dose of more than 150 mSv. However, the revealed excess per unit dose was not adjusted for other factors such as excessive weight and smoking habits, and therefore, the authors qualified their results as preliminary. Furthermore, the latency interval for cardiovascular disease mortality was too short to be consistent with what is already known about radiation-related heart disease from higher dose studies. Further study is required before it can be concluded whether or not radiation exposure due to the Chernobyl accident has increased the risk of cardiovascular and cerebrovascular disease and associated mortality.

8. The eye and cataractogenesis

(a) Introduction

D213. Although all tissues of the eye and adnexa may suffer radiation injury, lesions are far more common in the lens, eyelid and retina than in the sclera. The eye is considered a relatively radiosensitive organ compared with other organs and tissues mainly because of the frequent development of posterior subcapsular cataracts. It is usually thought that cataract development due to radiation exposure requires single acute doses of low-LET radiation of 2 Gy or more, or higher cumulative doses if the exposure is protracted or fractionated. If the exposure is fractionated, vision-impairing damage to the retina and the optic nerve may require a cumulative dose of the order of 50–60 Gy. Recent studies have suggested that the lens of the eye may be more radiosensitive than previously considered [C17, M4, N18, W1, W7].

D214. It is common practice to grade radiation-induced cataracts. Grade I cataracts or opacities are subclinical effects that have little or no impact on daily life, while the higher grades may result in visual impairment. Cataracts are believed to be a deterministic effect of radiation exposure, i.e. one in which the severity of the effect varies with dose and for which a threshold may therefore occur. The vast majority of radiation-induced opacities identified after radiation exposure do not impair vision. However, especially high doses, e.g. 7 Gy, may lead to severe visual impairment that requires replacement of the lens.

D215. While not pathognomonic, typically radiation-induced cataracts initially manifest themselves as defects in the transparency of the posterior superficial cortex of the tissue and are referred to as posterior subcapsular cataracts (PSC).

D216. Cataracts appear after a latent period, the length of which is inversely related to dose. The latent period is dependent on the rate at which damaged epithelial cells undergo aberrant differentiation and accumulate in the PSC region [I37, K1, M1, U9].

(b) Studies of Chernobyl ARS survivors

D217. Among the ARS patients surviving the Chernobyl accident, the time of appearance and dose dependence of PSCs did not reveal any new features. With more than 15 years of clinical observation of 77 workers, 11 cases of clinically significant radiation-induced cataract were found among persons who survived doses from 2.6 to 8.7 Gy. The latent period varied from 1.5 years (for the most exposed person) to 12 years (for the least exposed person) [K1, N2, N5]. Table D21 and figure D-II present these data.

D218. The Committee is aware that a number of other Ukrainian studies of cataracts among the ARS survivors and the recovery operation workers are currently under way. Unfortunately, the Committee has not yet seen and evaluated this material.

(c) Studies of emergency and recovery operation workers

D219. *The Ukrainian–American Chernobyl Ocular Study (UACOS)* [C17, W1, W7]. Two ophthalmological examinations have been conducted among the Ukrainian recovery operation workers 12 and 14 years after the accident. Reconstruction of the individual doses received by these workers has also been undertaken. Ophthalmic examinations of 8,607 workers were conducted in six cities located in five

Ukrainian oblasts. A variation of the Merriam/Focht radiation-induced cataract scoring method was used on all workers [W7]. The ophthalmologists were kept "blinded" as to the doses to the lens of the eye, and those undertaking the dose reconstruction were not informed as to ophthalmological status. The recovery operation workers in the study were 32.7 years of age on average at the time of exposure (standard deviation: 7.3 years), 44.9 years at the first examination and 47.0 years at the second examination. The dose reconstruction involved a comparison of the gamma doses obtained from the official records of occupational exposure with the estimates of dose and their uncertainties obtained by ESR analyses of teeth from a sample of workers [C17]. Beta doses to the lens of the eye were modelled using information about beta exposure levels at various work locations within the Chernobyl complex during particular time periods. The doses to the recovery operation workers were moderately fractionated/protracted and the cumulative doses to the lens of the eye were low to moderate. The median estimated lens dose was 0.12 Gy, and 95% of the doses were less than 0.5 Gy.

D220. Although the UACOS workers examined were still relatively young (76% were under age 50 at the first examination), there was a high frequency of lens opacity: a total of 26% (2,251) had grade I opacities, including 20% (1,716) with posterior subcapsular opacities found during one or other of the examinations [W7]. Only 1.5% (131) had grade II–V cataracts, but these are of importance because higher grade opacities are more likely to cause visual disability than the grade I opacities. Since the radiation exposures occurred at young ages, the opacities observed largely represent the cumulative incidence of opacities that had developed subsequent to the exposures due to the accident.

D221. The analyses of the UACOS data were controlled for a number of potential risk factors for cataract development, including age at exposure, age and clinic at first examination, sex (96% males), current and past smoking habits, diabetes mellitus, history of corticosteroid or phenothiazine use, and occupational exposures to hazardous chemicals, ionizing radiation exposure (other than that due to the recovery operations), and exposure to infrared or ultraviolet radiation.

D222. In order for selection factors to bias the results of the Chernobyl worker cataract study, they would have to be related to both dose and cataract risk. Consideration of the selection process suggests that most factors would not have produced such bias. The Chernobyl worker cataract cohort was based almost wholly on the Ukrainian SCRM dose registry, which consisted of 32,826 individuals. Many of the individuals had no addresses, had addresses outside the regions of the ophthalmologic clinics, or had died. It seems unlikely that these factors would have been substantially related to both dose and cataract risk. A total of 12,051 were considered eligible and contacted. Of those, 507 either had only one examination or had another ocular condition that disqualified them; it also seems unlikely that either of those factors was related to radiation dose. For another 1,346, there was insufficient information in the USCRM registry to enable estimates to be made of their dose; there is no reason why this would be related to cataract risk. Finally, 1,337 did not complete the epidemiologic/health questionnaire, primarily because personnel were unavailable to administer it; this also is probably not related to dose, since clinic personnel were "blinded" as to the doses. This left a total of 8,607 in the study. Perhaps the greatest uncertainty regarding selection bias relates to self-chosen participation. Although the participation rate of 71% was reasonably good for a clinical study of basically healthy individuals, the possibility exists of a higher participation rate among individuals who knew that they had received substantial doses and who thought that they might have some loss of visual acuity; there was no direct way to check this. However, since the main findings pertain to subclinical cataracts that, at that stage of development, caused little loss of visual acuity, this possibility seems rather unlikely as well.

D223. For grade I opacities, the OR was 1.49 (95% CI: 1.08, 2.06) at 1 Gy, with adjustment for the other cataract risk factors mentioned above. Similarly, for grades II–V cataracts, the OR was 1.57 (95% CI: 0.79, 3.11) at 1 Gy, but was not statistically significant, possibly owing to the smaller numbers ($n = 131$ cataract cases). When grade I opacities were examined by location, posterior subcapsular opacities (OR = 1.42 (95% CI: 1.01, 2.00) at 1 Gy) and the somewhat more inclusive category of cortical opacities (OR = 1.51 (95% CI: 1.09, 2.10) at 1 Gy), both of which may be radiation-related, showed statistically significant increases with dose, whereas nuclear opacities/cataracts (of any stage), which are not thought to be associated with radiation exposure, showed no elevation (OR = 1.07 (95% CI: 0.56, 2.04) at 1 Gy). When the data were examined by dose group, both posterior subcapsular and cortical lens opacities showed suggestive or significant elevations in risk at about 0.5 Gy or more (table D22) [W7].

D224. Because cataract formation is thought to be a deterministic effect, a statistical analysis was made for a dose–effect threshold. Maximum likelihood estimates of the dose–effect threshold for various classes of cataracts are shown in table D23. The results from the UACOS study [W7] suggest that the data are incompatible (at the 95% confidence level) with a dose–effect threshold of more than 0.7 Gy for grades I–V cataract in total, with a strong prevalence of grade I opacity, although this statement needs to be qualified because of the uncertainties in the individual dose estimates [C17].

D225. In summary, the UACOS study indicates that cataracts arising in the population of recovery operation workers, corrected for the most important confounding factors, are related to the dose received. For the most part, the doses were less than 0.5 Gy of low-LET radiation acquired in a somewhat protracted/fractionated manner. A key finding was that the data were not compatible with a dose–effect threshold of more than 0.7 Gy, although this needs to be tempered by consideration of the uncertainties in the dosimetry.

(d) Studies of general population

D226. An extensive study [D3] was conducted to determine the prevalence and characteristics of lens changes in a paediatric population (5–17 years of age) that had lived in an area close to Chernobyl. Representative groups of 996 exposed and 791 unexposed children were given ophthalmological examinations, and opacities were graded according to a standard scoring system (LOCSIII; [C18]). Many (38%) of the PSC opacities were examined a second time to confirm the original findings. A small (3.6%) but significant (p = 0.0005) group of exposed children manifested PSC lens changes [D3]. This included 2.8% scored as having grade I or greater PSC opacities, as compared to 1.0% in the unexposed group (p = 0.007). The study had some weaknesses in that it was not possible to reconstruct individual doses, and the examiners were not “blinded” as to the examinee’s exposure status (which was defined by the geographical location of the examination). Nevertheless, the study was carefully conducted, with standardized examination and cataract scoring procedures, and with examiner training and other quality-control measures in place.

(e) Other recent studies of low-dose radiation exposure and cataracts

D227. A number of studies have been published that are relevant to exposures at low doses and can be used for comparison purposes. Two cross-sectional studies have examined cataract prevalence in relation to individuals’ own reporting of their history of computed tomography (CT) scans of the head. One reported a positive association [K9], but the other did not [H10]. A study of US astronauts reported that those with higher lens doses from space flights (mean of 45 mSv) showed a significant elevation in cataract risk compared to those with lower doses (mean of 4 mSv) [C7]. The astronaut exposures were primarily due to high-LET heavy ions and secondary neutrons in space.

D228. A Swedish study examined 484 individuals with a mean age of 46 years (range 36–54 years) who were treated with radium plaques in infancy (at ages 0–18 months) for haemangiomas, and 89 unexposed individuals, who had been treated by other means [H12]. The median dose rate to the lens was 0.05 Gy/h (mean 0.13 Gy/h). Individual doses to the lens were estimated and examinations were conducted using a standardized protocol and cataract scoring system (LOCSII; [C19]). A dose gradation was seen with regard to the prevalence of cortical and PSC cataracts of grade I or greater. The prevalences and, in parentheses, the number of cataracts compared with the number of lenses examined were: unexposed, 5% (9/178); <0.5 Gy, 12% (89/748); 0.5–1.0 Gy, 18% (20/115); and >1 Gy, 22% (20/89). Because of concerns about the possible dissimilarity of the unexposed and exposed groups, the investigators limited their analyses of dose response to the exposed group. After adjusting for age at examination, dose rate and steroid treatment, the OR at 1 Gy for cataracts of grade I or greater was 1.49 (95% CI: 1.07, 2.08) for PSC and 1.50 (95% CI: 1.15, 1.95) for cortical cataracts.

D229. An ophthalmological examination was conducted based on the Japanese survivors of the atomic bombings, primarily on those who were younger than 13 years at the time of the bombings [M4]. The examiners were “blinded” as to the dose due to the atomic bombings, and the examination was standardized through examiner training and use of the LOCSII scoring system [C19]. The data were analysed on the LOCSII graded scale, so the analysis estimated the incremental risk of more severe grades of cataract using a proportional OR. The models included adjustment for city, sex, age at examination and smoking. They found no association for nuclear cataracts (OR = 1.1 (95% CI: 0.9, 1.3) at 1 Gy), but found statistically significant dose–response relationships for cortical cataracts (OR = 1.3 (90% CI: 1.1, 1.5) at 1 Gy) and posterior subcapsular cataracts (OR = 1.4 (90% CI: 1.2, 1.6) at 1 Gy).

D230. A further analysis of the data from the ophthalmological examinations on the survivors of the atomic bombings provided estimates of the dose–effect threshold. For cortical cataracts, the maximum likelihood estimate of the dose–effect threshold was 0.6 (90% CI: <0, 1.2) Gy and for posterior subcapsular cataracts, it was 0.7 (90% CI: <0, 2.8) Gy [N18] (table D23). The most recent analysis considered the prevalence of surgically removed cataracts in the cohort of survivors of the atomic bombings late in life, by 2000–2002. These data are important because they refer primarily to cataracts of sufficient severity to cause visual limitation. Again, a statistically significant dose–response association was found (OR = 1.4 (95% CI: 1.2, 1.6) at 1 Gy). A dose–effect threshold analysis yielded a maximum likelihood estimate of 0.1 (95% CI: <0, 0.8) Gy [N17].

D231. The UNSCEAR 1993 Report [U6] which dealt with late deterministic effects in children contained very limited evidence of cataractogenic sensitivity in young persons. The only substantial study available was based on the survivors of the atomic bombings in Japan, which suggested that the risk of cataract formation was higher in persons younger than 15 years of age at the time of the bombings, compared to persons who were 15 or more years of age [C20]. The newer ocular examination data on the survivors of the atomic bombings have confirmed that the radiation effect diminishes among those exposed at older ages [N18].

D232. Both the study of children exposed to radioactive deposition arising from the Chernobyl accident [D3] and those given radium treatments for haemangiomas [H12] confirm that children are sensitive to cataract induction by ionizing radiation, although it is not possible to determine a specific age effect from these studies.

(f) Conclusions

D233. While posterior subcapsular cataracts are characteristic of radiation exposure, several sets of data suggest that the broader category of posterior cortical cataracts may also be regarded as radiation-associated. PSC are not pathognomonic for radiation but can be caused by: drugs (steroids, allopurinol, dilantin, chlorpromazine and others); systemic disorders (diabetes, hypocalcaemia, riboflavin deficiency); certain inflammatory or degenerative eye diseases; and eye trauma. The Chernobyl childhood exposure study [D3], the childhood haemangiomas study [H6], the UACOS Chernobyl worker study [W7] and the study of the survivors of the atomic bombings [M4] have largely addressed the issue of other causes of cataracts by statistically evaluating and adjusting for these other risk factors. Continuing the above studies would be useful in order to generate a clearer picture of the risk of radiation-induced cataracts at low doses.

D234. In summary, several new sets of data suggest that cataract formation occurs after relatively low doses of ionizing radiation and that the dose–effect threshold is probably under 1 Gy. Although most of these data relate to the lower grade cataracts, a recent finding from the study of the Japanese survivors of the atomic bombings suggests that higher grade cataracts are also in excess following exposure to relatively low doses after a sufficient latent period [N17]. Whether or not some fraction of the radiation-associated grade I opacities eventually progress to become more severe vision-disabling cataracts remains to be resolved.

D235. A critical analysis of all existing information on the subject, especially in order to better understand the reasons for the differences between the new and older data, is necessary. Follow-up of the major cohorts is also needed in order to better evaluate latency of cataract induction and its subsequent progression, and to better characterize the risk at low-to-moderate doses to the lens of the eye. A number of study designs and methodological issues need to be considered for all the studies, such as developing accurate dose reconstructions, having an adequate control group, assessing subjects in a “blinded” and standardized manner to guard against bias, using a sufficiently sensitive observational method (e.g. slit-lamp examination with adequate pupil dilation), documenting the presence of other cataract risk factors, and conducting analyses of the dose–response relationship, cataract severity and cataract latency.

D. Risk projection

D236. The possible health risk to large populations exposed to radiation can be projected by means of radiation risk models that are based partially on epidemiological data and partially on biophysical modelling [U3, U7, U17]. The practical aim of risk projection may be for the provision of information for decision-making on specialized health care of relevant populations, for the provision of public information or both. It can also be used for the purposes of assessing the statistical power and hence the feasibility of a proposed epidemiological project. It should be stressed that radiation risk projections are not directly applied for the purposes of radiation protection, since decision-making for such purposes is usually based on practical dose criteria [B49, F11, I37].

D237. The major source of data for modelling stochastic risks due to radiation exposure remains the “Life Span Study” (LSS) of the survivors of the atomic bombings, which has involved more than half a century of detailed study of the long-term health effects in a large population exposed to a wide range of radiation doses [P3]. However, application of LSS results to those exposed as a consequence of the Chernobyl accident requires a number of assumptions relating to such matters as the magnitude of the dose and dose-rate and the nature of the population. Such assumptions increase the uncertainty of any projections that are made using the LSS results [J7]. Additional data from other human and experimental radiobiological studies, for example, on the value of the dose and dose-rate effectiveness factor (DDREF) are therefore necessary.

D238. Projections of potential radiation risks have been made by many research groups in the high dose range relevant to hypothetical nuclear war scenarios [I42], in the intermediate dose range relevant to nuclear and radiological accidents and in the low dose range relevant to the routine operation of nuclear facilities. Various risk models were used for different types of radiation and dose ranges, taking into account age at exposure, sex and other factors. A large number of radiation risk projections have been conducted with regard to the health consequences of the Chernobyl accident [A11, C1, C11, I43, T4, W5].

D239. All of the risk projections were based on information known at the time on the doses to the public; they usually assumed the linear non-threshold (LNT) model for the dependence of the probability of radiogenic cancers on dose, and used parameters from UNSCEAR and ICRP reports [I44, I45, U9] and from some national publications, for example, reference [N4]. As new epidemiological data became available, the risk models and projections were updated.

D240. The first projections of the potential health consequences of the accident were prepared by a group of Soviet specialists at the request of the authorities in the autumn of 1986 and published in the collected proceedings of a symposium held in Moscow in June 1987 [I43], which were classified until 1989. The morbidity prognosis for the recovery operation workers was not examined in these articles.

D241. One article was concerned with the possible health consequences for inhabitants of the areas in Belarus, the Russian Federation and Ukraine with the highest levels of radioactive deposition [B47]. Among the 1.1 million inhabitants of these areas, it was predicted that the death rate due to cancer in the 70 years following the accident, might increase, on average, by 3.3%, and that there would be approximately 7,500 cases of thyroid cancer, including around 1,000 cases in children who were below the age of seven at the time of the accident.

D242. A second article examined separately the possible health consequences for the Russian population [R4]. For the 600,000 inhabitants of the most contaminated areas in four oblasts (Bryansk, Tula, Kaluga and Orel), the potential increase in the death rate due to cancer was predicted to be 3.5%, while for the 60 million inhabitants of the European part of the Russian Federation, it was predicted to be 0.2%. In addition, 1,400 cases of thyroid cancer were predicted to occur in the four oblasts, including more than 300 cases in children below the age of seven, and up to 9,000 cases (3,000 of them in children) in the European part of the Russian Federation. Overall, these studies yielded four important conclusions:

- There would be no deterministic radiation effects in the general population;
- The potential increase in radiogenic cancers would not be significant from the point of view of organizing health care, although those effects on some population groups at specific periods of time could be detected using epidemiological methods;
- A considerable increase in the incidence of radiogenic thyroid cancer should be expected, particularly among children;
- Psychological trauma caused by the accident could affect millions of people.

D243. In 1988, US scientists published the first assessment of the global impact of the Chernobyl accident [A11]. Based on monitoring data and on available environmental models, they estimated the lifetime collective whole-body dose commitment to the population of the Northern Hemisphere to be about 900,000 man Gy and its distribution among countries of Europe (97%), Asia and North America. They projected 2–17 thousand possible cancer deaths due to radiation exposure from the accident—40% in the former Soviet Union and 60% in the rest of Europe. However, the corresponding average increase in the population cancer mortality would be negligible, i.e. 0.02% in the former Soviet Union and 0.01% in Europe. The authors also noted the huge economic and social effect of the accident.

D244. Ten years after the accident, an international group of specialists, who had participated actively in the post-accident epidemiological studies, gave a more detailed projection of the potential consequences in terms of cancer incidence, based on more accurate estimates of the effective doses, the relevant radiation risk factors and the LNT model (table D24) [C1]. Populations were divided into the 600,000 more exposed groups of people—the recovery operation workers who worked in 1986–1987, the evacuees and the residents of the strict control zone[1]—and around 7 million residents of other contaminated territories with radioactive deposition.

D245. According to the 1996 assessment, approximately 4,000 additional premature deaths from cancer (solid cancer and leukaemia) due to the increased radiation exposure were estimated to occur over the lifetime of the more exposed groups of people (600,000) and a further 5,000 cases among the other 7 million residents. The predicted average increase in the frequency of radiation-induced solid cancers over a lifetime was 3.3% among the more exposed population and 0.6% among the other residents. The predicted average increases in the frequency of radiation-induced leukaemia were 12% and 1.5%, respectively.

D246. There is reasonable agreement between the projections of 1986, 1988 and 1996. From table D24, it is also evident that for large cohorts, any increase in cancer incidence due to radiation exposure would be scarcely noticeable. However, an increase in cancer incidence should be detectable using scientific methods in particular population groups at specific periods of time after the Chernobyl accident. In particular, an increased frequency of leukaemia among the recovery operation workers ought to have been detected during the first decade. However, no increase in cancer incidence was apparent in 1996 in the more exposed population groups [C1].

D247. Thyroid cancer resulting from internal exposure to radioiodine was not examined in reference [C1] or in reference [A11]. The reason for this was because the increased incidence of thyroid cancer among children and adolescents who were living in the spring of 1986 in the more contaminated areas was already widely recognized [K32, L9] and efforts were focused on analysing the surveillance data.

D248. The issues arising from a comparison of the projections of the possible increased incidence of cancer due to the accident and data from 20 years of surveillance of the various population groups were examined by the Chernobyl Forum in 2003–2005 [C22, W5]. Based on the available epidemiological data, the Forum did not consider it necessary to change the projections of Cardis et al. [C1], despite there being some differences in the demographic and dosimetric data.

D249. In 2006, a UK Committee published an independent assessment of the environmental and potential health consequences of the Chernobyl accident for the European population [F10]. In essence, they considered many published assessments of the collective dose and the predicted health effects and apparently selected the maximum values. They selected 30–60 thousand as the most credible range for the number of additional deaths due to radiation exposure and estimated that most of these would occur in Europe beyond Belarus, the Russian Federation and Ukraine. In undertaking this assessment, the UK Committee erroneously estimated that "more than half of Chernobyl's fallout was deposited outside these countries" (i.e. outside Belarus, the Russian Federation and Ukraine). In fact, only 23% of the radiocaesium from Chernobyl was deposited in the rest of Europe [E5].

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[1] The strict control zones are the areas which had levels of ^{137}Cs deposition density above 555 kBq/m^2 in 1986.

D250. In 2006, Cardis et al. made another attempt to project the possible incremental increase in cancer incidence in European populations due to the additional radiation exposure arising from the Chernobyl accident. They used updated estimates of the collective dose and state-of-the-art risk models developed recently by the BEIR (Biological Effects of Ionizing Radiation) VII Committee [C11, C23]. The risk projections suggested that by then the Chernobyl accident may have caused about an additional 1,000 cases of thyroid cancer and an additional 4,000 cases of other cancers in Europe, representing about 0.01% of all cancers since the accident. The models predicted that by 2065, about 16,000 (95% CI: 3,400, 72,000) cases of thyroid cancer and 25,000 (95% CI: 11,000, 59,000) cases of other cancers could occur owing to radiation exposure resulting from the accident, whereas several hundred million cancer cases would be expected from other causes. It is very unlikely that this additional cancer burden due to the largest nuclear accident to date could be detected by monitoring national cancer statistics.

D251. In order to adequately interpret and communicate radiation risk projections, it is necessary to understand their scientific limitations. At today's level of knowledge, there are reliable epidemiological data on risks of cancer morbid-ity and mortality due to radiation exposure of cohorts of individuals with an acute average dose of the order of 100 mSv and above. So far, neither the most informative LSS study nor any other studies have provided conclusive evidence of carcinogenic effects of radiation at smaller doses. This is the position formulated by UNSCEAR in annex G, "Biological effects of low radiation doses", of the UNSCEAR 2000 Report [U3], which states "For most tumour types in experimental animals and in man a significant increase in risk is only detectable at doses above about 100 mGy".

D252. Since predictions of possible health consequences are not directly intended for substantiating necessary radiation protection measures, they do not have to be based on a cautious approach (such as the LNT model) but rather they should be based on firmly established scientific facts. In the dose range below 0.1 Sv, because of the absence of persuasive evidence related in part to the substantial statistical uncertainties, the dependence of the frequency of adverse radiation effects on dose can be assessed only by means of biophysical models among which the models based on the LNT approach are the most popular [B48, U3]. However, there are also others, including superlinear and threshold ones, and even models that account for a possible beneficial effect of radiation, termed hormesis. For these reasons, the Committee will not use these models to project absolute numbers of possible health effects in populations exposed to low doses of radiation, because of unacceptable levels of uncertainty in the predictions.

D253. Two important features of radiation-induced cancer projection should be noted. First, there are as yet no known markers that are specific to radiogenic cancer. This means that it is impossible to determine whether a particular cancer is due to the effects of radiation exposure or to other causes or, more specifically, whether it is due to radiation resulting from an accident or from natural sources. It is possible only to estimate the risk to an individual based on the dose to that individual. This is fundamentally different from the situation with the ARS victims in 1986, when all of them were known by name and ARS was diagnosed based on conclusive medical findings. Secondly, it is important to understand the considerable statistical uncertainty of any projection based on the LNT model. This model only really lends itself to estimations that are within an order of magnitude.

D254. For cohorts of the residents of the areas of Belarus, the Russian Federation, Ukraine and other countries in Europe [A11, C1, C11, R4, T4] with average effective doses of below 30 mSv over 20 years, there are today no conclusive data for predicting radiogenic morbidity and mortality with any reasonable certainty. At the same time, it cannot be ruled out that adequate data on the health effects of low-dose human exposure will be developed as further progress is made in understanding the radiobiology of man and other mammals. This may provide in the future the scientific basis for evaluating the health consequences of the Chernobyl accident among residents of areas with low radiation levels.

D255. In view of the above, any projection of potential health effects caused by low radiation doses to large population groups should be accompanied by a detailed explanation of the associated conceptual caveats and projection uncertainties. In order to put such projections in an appropriate context, they should preferably be presented as relative increments over the underlying incidence or mortality rates, with associated statements regarding their uncertainty. This will allow comparison of the health risk of ionizing radiation with other health risks and with the underlying incidence or mortality rate.

D256. During the last decade, the Committee has avoided making projections of the health effects that might be caused by low-level exposure of large population groups, mainly because of the substantial uncertainties associated with any such projection and potentially serious misinterpretation in communication with the public.

IV. GENERAL CONCLUSIONS

D257. The long-term nature and severity of the radiation-induced skin injuries to those persons who survived ARS in 1986 was naturally related to the severity of injuries during the acute period. In the long term, telangiectasia, repeated ulcers and fibrosis were observed in patients with higher doses, and there were moderate atrophic changes and hyperkeratosis in other patients. The prevalence of radiation-induced cataracts in the long term increased with the ARS grade and the level of dose received. Most of the radiation-induced cataracts developed during the first five years after exposure. The latent period for cataract development was lower in persons with high doses.

D258. A significant frequency of neurosomatic diseases in the ARS survivors, who have been subjected to ongoing detailed medical surveillance, was revealed during the first five years after the accident, including those of the otolaryngological organs, the nervous system and the gastrointestinal tract. An increase in the frequency of cardiovascular disease was detected later and it correlated with the ageing of patients. Out of 13 cases of solid cancer, four cases were found among the ARS survivors and nine cases among persons with unconfirmed ARS. The mean latent period for the solid cancers diagnosed by 2006 was 14 years.

D259. Over the 20 years since the accident (1987–2006), 19 out of 106 ARS survivors and 14 out of 99 persons with unconfirmed ARS diagnosis have died for various reasons. There is a tendency for increased mortality rates due to somatic disease with the grade of ARS although there has been no formal epidemiological analysis of mortality rates among the ARS survivors. Among the causes of death of those who survived ARS, there were four cases of onco-haematological disease.

D260. The Chernobyl registries have the potential to become important sources of information on the long-term health effects of radiation exposure. Standardization of the procedures across the three registries would greatly improve their usefulness for epidemiological research.

D261. The possible long-term health effects resulting from radiation exposure due to the Chernobyl accident remain an issue. This annex focuses on studies of the incidence of thyroid cancer, leukaemia, all solid cancers as a whole, cardiovascular morbidity and mortality, cataract development and autoimmune thyroiditis. This selection was based on the potential sensitivity of these outcomes to radiation, and because the Committee considered that there were insufficient new data in other areas that would justify modifying the conclusions of the UNSCEAR 2000 Report.

D262. Two types of studies are considered when evaluating the cancer risk to populations exposed during the Chernobyl accident: geographical correlation studies relating aggregated rates of disease with average exposures; and analytical studies (case-control or cohort) where individual information is used. The latter are considered to be more reliable and valid for examining the dose–response relationship.

D263. Bias due both to screening and to diagnostic suspicion may operate in studies of the emergency and recovery operation workers, who are examined every year for various diseases and for whom there is consequently a greater likelihood of detection of small tumours. Trends in disease rates in groups of emergency and recovery operation workers are only scientifically informative if the same methods of detection in diagnosis are applied over the whole period of interest and are independent of the individual exposure level. Overall, interpretation of the results from studies on the populations exposed as a consequence of the Chernobyl accident have to take into account the variation of detection methods with time, and the likelihood of different screening frequencies for different populations.

D264. The substantial increase in thyroid cancer incidence seen amongst those exposed as children or adolescents in Belarus, the Russian Federation and Ukraine since the Chernobyl accident shows no signs of diminishing up to 20 years after exposure. Amongst those under age 14 years in 1986, 5,127 cases (for those under age 18 years in 1986, 6,848 cases) of thyroid cancer have been reported between 1991 and 2005 for the whole of Belarus and Ukraine and the four more affected regions of the Russian Federation [I8]. Continuing the systematic follow-up of these populations should help to ensure early detection and medical treatment of any benign or malignant tumour.

D265. There is no doubt that a substantial contributor to the excess incidence of thyroid cancer has been exposure to radioiodine released during the Chernobyl accident. From the geographical correlation studies, it would appear that the excess absolute risk (EAR) due to exposure to radioiodine is somewhat smaller than the corresponding risk due to external exposure. However, this difference can be explained by the shorter time after exposure in the Chernobyl studies than those of studies of thyroid cancer after exposure to external radiation.

D266. Evidence has also emerged that iodine deficiency may well increase the risk of thyroid cancer resulting from exposure to radioiodine released during the accident. Two studies suggest that iodine deficiency sometime between exposure and diagnosis may double the corresponding radiation risk. If confirmed by future studies, this will be important in terms of extrapolating the results from the studies of the Chernobyl accident to other scenarios in which iodine deficiency may play a role.

D267. The most significant radionuclide among the mixture of radioactive isotopes of iodine irradiating the thyroid gland was ^{131}I. The possibility has been suggested that shorter-lived isotopes of iodine are more effective in causing thyroid cancer than ^{131}I. The contributions of other radioactive isotopes of iodine than ^{131}I to the thyroid dose were relatively small and therefore their influence cannot be evaluated in epidemiological studies of groups exposed to radiation from the accident.

D268. The evidence from studies of thyroid cancer among adult residents of Belarus, the Russian Federation and Ukraine and among the recovery operation workers is somewhat mixed, with some groups showing elevated SIRs and others showing substantially smaller effects. Lack of persuasive evidence of any association with the estimated thyroid doses strongly suggests that increased screening of the exposed groups compared to the general population would account for a large part of the observed excess.

D269. The UNSCEAR 2000 Report [U3] suggested, based on the evidence then available, that there may be a link between the morphological subtypes (i.e. solid/follicular variant) of papillary cancer observed in children and exposure to radiation. More recent evidence raises questions regarding this postulated causal relationship between solid/follicular morphology of papillary cancer and radiation exposure.

D270. The evidence so far suggests that the molecular biology of post-accident childhood thyroid cancer is similar to that seen in age-matched series from non-irradiated populations. There are a number of large studies of the molecular biology of post-accident thyroid cancer currently underway using pathologically verified material supplied by the Chernobyl Tissue Bank.

D271. Among those exposed in utero and as children, no persuasive evidence has accrued to suggest that there is a measurable increase in the risk of leukaemia due to radiation exposure. This is not unreasonable since the doses involved were generally very small, and therefore it is expected that epidemiological studies would lack sufficient statistical power to observe any effect had there been one.

D272. Among the recovery operation workers, there is some evidence of a detectable increase in the risk of leukaemia, primarily based upon results from the Russian Federation. As yet, it would be premature to compare any risk estimates based on this evidence directly with the estimates obtained from studies of populations exposed at high doses and dose-rates, such as the survivors of the atomic bombings in Japan; the limitations of studies of the recovery operation workers must be borne in mind. Future evidence from such studies will, hopefully, provide meaningful data.

D273. At present, there is no persuasive evidence of any measurable increase in the risk of all solid cancers combined or breast cancer for the general populations of the three most affected republics. There appears to be no pattern of increased risk in those areas with high levels of radioactive deposition compared to those with low levels, and no difference in rates with time for areas with different levels of radioactive disposition. With regard to solid cancer incidence among the recovery operation workers, some groups show elevations in SIRs; however, quantitative risk estimates of cancer incidence per unit of dose have not yet been reported.

D274. Assessments, based on the follow-up to date and using the findings from the study of the survivors of the atomic bombings and other studies, would suggest that the doses received by the general population after the accident were too low to yield sufficient statistical power for studies to be able to detect any increase in the risk of all solid cancers combined, had there been an increase. Although the numbers of cancers projected to be induced by radiation exposure from the accident are very small relative to the baseline cancer risk, they could potentially be substantial in absolute terms. Certainly, the empirical studies to date do not suggest that the risks are substantially greater than would be predicted by the existing risk projection models.

D275. There have been few studies of significant size and quality that have addressed the relationship between autoimmune thyroiditis and exposure to radiation following the Chernobyl accident. The clinical significance of elevated thyroid autoantibodies in the absence of any signs of destruction of thyroid cells by an autoimmune response remains unclear. The evidence to date does not suggest an association between radiation exposure and clinically significant autoimmune thyroiditis.

D276. Little solid evidence exists of any demonstrable effect of radiation exposure due to the Chernobyl accident on the incidence of cardiovascular and cerebrovascular disease and mortality rates. One study of the recovery operation workers in the Russian Federation has provided indications of a statistically significant association between radiation dose and both cardiovascular disease mortality rates and the incidence of cerebrovascular disease. Although the results of this study are statistically compatible with those of the study of the survivors of the atomic bombings, the increase in circulatory disease is not consistent with most other studies involving doses below about 4 Gy. Furthermore, the increase seen among the recovery operation workers is inconsistent with the expected latency interval seen in other investigations. It will be necessary to have more persuasive evidence to conclude whether or not radiation exposure due to the Chernobyl accident has increased the risk of cardiovascular and cerebrovascular disease and associated mortality.

D277. Cataracts developed among the ARS survivors who were exposed to high radiation doses. However, several new sets of data suggest that cataract formation also occurs after relatively low doses of ionizing radiation and that the dose–effect threshold may be under 1 Gy. Although most of these data are related to lower grade cataracts/lens opacities, a recent finding from the study of the survivors of the atomic bombings suggests that the incidence of higher grade cataracts is also in excess at relatively low doses after a sufficient latent period. Whether some fraction of the radiation-associated grade I opacities eventually progress to become more severe, vision-disabling cataracts is still an unresolved issue.

D278. Even if an empirical epidemiological study provides evidence of an increased incidence of a potentially radiogenic disease, it is still necessary to consider the issue of the attributability (i.e. the likely causal nature of the reported association) of that effect to radiation exposure. It is necessary to take detailed account of possible confounding and bias factors, such as industrial pollution, environmental features (e.g. stable iodine levels in soil), lifestyle (e.g. smoking habits or alcohol consumption), reproductive history, improvement of diagnostic tools, and increased medical attention of the affected populations (e.g. screening).

D279. Projections of the health risk for large populations exposed to radiation are often made using radiation risk models based on epidemiological studies obtained from other exposure situations and on biophysical modelling. The practical aims of such risk projection may be to provide information for decisions on health care for the population or for public information. Several projections of the health consequences of the Chernobyl accident based on the linear non-threshold model have been conducted by various groups. However, there is a limit to the use of the data derived from epidemiological studies. Below doses of about 0.1 Sv, the experimental evidence for radiation-induced health effects is ambiguous and risk coefficients become more uncertain. Therefore, any radiation risk projections in the low-dose area should be considered as extremely uncertain, especially when the computation of cancer deaths is based on collective effective doses involving very small additional exposures to very large populations over many years. It is inappropriate to use collective effective dose for risk projections because the biological and statistical uncertainties are too great.

D280. Based on 20 years of study, the conclusions of the UNSCEAR 2000 Report can now be confirmed. 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 an increased risk of radiation-induced health effects. The vast majority of the population were exposed to low levels of radiation comparable, at most, to or a few times the annual natural background radiation levels and need not live in fear of serious health consequences. This is true for the populations of the three countries most affected by the Chernobyl accident, Belarus, the Russian Federation and Ukraine, and even more so for the populations of other European countries. Lives have been disrupted by the Chernobyl accident, but from the radiological point of view, generally positive prospects for the future health of most individuals should prevail.

Table D1. Number of patients followed up at the hospital of the Burnasyan Federal Medical Biophysical Centre (FMBC), Russian Federation according to severity grade of ARS and radiation injury [G9]

ARS grade	*Acute phase*	*1986–1990*	*1991–1995*	*1996–2000*	*2001–2006*
I	23	26	8	1	2
II	43	42	16	5	4
III	14	14	5	3	3
IV	1	1	1	1	1
I-IV	81	83	30	10	10
Mean age (years)	35.0±2.5 (range 17–72)	35.2	39.6±3.6	44.0±5.0	48.7±4.9
Local injury	54	40	18	5	5
Died	27			1	

Table D2. Number of patients followed up at the clinic of URCRM, Ukraine according to severity grade of ARS [G9]

ARS grade	*1986–1990*	*1991–1995*	*1996–2000*	*2001–2005*
I	30	30	26	26
II	31	30	28	25
III	11	11	8	8
Died ARS	2	8	3	5
Unconfirmed ARS[a]	96	93	90	90
Died (unconfirmed ARS)	3	3	—	1

[a] These are people who were initially suspected of having ARS, but were later confirmed not to have the syndrome. They are known variously as "unconfirmed ARS" patients, or "ARS grade 0".

Table D3. Number of ARS survivors with blood values deviating from normal during the 20 years after the accident (FMBC, Russian Federation) [G9]

Blood values	*Number of patients[a]*
Erythrocytes ($\times 10^{12}$/L)	
<4.0	10 (8.7%)
>5.0	11 (8.9%)
Haemoglobin (g/L)	
<130	10 (8.7%)
>160	19 (16.6%)
Leukocytes ($\times 10^{9}$/L)	
<4.0	14 (12.2%)
>9.0	10 (8.7%)
Neutrophils ($\times 10^{9}$/L)	
<2.0	15 (13.1%)
>5.5	8 (7.0%)

Blood values	*Number of patients*[a]
Lymphocytes ($\times 10^9$/L)	
<1.2	12 (10.5%)
>3.0	6 (5.2%)
Thrombocytes ($\times 10^9$/L)	
<180	26 (22.7%)
>320	4 (3.5%)

[a] Percentages are expressed with respect to the total number under observation.

Table D4. Estimated beta and gamma doses to various portions of the eyes of ARS survivors [G9]

Gamma dose (Gy)	*Beta dose to the front surface of the eye (Gy)*	*Beta dose to the retina and posterior surface of the eye (Gy)*
1	3.0	0.8
2	6.0	1.5
3	9.0	2.3
4	12.0	3.0
5	15.0	3.8
6	18.0	4.5
7	21.0	5.3
8	24.0	6.0
9	27.0	7.0
10	30.0	7.5

Table D5. Solid cancer morbidity among the 72 ARS survivors and 96 persons with unconfirmed ARS [B44]

Number	*ARS grade*	*Diagnosis*	*First diagnosed*	*Outcome*
1	0	Sarcoma of hip soft tissues	1992	Died in 1993
2	0	Leiomyosarcoma of shin	1998	Operated in 1998
		Cancer of colon	1999	Operated in 1999
3	0	Cancer of colon	2001	Died in 2005
4	0	Cancer of kidney	2000	Operated in 2001
5	0	Cancer of stomach	2004	Died in 2004
6	0	Cancer of stomach	2004	Died in 2005
7	0	Cancer of lung	2001	Operated in 2003
8	0	Cancer of prostate	2001	Died in 2003
9	0	Cancer of throat	2000	Died in 2001
10	1	Cancer of colon	1997	Operated in 1997
11	2	Cancer of thyroid gland	2000	Operated in 2000
12	2	Cancer of thyroid gland	2000	Operated in 2001
13	2	Neurinoma of lower jaw	2003	Died in 2004

Table D6. Number of patients followed up at the hospital of FMBC over time with diseases of four systems of the body [G9]

Diseases	*Time periods*							
	1986–1990		*1991–1995*		*1996–2000*		*2001–2006*	
	Number of persons	*%*	*Number of persons*	*%*	*Number of persons*	*%*	*Number of persons*	*%*
Gastrointestinal	60	72.3	23	76.7	8	80.0	9	90.0
Cardiovascular	44	53.0	22	73.3	9	90.0	10	100.0
Endocrine	16	19.2	3	10.0	4	40.0	7	70.0
Respiratory	11	13.3	7	23.3	2	20.0	3	30.0

Table D7. Causes of death among Chernobyl ARS survivors in the later period [B10, B39, B41, B42, B44, G9, U3]

Number	*Name*	*ARS grade*	*Year of death*	*Age (years)*	*Cause of death*
1	P.V.A.	I	1993	41	Sudden cardiac death
2	V.O.E.	I	1995	51	Lung TB
3	K.A.P.	I	1995	53	Post-traumatic fatty embolism
4	S.M.A.	I	1995	26	Sudden cardiac death
5	S.V.G.	I	2002	51	Myelodysplastic syndrome
6	R.G.I.	I	2002	51	Trauma
7	V.M.P.	II	1987	81	Lung gangrene
8	K.Ya.F.	II	1990	68	Sudden cardiac death
9	B.V.I.	II	1995	46	Liver cirrhosis
10	G.M.Yu.	II	1998	45	Liver cirrhosis
11	Sh.V.K.	II	1998	61	Acute myelomonoblastic leukaemia
12	B.V.M.	II	1998	80	Sudden cardiac death
13	M.A.S.[a]	II	1999	61	Stroke
14	T.L.P.	II	2004	53	Lower jaw neurinoma
15	V.M.P.	III	1992	67	Sudden cardiac death
16	B.G.V.	III	1993	52	Myelodysplastic syndrome
17	D.A.S.	III	1995	64	Myelodysplastic syndrome
18	B.I.Z.	III	2001	87	Sudden cardiac death
19	P.A.N.	III	2004	41	Lung TB

[a] Patient lived in Russia; other 18 patients lived in the Ukraine.

Table D8. 20 years mortality due to somatic diseases among patients surviving different grades of ARS in 1986 [B39, G9]

ARS grade	*Number of survivors followed-up*	*Number of deaths from somatic diseases[a] in 1987–2006*	*Mortality from somatic diseases[a] in 1987–2006 (rel. units)*
0	99	12	0.12
I	41	5	0.12
II	49	8	0.16
III	15	5	0.33

[a] Deaths caused by trauma and accidents have been excluded.

Table D9. Number of people in the Chernobyl registries

Registration category	Belarus (2005)	Russian Federation (2006)	Ukraine (2006)
Group 1: Emergency and recovery operation workers	72 362[a]	186 395	229 884
Group 2: Evacuees from the exclusion zone	5 951	9 944[b]	49 887
Group 3: Residents of the contaminated regions	1 513 826	367 850	1 554 269
Group 4: Children born to parents of above three groups	17 914[c]	35 552[d]	428 045
Total	1 610 053	599 741	2 262 085

[a] As of 2005 in contrast to table B1 where the data for Belarus are presented as of 1996.
[b] For Russia, the number of both evacuees from 1986 and some migrants from later years is presented.
[c] Children born to parents included in groups 1–3.
[d] Children born to recovery operation workers only.

Table D10. Summary of screening activities in the three countries

Registration category	Belarus		Russian Federation		Ukraine	
	Frequency	Completeness (%)	Frequency	Completeness (%)	Frequency	Completeness (%)
Group 1 – Emergency and recovery operation workers, 1986–1987	Annually	97–99	Annually	75	Annually	83–85
– Recovery operation workers after 1987	Annually		Biennially	[a]	Annually	
Group 2	Annually		Annually	47	Annually	
Group 3	Annually		Annually/ biennially[b]	47	Annually	
Group 4	Annually		Annually	81	Annually	

[a] No data available.
[b] Depending on age and radionuclide levels in the environment.

Table D11. Thyroid cancer incidence rates in those exposed under the age of 18 years

Age at exposure (years)	*Sex*	*Parameter*	*Calendar year periods*				
			1982–1985	*1986–1990*	*1991–1995*	*1996–2000*	*2001–2005*
Belarus [I8, K22]							
0–4	F	Number of cases		11	155	258	209
		Crude rate per 10^5 PY		0.57	8.02	13.35	10.82
	M	Number of cases		9	103	146	79
		Crude rate per 10^5 PY		0.45	5.21	7.38	3.99
5–9	F	Number of cases		9	108	91	169
		Crude rate per 10^5 PY		0.50	6.02	5.07	9.42
	M	Number of cases		10	66	42	59
		Crude rate per 10^5 PY		0.54	3.59	2.29	3.21
10–14	F	Number of cases		8	67	131	202
		Crude rate per 10^5 PY		0.46	3.85	7.52	11.60
	M	Number of cases		7	12	43	60
		Crude rate per 10^5 PY		0.39	0.67	2.39	3.34
15–18	F	Number of cases		15	57	109	223
		Crude rate per 10^5 PY		1.11	4.21	8.05	16.46
	M	Number of cases		5	9	33	40
		Crude rate per 10^5 PY		0.37	0.66	2.41	2.93
Total (0–18)	F	Number of cases	2	43	387	589	803
		Crude rate per 10^5 PY	0.04	0.64	5.72	8.71	11.88
	M	Number of cases	1	31	190	264	238
		Crude rate per 10^5 PY	0.02	0.45	2.75	3.82	3.44
Russian Federation (Bryansk, Kaluga, Orel and Tula oblasts) [I8]							
0–4	F	Number of cases	0	1	13	36	46
		Crude rate per 10^5 PY	0.0	0.12	1.47	3.91	5.18
	M	Number of cases	0	0	12	26	24
		Crude rate per 10^5 PY	0.0	0.0	1.32	2.75	2.7
5–9	F	Number of cases	1	2	20	37	52
		Crude rate per 10^5 PY	0.15	0.24	2.35	4.28	6.44
	M	Number of cases	0	1	6	10	14
		Crude rate per 10^5 PY	0.0	0.12	0.69	1.13	1.67
10–14	F	Number of cases	0	3	24	48	108
		Crude rate per 10^5 PY	0.0	0.36	3.02	5.95	13.9
	M	Number of cases	0	1	9	9	10
		Crude rate per 10^5 PY	0.0	0.12	1.07	1.05	1.23
15–18	F	Number of cases	1	8	43	61	87
		Crude rate per 10^5 PY	0.18	1.24	7.21	9.97	13.87
	M	Number of cases	0	1	8	14	17
		Crude rate per 10^5 PY	0.0	0.15	1.26	2.14	2.64
Total (0–18)	F	Number of cases	2	14	100	182	293
		Crude rate per 10^5 PY	0.09	0.44	3.2	5.68	9.46
	M	Number of cases	0	3	35	59	65
		Crude rate per 10^5 PY	0.0	0.09	1.07	1.77	2.04

Age at exposure (years)	*Sex*	*Parameter*	*Calendar year periods*				
			1982–1985	*1986–1990*	*1991–1995*	*1996–2000*	*2001–2005*
Ukraine [L4, T2]							
0–4	F	Number of cases		6	85	202	254
		Crude rate per 10^5 PY		0.1	0.9	2.2	2.9
	M	Number of cases		9	55	91	103
		Crude rate per 10^5 PY		0.1	0.6	0.9	1.1
5–9	F	Number of cases	1	20	106	181	326
		Crude rate per 10^5 PY	0.01	0.2	1.2	2.0	3.9
	M	Number of cases		7	40	57	74
		Crude rate per 10^5 PY		0.1	0.4	0.6	0.8
10–14	F	Number of cases	9	35	113	252	496
		Crude rate per 10^5 PY	0.1	0.4	1.2	2.8	5.7
	M	Number of cases	7	18	34	55	99
		Crude rate per 10^5 PY	0.1	0.2	0.4	0.6	1.1
15–18	F	Number of cases	15	54	176	277	403
		Crude rate per 10^5 PY	0.3	0.8	2.6	4.0	5.4
	M	Number of cases	7	15	37	53	74
		Crude rate per 10^5 PY	0.1	0.2	0.5	0.7	1.0
Total (0–18)	F	Number of cases	25	115	480	912	1 479
		Crude rate per 10^5 PY	0.1	0.3	1.4	2.7	4.4
	M	Number of cases	14	49	166	256	350
		Crude rate per 10^5 PY	0.05	0.1	0.5	0.7	1.0

Table D12. Thyroid cancer incidence rates in different age groups (age at diagnosis) of the Belarusian population between 1982 and 2005 [I8, K22]

Age at diagnosis (years)	*Sex*	*Parameter*	*Calendar year periods*				
			1982–1985	*1986–1990*	*1991–1995*	*1996–2000*	*2001–2005*
0–9	F	Number of cases	0	17	126	10	6
		Crude rate per 10^6 PY	0.00	4.36	33.27	3.43	2.59
	M	Number of cases	0	16	74	8	5
		Crude rate per 10^6 PY	0.00	3.94	18.70	2.61	2.12
10–19	F	Number of cases	1	25	191	333	205
		Crude rate per 10^6 PY	0.70	6.99	51.11	83.86	54.33
	M	Number of cases	0	14	106	177	90
		Crude rate per 10^6 PY	0.00	3.84	27.76	43.27	23.25
20–29	F	Number of cases	1	3	81	231	357
		Crude rate per 10^6 PY	0.58	0.75	22.50	65.39	97.00
	M	Number of cases	0	2	12	79	111
		Crude rate per 10^6 PY	0.00	0.50	3.37	22.31	29.79
Total (0–29)	F	Number of cases	2	45	398	574	568
		Crude rate per 10^6 PY	0.43	3.92	35.78	55.08	58.14
	M	Number of cases	0	32	192	264	206
		Crude rate per 10^6 PY	0.00	2.73	16.93	24.68	20.70

Table D13. Thyroid cancer incidence rates in different age groups (age at diagnosis) of the Russian population (Bryansk, Kaluga, Orel and Tula oblasts) between 1982 and 2005 [I8]

Age at diagnosis (years)	*Sex*	*Parameter*	*Calendar year periods*				
			1982–1985	*1986–1990*	*1991–1995*	*1996–2000*	*2001–2005*
0–9	F	Number of cases	1	1	7	0	0
		Crude rate per 10^6 PY	0.7	0.6	4.4	0.0	0.0
	M	Number of cases	0	0	1	2	1
		Crude rate per 10^6 PY	0.0	0.0	0.6	1.5	0.9
10–19	F	Number of cases	1	11	39	61	51
		Crude rate per 10^6 PY	0.7	6.6	23.0	33.3	28.3
	M	Number of cases	1	3	21	32	20
		Crude rate per 10^6 PY	0.7	1.7	12.0	17.1	11.0
20–29	F	Number of cases	28	48	97	101	135
		Crude rate per 10^6 PY	18.4	27.6	62.4	63.4	83.7
	M	Number of cases	2	11	20	23	28
		Crude rate per 10^6 PY	1.3	6.1	12.2	13.6	16.7
Total (0–29)	F	Number of cases	30	60	143	162	186
		Crude rate per 10^6 PY	7.0	11.8	29.4	34.6	42.2
	M	Number of cases	3	14	42	57	49
		Crude rate per 10^6 PY	0.7	2.6	8.3	11.6	10.7

Table D14. Thyroid cancer incidence rates in different age groups (age at diagnosis) of the Ukrainian population between 1982 and 2005 [L4, T2]

Age at diagnosis (years)	*Sex*	*Parameter*	*Calendar year periods*				
			1982–1985	*1986–1990*	*1991–1995*	*1996–2000*	*2001-2005*
0–9	F	Number of cases	3	14	38	7	7
		Crude rate per 10^6 PY	0.2	0.8	2.2	0.5	0.8
	M	Number of cases	—	12	32	4	—
		Crude rate per 10^6 PY		0.6	1.8	0.3	
10–18	F	Number of cases	32	69	191	251	200
		Crude rate per 10^6 PY	2.6	4.3	11.7	15.0	13.3
	M	Number of cases	19	30	76	118	83
		Crude rate per 10^6 PY	1.5	1.8	4.5	6.8	5.4
19–30	F	Number of cases	—	33	252	627	863
		Crude rate per 10^6 PY		1.7	12.6	30.0	41.0
	M	Number of cases	—	7	58	136	193
		Crude rate per 10^6 PY		0.4	2.8	6.3	9.0
Total (0–30)	F	Number of cases	35	116	481	885	1 070
		Crude rate per 10^6 PY	0.8	2.2	9.0	17.4	22.1
	M	Number of cases	19	49	166	258	276
		Crude rate per 10^6 PY	0.4	0.9	3.0	4.9	5.5

Table D15. Risk estimates for thyroid cancer resulting from exposure to 1 Gy using different models [C8]

People exposed as children/adolescents in Belarus and the Russian Federation

Model	*OR at 1 Gy (95% CI)*
Logistic regression—excess relative risk model	
Linear-quadratic model over the entire dose range	4.9 (2.2, 7.5)
Linear model up to 2 Gy	5.5 (2.2, 8.8)
Linear model up to 1.5 Gy	5.8 (2.1, 9.4)
Linear model up to 1 Gy	6.6 (2.0, 11.1)
Logistic regression—log-linear risk model	
Linear-quadratic model up to 2 Gy	5.5 (3.1, 9.5)
Linear quadratic model up to 1.5 Gy	5.9 (3.3, 10.5)
Linear model up to 1 Gy	8.4 (4.1, 17.3)

OR = odds ratio at 1 Gy compared with no exposure.
CI = confidence interval.

Table D16. Summary of ERR and EAR estimates for thyroid cancer among those exposed as children or adolescents

Reference	*ERR (95% CI)* *(Gy^{-1})*	*EAR (95% CI)* *($(10^4$ PY $Gy)^{-1}$)*
Geographical correlation studies		
Jacob et al. [J1, J2, J4]	18.9 (11.1, 26.7)	2.66 (2.19, 3.13)
Kenigsberg et al. [K10, K22]	37.7 (35.1, 40.2)	1.93 (1.79, 2.06)
Ivanov et al. [I22]		
Girls	10.0 (4.2, 21.6) external control	1.8 (1.0, 2.9)
Boys	67.8 (17.1, 5 448) external control	2.0 (1.1, 3.0)
Shakhtarin et al. [S6]	4.4 (2.8, 6.6)	
Likhtarov et al. [L5]	8 (4.6, 15)	1.55 (1.2, 1.9)
Analytical studies		
Astakhova et al. [A1]	6.04 (2.5, 17.7)	
Cardis et al. [C8]	4.5 (2.1, 8.5) to 7.4 (3.1, 16.3)	
Tronko et al. [T3]	5.25 (1.70, 27.5)	
Kopecky et al. [K17]	48.7 (4.8, 1 151)	
Davis et al. [D1]	1.65 (0.10, 3.20)	

Table D17. Thyroid cancer incidence among those exposed as adults

Standardized incidence ratios for exposed population, by country and calendar year period

Country/exposed group	*Calendar year periods*	
Russian Federation, residents of Bryansk oblast [I3]	1986–1990	1991–1998
Males (95% CI)	1.27 (0.92, 1.73)	1.45 (1.20, 1.73)
Females (95% CI)	1.94 (1.70, 2.20)	1.96 (1.82, 2.10)
Ukraine [S18]	1990–2004	
Evacuees from 30-km zone	5.12 (*n* = 174) (4.36, 5.88)	
Adult residents of contaminated areas	1.63 (*n* = 247) (1.43, 1.83)	

Table D18. Thyroid cancer incidence among emergency and recovery operation workers

Standardized incidence ratios, by country and calendar year period

Emergency and recovery operation workers	*Calendar year periods*					
Russian Federation [I9]	Period working in 30-km zone					
	April–July 1986	Aug–Dec 1986	April–Dec 1986	1987	1988–1990	1986–1990
	1986–1991 (latent)					
SIR (95% CI)	4.20 (*n* = 4) (1.13, 10.74)	0 (*n* = 0) (n.a., 3.22)	1.91 (*n* = 4) (0.51, 4.89)	2.15 (*n* = 3) (0.43, 6.28)	3.61 (*n* = 2) (0.41, 13.04)	2.23 (*n* = 9) (1.02, 4.22)
	1992–1998 (post-latent)					
SIR (95% CI)	9.16 (*n* = 17) (5.33, 14.7)	5.14 (*n* = 12) (2.65, 8.97)	6.92 (*n* = 29) (4.63, 9.93)	3.78 (*n* = 13) (2.01, 6.47)	4.08 (*n* = 7) (1.63, 8.40)	5.24 (*n* = 49) (3.88, 6.93)
Ukraine [S18]	1990–2004					
SIR (95% CI)	8 (*n* = 164) (6.78, 9.23)					

Table D19. Incidence of all solid cancers combined for exposed population groups in Russia and Ukraine (thyroid cancer excluded)

Standardized incidence ratios, by country and calendar year period

Country/exposed group	*Calendar year periods*			
Russian Federation [I25, I26]	1991–1995	1996–2000	2001–2005	1991–2005
Population of seven contaminated districts (raions) of the Bryansk oblast (95% CI)	1.03 (*n* = 4 701) (1.00, 1.06)	0.99 (*n* = 4 751) (0.96, 1.02)	0.97 (*n* = 5 018) (0.95, 1.00)	1.00 (*n* = 14 470) (0.98, 1.02)
Ukraine [P16, S18]	1990–2004			
Evacuees from 30-km zone (males and females) (95% CI)	0.84 (*n* = 2 182) (0.80, 0.88)			
Adult residents of contaminated areas (males and females) (95% CI)	0.85 (*n* = 11 221) (0.83, 0.86)			

Table D20. Incidence of all solid cancers combined among emergency and recovery operation workers (thyroid cancer excluded)

Standardized incidence ratios, by country and calendar year period

Country/exposed group	*Calendar year periods*			
Russian Federation [I25, I26]	1991–1995	1996–2000	2001–2005	1991–2005
Emergency and recovery operation workers (males) (95% CI)	1.25 (*n* = 1 018) (1.17, 1.33)	1.18 (*n* = 1 461) (1.12, 1.24)	1.10 (*n* = 1 741) (1.05, 1.15)	1.16 (*n* = 4 220) (1.12, 1.19)
Ukraine [P16, S18]	1990–2004			
Emergency and recovery operation workers (males) (95% CI)	1.17 (*n* = 5 396) (1.14, 1.20)			

Table D21. Latent period and grades of posterior subcapsular cataract (PSC) among Chernobyl ARS survivors (beta plus gamma exposures)

Parameter	*Dose range (Gy) (degree of ARS)*		
	2.7–4.0 (moderate ARS)	*4.7–5.7 (severe ARS)*	*7.1–8.7 (very severe ARS)*
Latent period (years)	4–12	2.8–4.0	1.5–2.5
Maximal grade of PSC	I–II	II	III
Time to development of maximal stage (years)	6.0–12	3.8–5.0	2.8–3.0

Table D22. Adjusted odds ratios and 95% confidence intervals by dose group among Chernobyl emergency and recovery operation workers with various cataract grades

UACOS Chernobyl liquidator study [W7]

Dose range (mGy)	*Odds ratios (95% confidence intervals) by dose group*[a]				
	100–249	*250–399*	*400–599*	*600–799*	*800+*
Grade 1 PSC opacity	0.9 (0.8, 1.0)	0.9 (0.7, 1.2)	1.2 (0.9, 1.7)	1.2 (0.8, 1.8)	1.7 (1.1, 2.7)
Grade 1 cortical opacity	0.9 (0.8, 1.0)	1.0 (0.8, 1.2)	1.1 (0.8, 1.5)	1.4 (1.0, 2.1)	1.6 (1.0, 2.5)
Grade 2–5 cataract	1.0 (0.7, 1.7)	1.6 (0.9, 2.8)	2.4 (1.2, 4.6)	1.3 (0.5, 3.1)	1.3 (0.5, 3.4)

[a] Odds ratios are given relative to the baseline group of those who incurred doses in the range 0–99 mGy. Odds ratios were adjusted for factors including age at exposure, age and clinic at first examination, sex (96% males), current and past smoking habits, diabetes mellitus, history of corticosteroid or phenothiazine use, and occupational exposures to hazardous chemicals, ionizing radiation exposure (other than due to recovery operations), and exposure to infrared radiation or ultraviolet radiation, using logistic regression.

Table D23. Dose-effect thresholds: maximum likelihood estimates and likelihood-profile based on 95% confidence intervals for various cataract classes

Ukrainian Chernobyl liquidator study (UACOS) [W7] and Japanese atomic bomb survivors study [N17, N18]

Study and cataract endpoint	*Estimated value for dose threshold (95% CI) (Gy)*
UACOS, Grade I-V cataract [W7]	0.50 (0.17, 0.65)
UACOS, Grade I opacity [W7]	0.34 (0.19, 0.68)
UACOS, Grade I cortical opacity [W7]	0.34 (0.18, 0.51)
UACOS, Grade I posterior subcapsular opacity [W7]	0.35 (0.19, 0.66)
Atomic bombings, cortical cataracts [N18]	0.6 (<0, 1.2)[a]
Atomic bombings, posterior subcapsular cataracts [N18]	0.7 (<0, 2.8)
Atomic bombings, surgically removed cataracts [N17]	0.1 (<0, 0.8)

[a] 90% confidence intervals were reported in the atomic bomb studies.

Table D24. Predictions of background and excess mortality from solid cancers and leukaemia in populations exposed as a result of the Chernobyl accident (based on reference [C1])

Population	*Population size and average dose*	*Cancer type*	*Period*	*Background cancer mortality*	*Predicted excess cancer mortality*	*AF[a] (%)*
Emergency and recovery operation workers (liquidators), 1986–1987	200 000 100 mSv	Solid cancers	Lifetime (95 years)	41 500	2 000	5
		Leukaemia	Lifetime (95 years)	800	200	20
			First 10 years	40	150	79
Evacuees from 30-km zone	135 000 10 mSv	Solid cancers	Lifetime (95 years)	21 500	150	0.7[b]
		Leukaemia	Lifetime (95 years)	500	10	2
			First 10 years	65	5	7
Residents of SCZs[c]	270 000 50 mSv	Solid cancers	Lifetime (95 years)	43 500	1 500	3
		Leukaemia	Lifetime (95 years)	1 000	100	9
			First 10 years	130	60	32
Residents of other contaminated areas	6 800 000 7 mSv	Solid cancers	Lifetime (95 years)	800 000	4 600	0.6
		Leukaemia	Lifetime (95 years)	24 000	370	1.5
			First 10 years	3 300	190	5.5

[a] AF: attributable fraction = (excess deaths/total death from the same cause) × 100.

[b] A misprint has been corrected which appeared in references [C1, W5].

[c] Strictly Controlled Zones, i.e. areas with ^{137}Cs soil deposition above 555 kBq/m^2 (15 Ci/km^2) in 1986.

Figure D-I. Frequency of granulocytopenia (A) and trombocytopenia (B) among persons with unconfirmed ARS and among ARS survivors [B9, B39, B42]

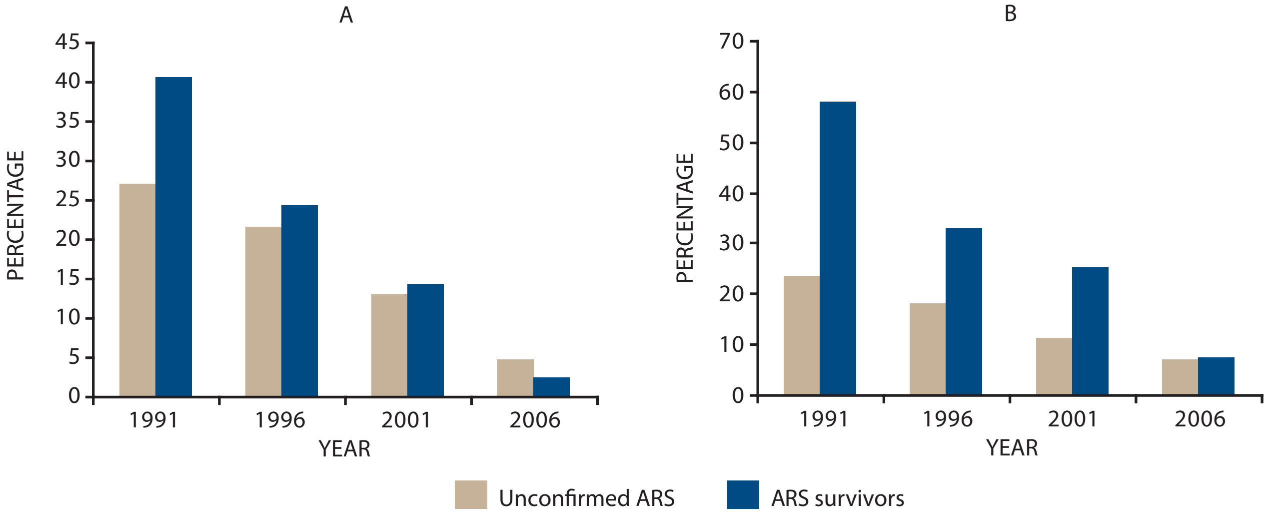


Figure D-II. Relationship between the dose due to beta and gamma irradiation and the length of the latency period for the development of radiation-induced cataracts

Data from FMBC, Russian Federation [G9]

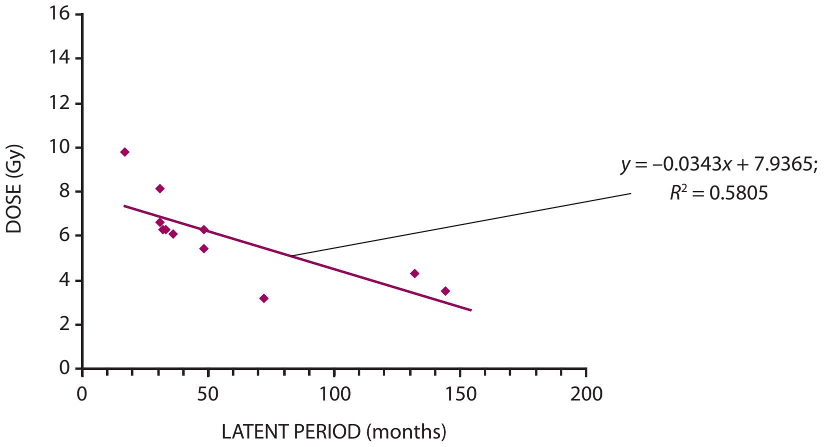


Figure D-III. Frequency of cataracts developed by 2006 among persons with unconfirmed ARS and among graded ARS survivors: ARS-I, ARS-II and ARS-III

Data from URCRM [B9, B39, B42]

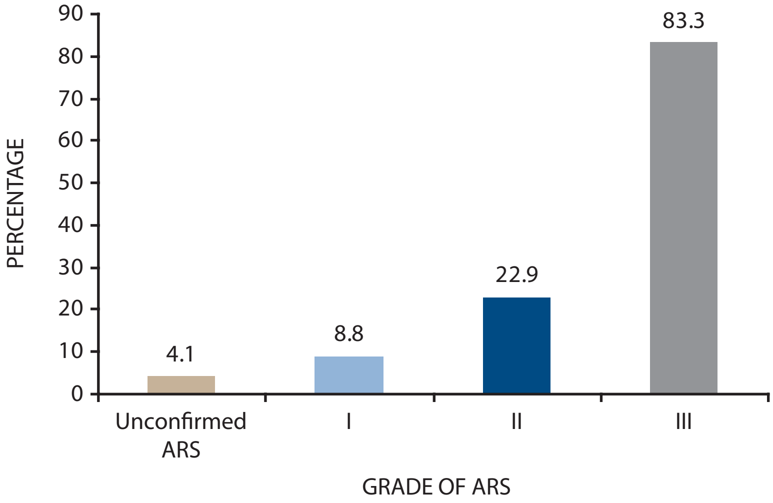


Figure D-IV. The number of ARS survivors with local radiation injuries as a result of the Chernobyl accident
Data from FMBC, Russian Federation [G9]

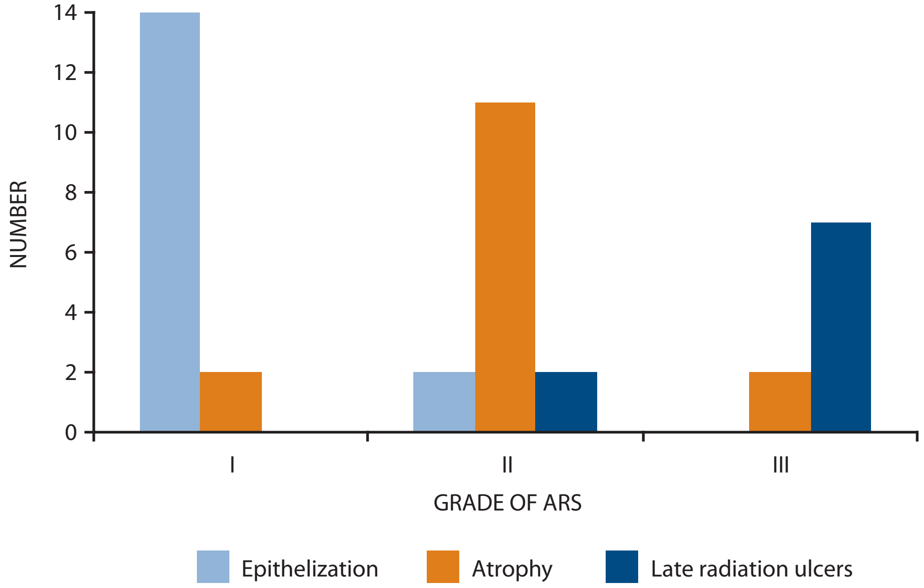


Figure D-V. The number of ARS survivors with local radiation injuries as a result of the Chernobyl accident
Data from URCRM [B39]

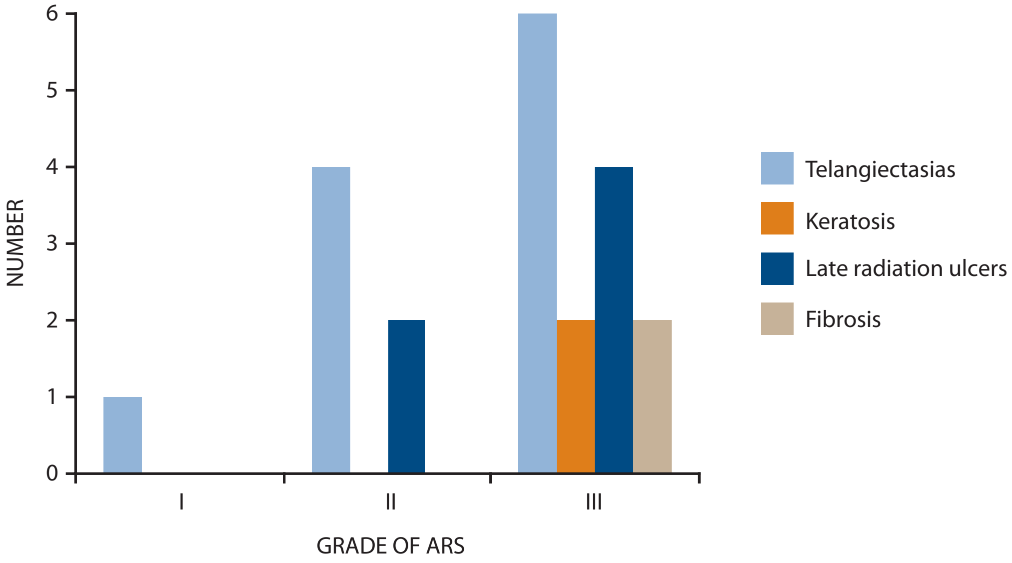


Figure D-VI. Prevalence of respiratory diseases among persons with unconfirmed ARS and among ARS survivors
Data from URCRM [B42]

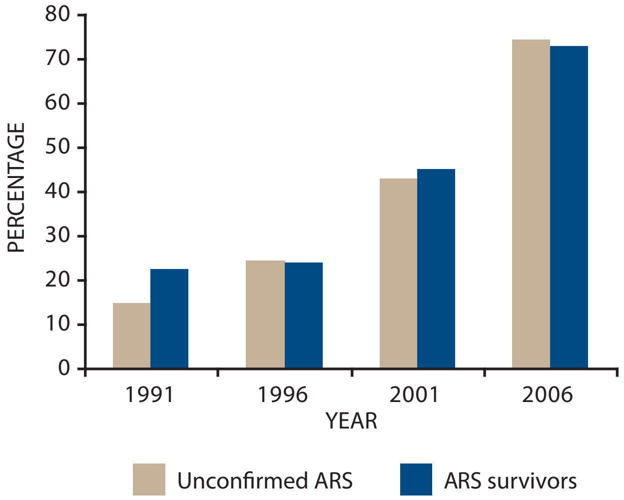


Figure D-VII. Number of ultrasound examinations performed per 10^5 inhabitants in the three regions in Ukraine in 1990, 1995 and 2002 [L5]

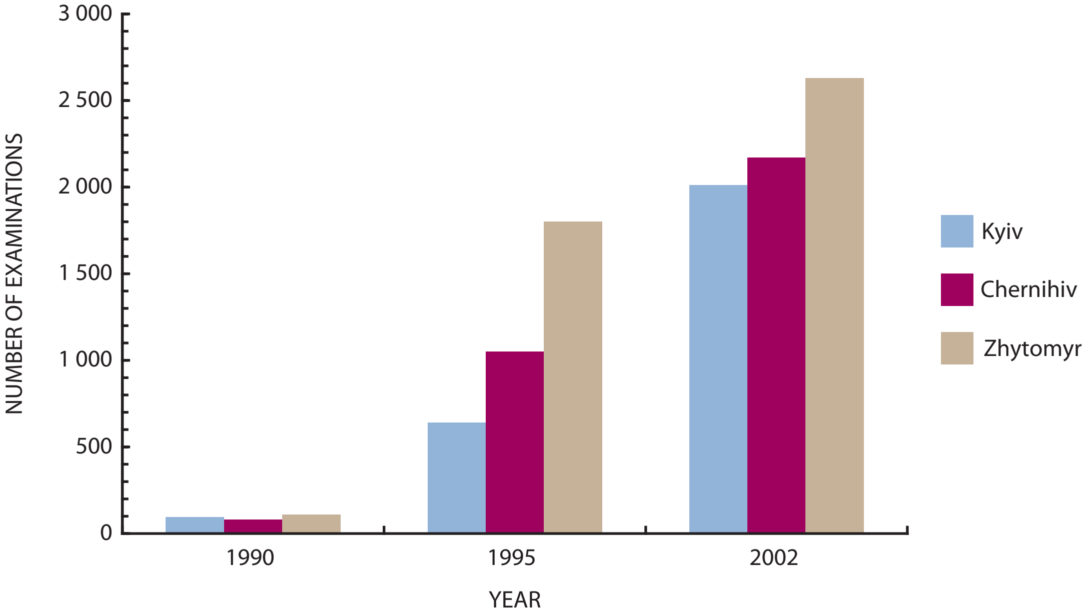


Figure D-VIII. Thyroid cancer incidence rates for different age groups (age at diagnosis) of the total Belarusian female population

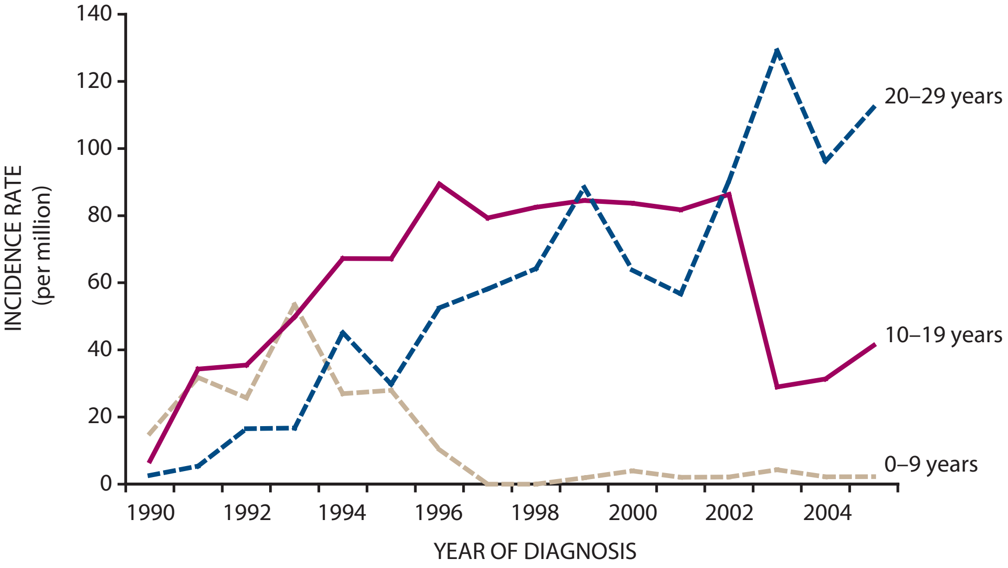


Figure D-IX. Thyroid cancer incidence rates for different age groups (age at diagnosis) of the Russian female population of the Bryansk, Kaluga, Orel and Tula oblasts

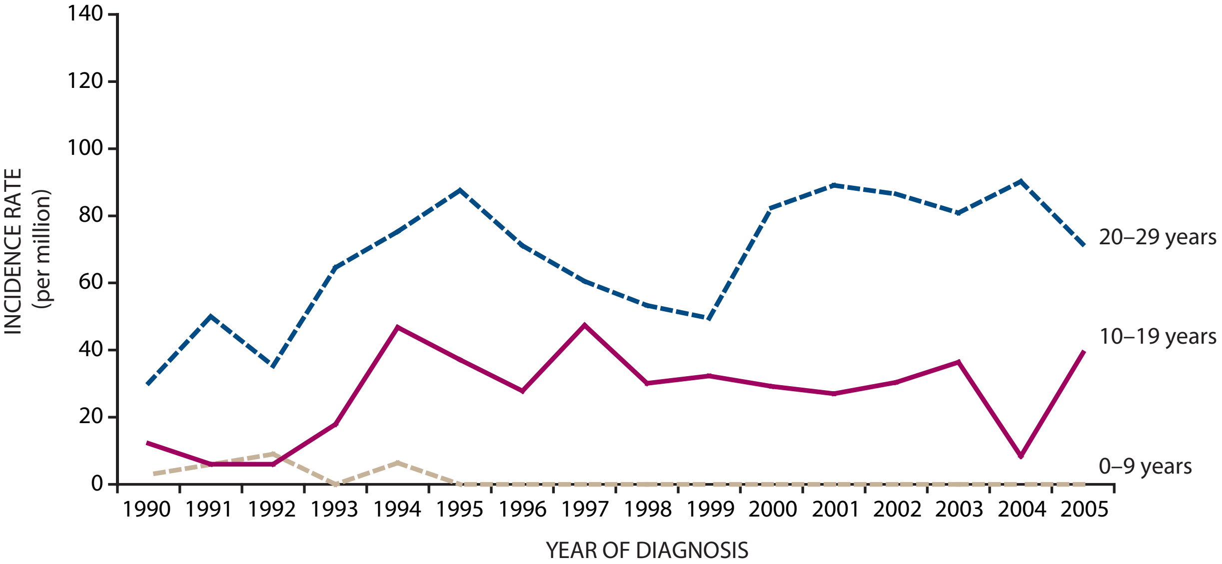


Figure D-X. Thyroid cancer incidence rates for different age groups (age at diagnosis) of the total Ukrainian female population

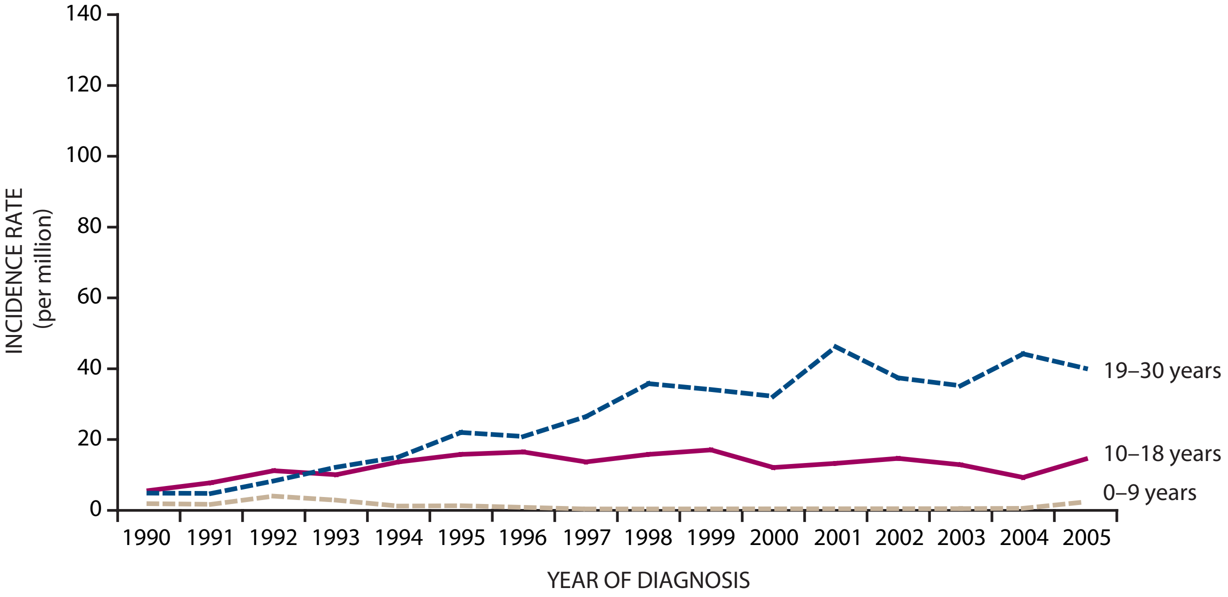


Figure D-XI. Thyroid cancer incidence rates for different age groups (age at diagnosis) of the total Belarusian male population

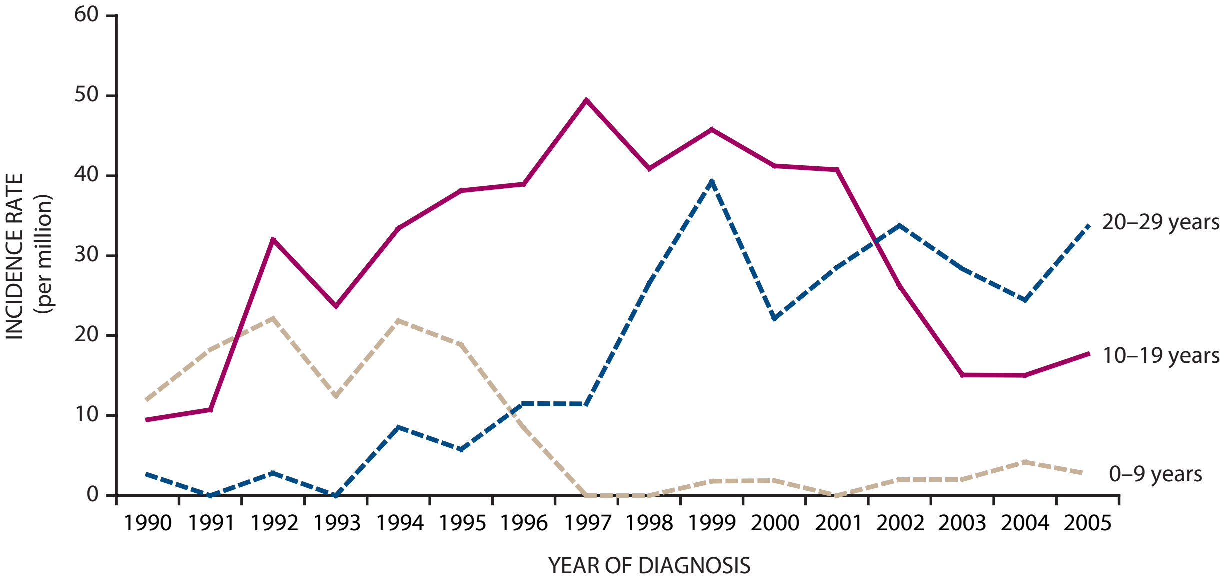


Figure D-XII. Thyroid cancer incidence rates for different age groups (age at diagnosis) of the Russian male population of the Bryansk, Kaluga, Orel and Tula oblasts

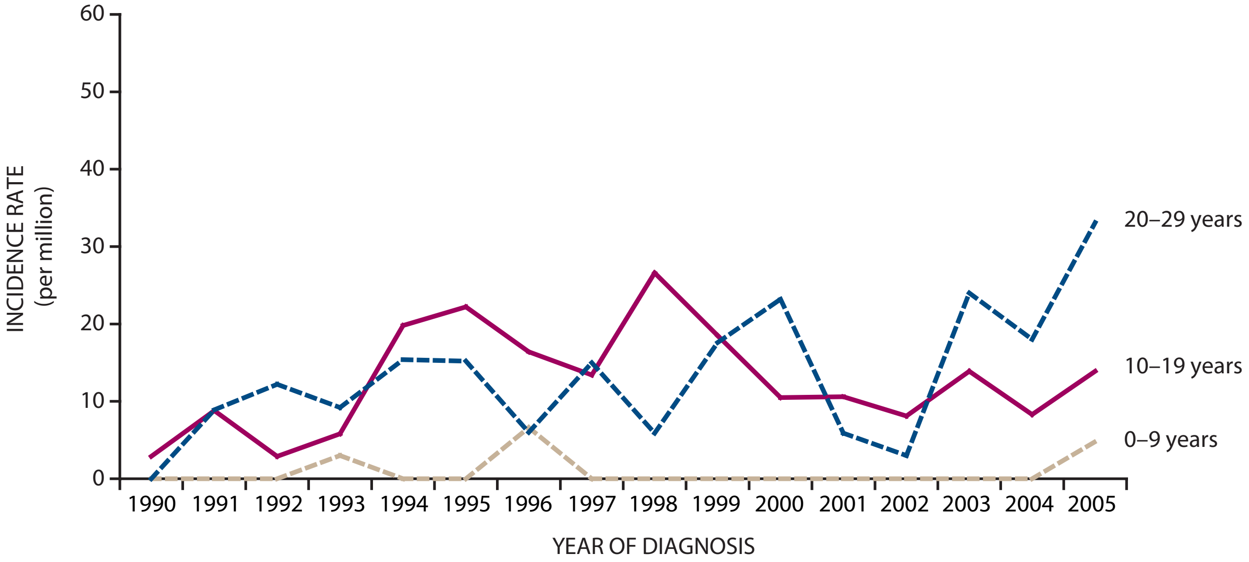


Figure D-XIII. Thyroid cancer incidence rates for different age groups (age at diagnosis) of the total Ukrainian male population

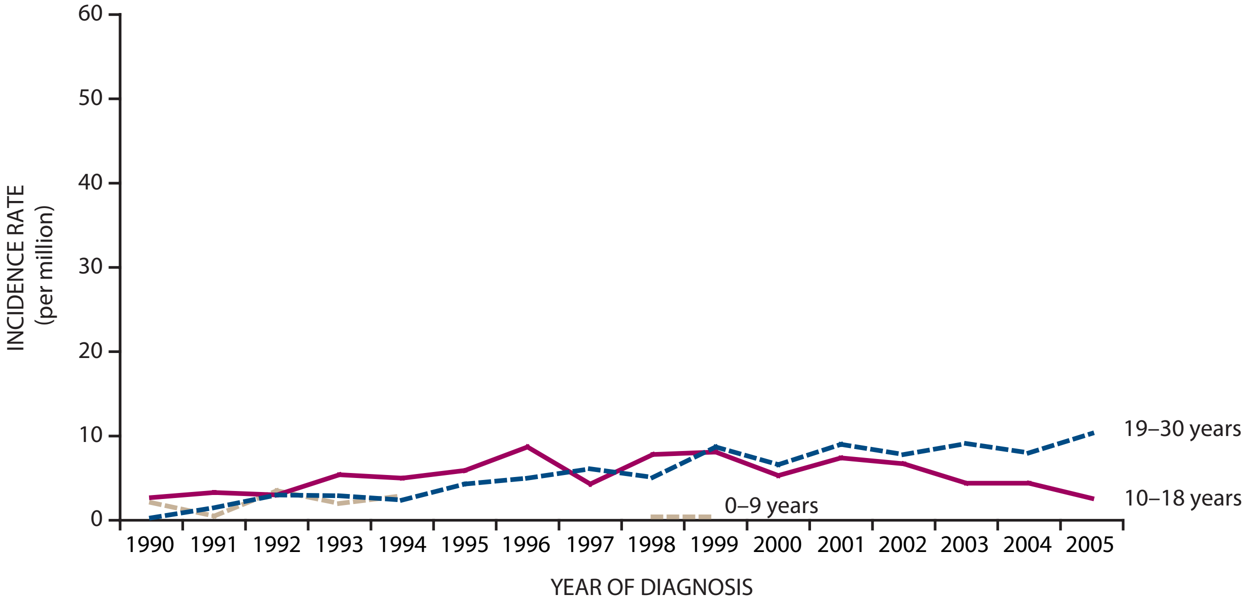


Figure D-XIV. Change in the proportion of papillary carcinoma subtypes with time after the accident

PTC SF = Solid/follicular subtype (Ukraine); PTC CP = Subtype composed mainly of papillae

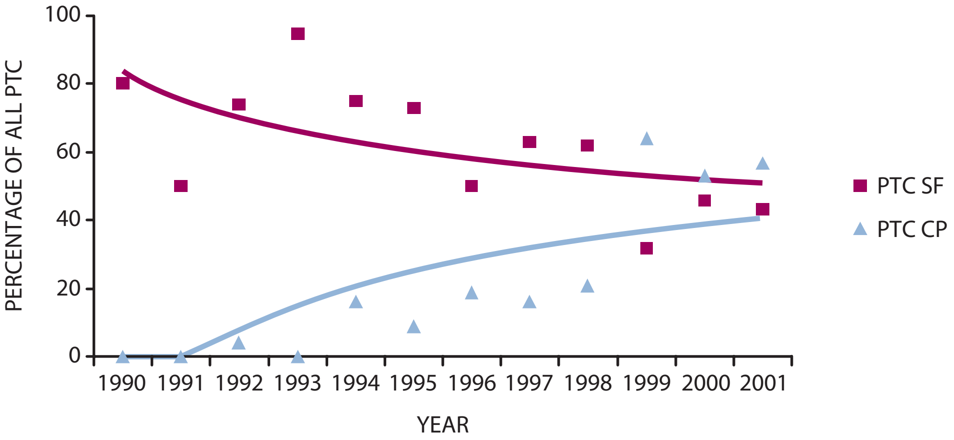
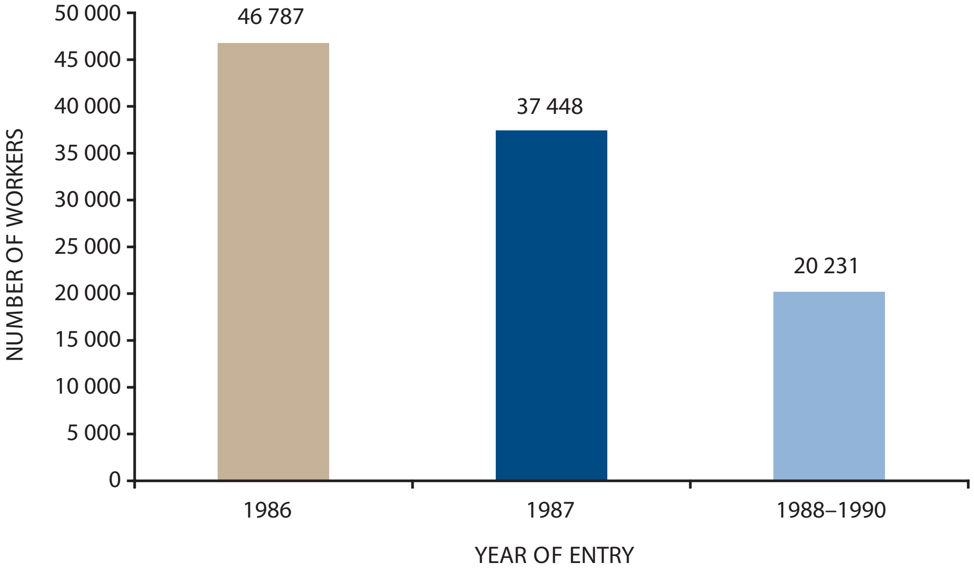


Figure D-XV. Distribution of Russian emergency and recovery operation workers by year of entry into the 30-km zone



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ANNEX E

EFFECTS OF IONIZING RADIATION ON NON-HUMAN BIOTA

CONTENTS

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INTRODUCTION

A. Background

1. The estimation of human exposure to ionizing radiation from radionuclides of natural and artificial origin is an important and ongoing function of the Committee. The Committee has used simplified generic models of the dispersion and transfer of radionuclides through the environment to estimate the internal and external exposure of humans and the resulting doses. Owing to the complexity and interactions of the underlying processes, special attention has been given to radionuclide transfer via human food chains and the assessment of ingestion doses. The underlying model assumptions and parameters are kept under review and revised as necessary. The last revision was documented by the Committee in annex A, "Dose assessment methodologies" of the UNSCEAR 2000 Report [U3].

2. In the past decades, scientific and regulatory activities related to radiation protection focused on the radiation exposure of humans. The prevailing view has been that, if humans were adequately protected, then "other living things are also likely to be sufficiently protected" [I8] or "other species are not put at risk" [I5]. Over time, the general validity of this view has been questioned on occasion and therefore consideration has been given to the potential effects of exposure to ionizing radiation of non-human biota. This has occurred, in part, as a result of the increased worldwide concern over the sustainability of the environment, including the need to maintain biodiversity and protect habitats and endangered species [U22, U23]; in part, because it has increasingly been recognized that the exposure scenarios and pathways for assessing human exposure may not apply to non-human biota; and, in part, as a result of various efforts to assess the effects of exposure to ionizing radiation on plants and animals [C1, D1, F5, I1, I2, I3, I4, I9, N6, P13, R9, T1, W16].

3. The Committee initially addressed the effects of radiation exposure on plant and animal communities in a scientific annex, "Effects of radiation on the environment", of the UNSCEAR 1996 Report [U4]. Prior to this, the Committee had considered living organisms primarily as part of the environment in which radionuclides of natural or artificial origin may be present and contribute to the internal exposure of humans via the food chain. Like man, however, organisms are themselves exposed internally to radiation from radionuclides that have been taken up from the environment and externally to radiation in their habitat. In general terms, the Committee, in its 1996 report, considered that population-level effects were of primary interest and, of those, that reproductive effects were the most sensitive indicator of harm. Furthermore, it also concluded that it was unlikely that radiation exposures causing only minor effects on the most exposed individual member of a population would have significant effects at the population level; that chronic exposures to low-LET radiation at dose rates of less than 100 mGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal populations; and that maximum dose rates of 400 mGy/h to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effects at the population level.

4. The International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA) and other international organizations have encouraged the exchange of information on the effects of radiation exposure on non-human biota [I19, N6]. The IAEA's action plan on the protection of the environment was discussed at the 2003 Stockholm Conference [I1], which concluded that "While accepting that there remain significant gaps in knowledge and that there needs to be continuing research … there was an adequate knowledge base to proceed and (the Conference) strongly supported the development of a framework for environmental radiation protection". It also found that "the time is ripe for launching a number of international initiatives to consolidate the present approach to controlling radioactive discharges to the environment by taking explicit account of the protection of species other than humans".

5. In 2000, the ICRP, recognizing that environmental protection is a global matter, set up a Task Group to examine the issues. It considered that an approach to environmental protection from ionizing radiation "should relate as closely as possible to the current system for human radiological protection, and that these joint objectives could therefore best be met by the development of a limited number of Reference Animals and Plants" [I9]. Subsequently, the ICRP decided to establish a new Committee (ICRP Committee 5) on the Protection of the Environment. The ICRP further noted that "as radiation effects at the population level—or higher—are mediated via effects on individuals of that population, it seems appropriate to focus on radiation effects on the individual for the purpose of developing a framework of radiological assessment that can be generally applied to environmental issues" [I10].

6. Since the preparation of the UNSCEAR 1996 Report [U4], the approaches to evaluating radiation doses to non-human biota have been reviewed and improvements made [C1, E1, F1, F5, U26]. Information on the levels of radiation

exposure below which biological effects are not expected or, alternatively, above which such effects might be expected, has been developed. This has been obtained, in part, for the projects on the Framework for Assessment of Environmental Impact (FASSET) [F1] and the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) [E1], in particular, as part of the development of the FASSET Radiation Effects Database (FRED) [F3]. This information was subsequently integrated with the database on the effects of radiation exposure from the project on Environmental Protection from Ionising Contaminants in the Arctic (EPIC) [B26] resulting in the so-called FREDERICA database [F20].

B. Scope of annex

7. The scientific information given in the FRED [F20] combined with that obtained in the subsequent ERICA programme [G11, J6] and that from more recent studies, especially those undertaken around the site of the Chernobyl accident, provided the basis for the Committee's review of the effects of exposure to ionizing radiation on non-human biota given in this annex. In particular, the Committee used the information from its review to re-evaluate its recommendations on dose rates below which exposure to ionizing radiation is unlikely to result in detrimental effects on populations of non-human biota, given in the UNSCEAR 1996 Report [U4].

8. This annex only provides the Committee's overview of the current data and methods to assess doses to non-human biota and a brief discussion of the nature of effects of radiation exposure on individual organisms and populations. Detailed discussion of these topics is beyond the scope of this annex.

C. Effects of exposure to ionizing radiation

9. Since the preparation of the UNSCEAR 1996 Report [U4], a number of radiobiological phenomena have been described, including genomic instability (genomic damage expressed post irradiation after many cell cycles) and the bystander effect (whereby non-irradiated cells in proximity to irradiated cells exhibit effects similar to those seen in the irradiated cells). These phenomena were discussed in annex C, "Non-targeted and delayed effects of exposure to ionizing radiation", of the UNSCEAR 2006 Report [U1]. While such phenomena are relevant to understanding mechanisms for the development of effects on non-human biota after exposure to ionizing radiation, a discussion of such phenomena is beyond the scope of this annex.

10. The immediate effects of ionizing radiation exposure may be seen at various levels of organization from the subcellular through individual organisms to populations and ecosystems [G16]. Responses of various biological functions to radiation exposure (e.g. reproductive success, metabolic impairment and changes in genetic diversity) can be traced to events at the cellular or subcellular level in specific tissues or organs.

1. Individual level effects

11. Even though mutational events in somatic cells are primarily responsible for cellular transformation and tumour formation, the occurrence of cancer in individual organisms is normally of low relevance to the ecosystem as a whole, except in the case of endangered or protected species [A13]. However, mutational effects in germ cells may lead to reproductive impairment [A14]. Genotoxic stressors, including ionizing radiation, may alter reproductive success by decreasing fertility via clastogenic and mutagenic effects in germ cells resulting in a decrease of the number of gametes. Such stressors may also increase the frequency of developmental abnormalities, e.g. when mutations are induced in germ cells and the progeny of exposed parents develop abnormally.

12. There are a number of weaknesses in the data on which to base estimates of the dose rates below which effects on non-human biota are not considered likely. In addition, there are also issues in extrapolating from the effects observed at cellular and subcellular levels to effects that might be observed in individual organisms, populations and ecosystems. Moreover, it is only under controlled conditions in the laboratory that organisms can be exposed to a single stressor. This presents a further source of uncertainty in extrapolating the results to real ecosystems where multiple stressors exist. Although beyond the scope of this annex, the Committee acknowledges that improved understanding of the mechanisms of radiation damage, of how to extrapolate information from lower to higher trophic levels, and of the possible consequences of multiple stressors is of great interest and worthy of further study.

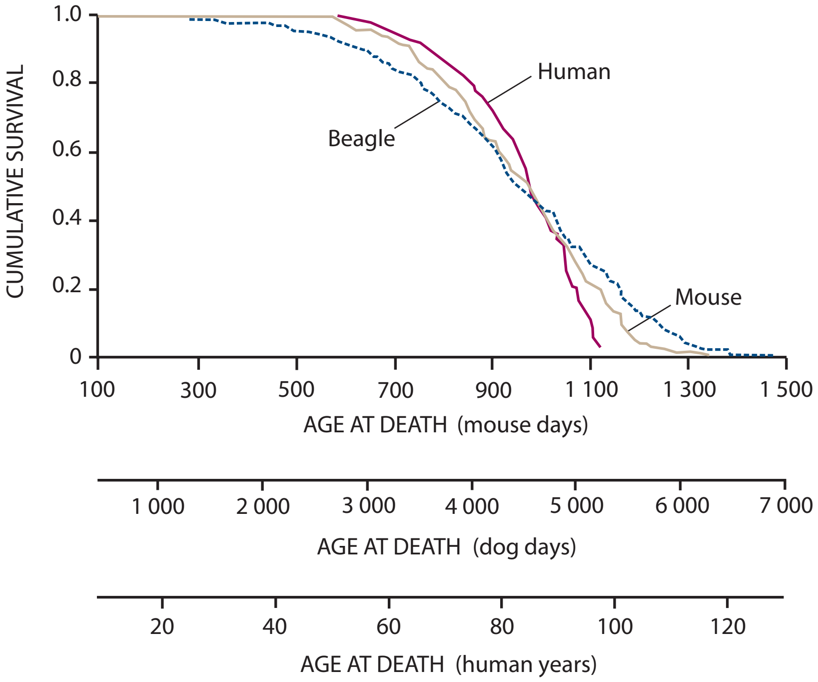
13. The scientific literature provides many examples of adaptive responses to and hormetic effects of exposure to ionizing radiation. Annex B of the UNSCEAR 1994 Report [U5] provided a comprehensive discussion of adaptive responses. In that report, the Committee concluded that there was evidence of an adaptive response in selected cellular processes following exposure to low doses of low-LET radiation but went on to suggest that it was premature to conclude that adaptive cellular responses had beneficial effects that outweighed the harmful effects of exposure. Subsequent to the UNSCEAR 1994 Report [U5], there have been numerous papers and considerable discussion concerning the possibility of hormetic responses to low doses of gamma radiation. For example, Boonstra et al. [B39] reported possible hormetic effects of gamma radiation exposure on populations of meadow voles. These authors suggested that increases in glucocorticoid levels associated with chronic gamma irradiation at a rate of about 1 mGy/d may be an important factor in the increased longevity of exposed meadow voles compared to non-exposed ones. Mitchel et al.

[M9] found that a single dose of 10 mGy to radiation-sensitive mice (Trp53 heterozygous) reduced the risk of both lymphoma and spinal osteosarcoma by greatly delaying the onset of malignancy. Further discussion of adaptive responses and potential hormetic effects of low dose and low dose-rate gamma radiation exposure is beyond the scope of this annex.

14. The various life stages of organisms differ in their sensitivity to exposure to ionizing radiation. It is often assumed that a population will be protected if the most sensitive stage of the life cycle is protected. For a large number of stressors, this assumption seems to be widely true [F9]. However, the most sensitive life stage is often difficult to identify a priori. Consequently, if data on effects only exist for one or two life stages, it may not be possible to know for certain if these data represent information for the most sensitive life stage, even though most of the available information indicates that gametogenesis and embryonic development are among the most radiosensitive stages of the life cycle [I4]. For example, Anderson and Harrison [A15] showed that the synchronous spawning in polychaete worms rendered the organisms susceptible to low-level cumulative impact of ionizing radiation exposure. Because they spawned synchronously and died, oocytes were formed all at once, and damaged gametes could not be replaced.

15. The propagation of effects on individuals to the population as a whole depends greatly on the characteristics of the specific life history. The relative importance of each stage in the life history also varies between species, depending on the specific reproductive characteristics (short generation time versus long generation time, iteroparous versus semelparous, sexual versus asexual reproduction, etc.). Changes in the value of an individual parameter such as age of reproduction (i.e. generation time) often have much stronger consequences for species with fast population growth rates (i.e. with short generation time and high fecundity rate) than for those with slow population growth rates [G3]. On the other hand, the National Council of Radiation Protection and Measurements (NCRP) [N8] noted that when natural causes of deaths are considered collectively on a biologically comparable time scale, natural mortality occurs at a biologically comparable age, as illustrated in figure I.

Figure I. Cumulative survival curves of the mouse, beagle and human for natural causes of death



2. Population and ecosystem level effects

16. Whatever the stressor considered, population-level effects are valuable indicators of ecological hazard (e.g. [F9]). However, because of experimental constraints, most available data describe the effects on the individual traits of irradiated organisms. Many studies have documented the effects of radiation exposure at the cellular, tissue and individual levels. The consequences have been found to be increases in morbidity and mortality, decreases in fertility and fecundity, and increases in mutation rate [W10]. These types of effect, observed at the individual level, may have consequences for a population of a species.

17. Matson et al. [M12] and Baker et al. [B29] investigated the possible genetic and population effects resulting from the chronic radiation exposure of bank voles, *Clethrionomys glareolus*, inhabiting contaminated sites near Chernobyl.

Both groups reported that genetic diversity was elevated in the contaminated sites when compared to relatively uncontaminated sites but were unable to attribute any significant detrimental effects among the bank vole populations to radiation exposure.

18. Ionizing radiation does not appear to have any direct effects at the population or higher ecological levels (i.e. community or structure and function of ecosystems). At present, it appears that all such effects are mediated by effects at the individual or lower levels. In addition, indirect effects through food-web mediated processes may occur [G16]. One approach to extrapolating from the effects on individuals to effects at the population level is to integrate the effects on survival and reproduction in terms of population growth rate. Population growth rate is one of the most important characteristics of a population and is defined as the population increase per unit time divided by the number of individuals in the population. Population models are used to extrapolate from the toxic effects on individuals, expressed as modifications to values of life-cycle parameters, to effects at the population level. This method has been used, for example, by Woodhead [W10] in a theoretical way and was implemented through experiments within the ERICA project for the chronic exposure of two invertebrates exhibiting contrasting life cycles: the earthworm and the daphnid [A26, G3].

19. An ecosystem has complex interactions between biotic and abiotic components and among biotic components. The latter are called interspecific interactions and include competition, predation and association. These interactions contribute to the flow or cycle of energy, materials and information in the ecosystem, and thus provide the ecosystem with its fundamental property of self-organization. It is possible that if one species is directly damaged by a toxic agent, another species more resistant to that agent is also indirectly affected by the depletion of interactions with the directly damaged species. As a result, the entire ecosystem can be affected in extreme cases. These indirect effects have been observed in ecosystems exposed to ultraviolet radiation [B37] and some chemicals [C23, H24, M24, T24, W20]. Similarly, some indirect effects through inter-species interactions have been observed in irradiated ecosystems, as reviewed in the UNSCEAR 1996 Report [U4]. Given this backdrop, the importance of indirect effects has been considered in reviews of the effects of exposure to ionizing radiation on ecosystems [B38, C21, I2, I3, I4, N1, U4]. Since these indirect effects cannot necessarily be deduced from effects on individuals and populations, ecosystem-level effects are evaluated using mathematical modelling, model ecosystem experiments and field irradiation experiments.

3. Multiple stressors

20. In general terms, the modifying effects of multiple stressors can be considered in one of two broad categories, namely *(a)* the modification by the other stressors of the organism's uptake of radioactive material and the distribution of radioactive material within the organism, and *(b)* the influence of the other stressors on the radiosensitivity of the species [A18, B28, F5, G18, L8, P9, R19, S17, S18].

21. Metabolic manifestations of exposure to ionizing radiation include impairment in enzyme function, altered protein turnover, impairment in general metabolism and inhibition of growth. Sugg et al. [S17] showed that the body condition of largemouth bass exposed to mercury and ^{137}Cs in different lakes near the Savannah River site could be related to DNA damage. Changes in lipid metabolism in fish liver and a stimulation of the ventilation rate of a lamellibranch species have also been shown to occur at low doses in this mixed exposure scenario [P22, P23].

22. Experiments involving multiple exposures to metals (cadmium and zinc), organic pollutants, such as polychlorinated biphenyl (PCB), polycyclic aromatic hydrocarbon (PAH), endocrine disruptors, and radionuclides (radioactive isotopes of cobalt, caesium, and silver) have been conducted both under controlled conditions and in the field [G17]. Experiments using a freshwater bivalve (*Dreissena polymorpha*) and a carnivorous fish (*Oncorhynchus mykiss*) exposed under chronic conditions to water containing concentrations of 1–4 µg/L of cadmium and/or 170–250 µg/L of zinc showed a 60% decrease in the bioaccumulation of the isotopes of silver and caesium in the bivalve and a 30% decrease in the fish. However, no effect was observed for other radionuclide/organism pairs (such as cobalt for the fish). On the other hand, prior exposure to organic micropollutants enhanced both the uptake and retention of ^{57}Co and ^{134}Cs in the fish. Several possible explanations, linked to a modification of the health status of the animal by the presence of stable pollutants, were advanced by the authors and supported by biomarker measurements: an increase in respiratory activity by alteration of the global metabolism; a decrease in the Na^+/K^+-ATPase in gills and therefore modification of the ionic flux; or an alteration of the epithelium permeability [A16, A17, F15].

23. Genotoxic/cytotoxic damages are not specific to ionizing radiation and may also be initiated by other toxins [S18]. Indeed, most biochemical techniques for detecting DNA damage at the molecular or cellular level lack specificity for radiation-induced DNA damage [T9]. However, Tsytsugina [T8] and Tsytsugina and Polikarpov [T6] analysed the distribution of chromosome aberrations in cells and the frequency of the different types of aberrations in order to discriminate between the contributions of radiation and chemical factors to the total damage to natural populations in aquatic organisms. These studies showed that the chromosome damage observed in aquatic worm populations exposed to dose rates of 10 µGy/h or more in lakes located in the vicinity of the site of the Chernobyl accident was mainly caused by radioactive contamination. Hinton and Bréchignac [H20], however, cautioned that, while there is a great potential value in using biomarkers for assessing risks to non-human biota, there remain many challenges in linking changes in biomarkers at

the molecular or cellular levels to effects on individual organisms and populations of organisms.

24. The antioxidant status modified by exposure to various stressors may influence the radiosensitivity of organisms. The cellular damage due to radiation exposure is mainly associated with oxidation. This oxidative stress may also be caused by other stressors, such as chemical pollutants, and cellular defence mechanisms against reactive oxidative species (ROS) that may be solicited are not stressor specific [S27]. Therefore, the interaction of heavy metals and radionuclides, and the resulting modification of radiosensitivity, may depend on the capability of the antioxidant defence systems of the organism [C13, C14, C15, S27, V1].

25. The potential effects of exposure to uranium in the environment may arise from the chemical toxicity of the metal and its radiotoxicity (arising from the uranium alpha particles) and thus, such situations can be regarded as being due to a mixture of stressors coming from a single element [B30, C19, P24]. Thus, while an evaluation of the chemical toxicity of uranium to non-human biota is beyond the scope of this annex, it is important to recognize that the chemical toxicity and the radiological effects of uranium occur concurrently, and that both may need to be considered in a practical assessment of risks to non-human biota.

4. Commentary

26. Most of the data on the effects of exposure to ionizing radiation on non-human biota are from observations made on individual organisms. Radiation effects on populations occur as a result of the exposure of individual organisms. The propagation of effects from individual organisms to populations is complex and depends on a number of factors. However, as suggested in the UNSCEAR 1996 Report [U4], the most important effects appear to be those on reproduction and reproductive success. Many questions remain with respect to the following: the mechanisms whereby radiation exposure can cause harm; inter-species extrapolation; propagation of harm from nuclear DNA to the population; and the effects of multiple stressors. Moreover the possibility of hormetic effects at low doses and dose rates of gamma radiation, the relation between changes in biomarkers at the molecular and cellular level and the effects on individual organisms or populations of organisms, and the effects of multiple stressors continue to be of considerable interest.

D. Observations from case studies

27. Ecological risk assessments (ERAs) have been conducted for a wide variety of situations where non-human biota are exposed to enhanced levels of radiation or radioactive material. ERA studies are available for a wide variety of nuclear fuel cycle activities from uranium mining to waste management, as well as for sites with enhanced levels of naturally occurring radioactive materials, and for sites contaminated as a result of accidents. Table 1 outlines the key elements of an ERA framework for assessing the effects of exposure to ionizing radiation on non-human biota. Various approaches for performing ERAs have been outlined including those of the IAEA [I2, I3, I4], NCRP [N1], the United States Department of Energy (DOE) [U26], Jones et al. [J1], Environment Canada and Health Canada [E2], FASSET [F1, L4] and ERICA [B17]. All of the approaches necessarily involve simplifications of the knowledge about the actual environment. A common approach to the assessment of the effects of radiation exposure on non-human biota involves the use of a screening index (*SI*), where *SI* is simply a dimensionless ratio of the estimated dose rate (to an individual organism) to the reference radiation dose rate, viz.:

$$SI = \frac{\text{estimated dose rate}}{\text{reference dose rate}} \qquad (1)$$

Table 1. Key elements of a framework for the assessment of the effects of radiation exposure on non-human biota

Element	*Considerations*
Exposure of biota	• Spatial and temporal patterns of radionuclide concentrations in environmental material • Uptake by organism • Non-uniform distribution within organism
Reference biota	• Not possible to evaluate all biota • Need to select reference biota or indicator species appropriate for area of interest and desirable basis for selection • Possible need to consider individual biota per se when species are endangered
Dosimetry model for (reference) biota	• Absorbed dose (to whole body or to tissue/organ) • Geometry corrections • Relative biological effectiveness (RBE): the effects of different qualities of radiation on biota
Endpoints in radiological assessment	• Selection of appropriate population-level (deterministic) “umbrella” effects such as mortality or reproductive capacity and corresponding reference doses
Effects on biota	• Connection between radiation effects on “umbrella” endpoint in individual, and consequent “possible” effects on population • Role of background radiation levels • Natural population variability

28. The reference dose rate refers to the chronic dose rate (commonly expressed in milligray per day) below which potential effects on populations of organisms are not expected. The ratio, *SI*, assumes that the estimated dose rate and the reference dose rate relate to the same endpoint (e.g. mortality, reproductive capacity). The estimation of dose rate to an individual organism is discussed in section I of this annex. As there are many complex factors involved, caution is needed in extrapolating from the effects of radiation exposure on an individual organism to those on a population of organisms [B17].

29. The reference radiation dose rates for particular endpoints developed by the Committee in the UNSCEAR 1996 Report [U4] have been the most commonly used for the denominator of the *SI* calculation. However, other guidance has also been developed [C1, E1, E2, F5, I4, N1] and, more recently, the concept of species sensitivity distributions (SSDs) has been introduced [B17, G3]. These developments may necessitate a re-evaluation of the reference dose rates obtained in the ERA case studies.

30. Because of the sparsity of peer-reviewed literature, all of the various sources of information on reference dose rates (e.g. various reports and supporting environmental assessments in Canada, technical reports of government agencies in various countries and conference proceedings) have been considered in this annex.

31. Of the numerous reports [A24, A25, B17, C1, C2, C20, C22, E2, E3, E5, E22, E23, F2, G2, G3, G27, J2, S10, S11, S32, S33, U26, W19], only a few provide studies of the radiation exposure of non-human biota arising from radioactive waste management activities or accidents involving dose rates close to or exceeding the reference dose rates [A25, E8, E22]. For example, one study [S39] which involved investigation of the risks to biota from exposure to ionizing radiation from nuclear fuel cycle activities in Canada concluded that the largest risk is associated with past uranium mining activities; that discharges of radioactive material from power reactors under normal operating conditions are not expected to cause environmental harm; that organisms within one of the waste management areas examined may be harmed by exposure to ionizing radiation; and that current radioactive discharges from uranium refineries and conversion plants are not expected to cause environmental harm. Similar results can be derived from a consideration of the case studies reported in ERICA [B17] of a wide variety of nuclear fuel cycle and other activities.

32. One study in which the estimated dose rates to biota exceeded the reference dose rates, at least over a limited area, was of the radioactive waste management site at the Chalk River Laboratories (CRL) located on the shore of the Ottawa River, 160 km north-west of Ottawa, Ontario, Canada [E23]. The CRL site was established in the mid-1940s and has a history of various nuclear operations and facilities, primarily related to research. An ERA was conducted to assess the doses to biota arising from elevated levels of tritium, ^{14}C, ^{41}Ar, ^{90}Sr, ^{131}I, ^{137}Cs and ^{239}Pu and from radionuclides that are naturally present in the environment, for example, the uranium series radionuclides, using standard methods for evaluating the uptake of these radionuclides by biota from the affected aquatic and terrestrial environments [B12]. A reference dose rate of 1 mGy/d was used for all organisms [B36]. Dose rates to some aquatic organisms such as frogs, small fish, snails and aquatic plants within the on-site waste management areas were estimated to be above the reference dose rate of 1 mGy/d; however, outside of the actual waste management areas, dose rates were estimated to be below the reference dose rate. The main contributor to the estimated dose rates to invertebrates and terrestrial plants was ^{90}Sr in surface soil, while that to the woodchuck (estimated at 51 mGy/d) was inhalation in the burrow of ^{222}Rn decay products from background levels of ^{226}Ra in the soil. A few individual invertebrates and terrestrial plants actually within the confines of small on-site waste management facilities were also estimated to have been subjected to dose rates above 1 mGy/d. Based on the limited spatial extent of the estimated dose rates that exceeded the reference dose rate and environmental observations, the authors considered that significant effects at the population level were unlikely.

33. Much of the new information on the effects of exposure to ionizing radiation on organisms has arisen from studies in the area surrounding the site of the Chernobyl accident, where dose rates to organisms were above the reference dose rate suggested in the UNSCEAR 1996 Report [U4]. A summary of the results of these studies up to 1996 is provided in this annex. Section III of this annex provides a comprehensive review of the more recent data from studies of non-human biota in the area surrounding the site of the Chernobyl accident.

E. Structure of this annex

34. The prime purpose of this annex is to build on the information reported in the UNSCEAR 1996 Report [U4]; to compile data that has since become available on the effects of exposure to ionizing radiation on non-human biota; and to determine if the reference dose rates need to be updated. However, it is necessary first to provide some general information on the relationships between the levels of radiation in the environment in which the biota live and the consequent dose (or dose rate) to biota as a whole or selected tissues and organs. Table 1 provides a summary of five key elements that form the basis for assessing the effects of exposure to ionizing radiation on non-human biota.

35. The relationships between the levels of radiation exposure and the activity concentration of radioactive material in the environment and the dose to an organism living in that environment is the subject of section I.

36. Section II provides a summary of the information considered in the UNSCEAR 1996 Report [U4] and the key observations from that report.

37. Section III provides an overview of the findings of the studies of non-human biota in the area surrounding the site of the Chernobyl accident. It includes the work of the Chernobyl Forum [E8].

38. Section IV provides a summary of the effects of exposure to ionizing radiation on non-human biota derived from the material given in earlier sections and reviews carried out by other scientific organizations and groups, namely, the IAEA [I4], Bird et al. [B1], the DOE [J1, U26], Environment Canada and Health Canada [E2], Canada's former Advisory Committee on Radiological Protection (ACRP) [A1], the UK Environment Agency [C1], the FASSET group [F1, F5, L1, L4], and the ERICA group [E1, G11, G15]. The published literature was also reviewed.

39. Section V provides an overall summary of the data reviewed and, based on these data, the Committee's evaluation of the dose rates below which effects on non-human biota are not considered likely. A few important areas for potential future study are also noted.

I. ESTIMATING DOSES TO NON-HUMAN BIOTA

40. Data on the effects of radiation exposure on non-human biota have been obtained from experimental studies carried out in the laboratory and in the field. Additional data have been obtained from the results of studies on environments with elevated levels of radiation or of radioactive material resulting from normal operations of nuclear facilities, waste management activities, or accidents. The interpretation of the results of these studies requires an understanding of the relationship between the levels of radiation and the activity concentrations of radionuclides in the various environmental media in which the organism resides, the consequent dose rate to an organism (or a tissue or organ of the organism) that lives in the environment, and the biological effect of interest. For example, radionuclides in the ambient environment may lead to external irradiation and internal irradiation as a result of radionuclides being taken into the organism via inhalation, ingestion, or uptake through its skin or membrane. Empirically determined concentration factors and transfer factors are commonly used to estimate contaminant concentrations in the organism (e.g. expressed for wet or dry weight in units of Bq/kg) from concentrations in the ambient environment (e.g. expressed in units of Bq/kg for sediment or soil, or Bq/L for water). Dosimetric models can then be used to derive, for selected organisms, dose conversion coefficients (DCCs) that relate ambient concentrations to internal or external exposure, as appropriate, and hence to dose.

A. Assessing exposures of biota

1. Choice of reference organisms

41. In view of the enormous variety of living organisms, it would be impossible to consider all species of flora and fauna as part of an environmental impact assessment even for a limited area. Instead, a concept has been developed involving the selection of reference organisms that are representative of large components of common ecosystems and for which models are adopted for the purpose of deriving doses and dose rates to organisms, tissues, or organs from radionuclides in the environment. The results of such dose assessments for these predefined reference organisms will allow a basic assessment to be made concerning the possible biological effects. This approach provides a strategy that allows the modelling effort to be reduced to a manageable level. It further provides information on the exposures of different organisms under varying exposure conditions, which allows the estimation of the impacts on those components of the environment for which data may be sparse or absent.

42. The reference organism approach of the ICRP had its genesis in some earlier publications [P6, P13]. In the framework of the FASSET project [F20, L4], reference organisms were defined as "a series of entities that provide a basis for the estimation of radiation dose rate". The idea was that these organisms would provide a basis for assessing the doses to organisms and consequential effects in general due to radionuclides in the environment. The main criterion for the selection of reference organisms within the FASSET project was that the habitats and feeding habits should be such that the external and internal exposures are maximized.

43. The ICRP is assembling databases that relate to a limited number of "reference animals and plants". These are defined as "hypothetical entities with the assumed basic characteristics of a specific type of animal or plant, as described to the generality of the taxonomic level of family, with defined anatomical, physiological, and life-history properties that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism" [I12].

44. Both the FASSET and the ICRP approaches were intended to simplify the process of estimation and evaluation of exposures to ionizing radiation of non-human biota. Whereas reference organisms in FASSET were specifically selected for different ecosystems (e.g. agricultural, semi-natural, freshwater, and marine), ICRP [I10] described the reference animals and plants in groups (family or taxonomic level). The reference organisms selected cover a range of ecosystems and taxonomic families (table 2). The generic (reference) organisms that are explicitly considered in this annex are summarized in table 2. Organisms similar to those adopted by the ICRP were selected for consistency. The features of the selected organisms are described in reference [I10].

Table 2. Comparison of reference organisms defined by different international bodies

Defined by	*Reference organisms*
FASSET Terrestrial ecosystems [L1]	Soil microorganisms Soil invertebrates Plants and fungi Bryophytes Grasses, herbs and crops Shrubs Above ground invertebrate Burrowing mammal Herbivorous mammals Carnivorous mammals Reptile Vertebrate eggs Amphibians Birds Trees
FASSET Aquatic ecosystems [L1]	Benthic bacteria Benthic invertebrates Molluscs Crustaceans Vascular plants Amphibians Fish Fish eggs Wading birds Sea mammals Phytoplankton Zooplankton Macroalgae
ICRP Proposal on Reference Animals and Plants [I10]	Deer Rat Duck Frog Trout Flatfish Bee Crab Earthworm Pine tree Wild grass Brown seaweed
This annex	Earthworm/soil invertebrate Rat/burrowing mammal Bee/above ground invertebrate Wild grass/grasses, herbs and crops Pine tree/tree Deer/herbivorous mammal Duck/bird Frog/amphibian Brown seaweed/macroalgae Trout/pelagic fish Flatfish/benthic fish Crab/crustaceans

2. Radioecological models

45. Three classes of radioecological model can be distinguished and are presented here in terms of increasing complexity—equilibrium models, dynamic models and research models.

46. Equilibrium models are primarily intended for the assessment of exposures due to routine discharges of radioactive material into air or water. They are based on two fundamental assumptions: *(a)* the emission rates of the radionuclides are constant in time; and *(b)* the duration of the discharges is long compared to the time needed for radionuclide transfer

along the environmental pathways considered. With these assumptions, the radionuclide concentrations reach equilibrium within each of the compartments into which the environment is subdivided for modelling purposes, and the transfers between compartments are easily characterized by time-invariant ratios of concentrations between the acceptor and donor compartments.

47. Since equilibrium radionuclide concentrations in the environment are typically attained after considerably long operational times of a nuclear facility, the equilibrium models are likely to give conservative exposure estimates. This type of radioecological model has been used to determine compliance of routine discharges from nuclear facilities with authorized limits [H4, I11, N3, U3].

48. Ciffroy et al. [C22] tested the influence of the time-dependence assumption frequently used in radioecological models in a case study conducted on the Loire River in France. For routine discharges of radionuclides from nuclear power plants, their main conclusions were that: *(a)* attention must be paid to the temporal variations in the discharges, and gaps between actual instantaneous discharges and maximum discharges on a yearly time scale must be analysed; *(b)* the equilibrium assumption at the water-suspended matter interface must be justified and eventually corrected when equilibrium conditions are not expected; and *(c)* for organisms showing slow uptake/elimination rates, a kinetic approach to the bioaccumulation process can avoid some overestimation of radionuclide concentrations. The assumption of equilibrium led to overestimations of one to two orders of magnitude in predicting ^{60}Co concentrations in invertebrates.

49. A number of inherent advantages have contributed to the proliferation of equilibrium models. The model structure can be kept simple, but there is flexibility to allow more detailed structure, if necessary. Under equilibrium conditions, dispersion of trace amounts of radionuclides in the atmosphere or rivers is adequately represented by analytical solutions of more general physical models; transfer via food chains is represented by simple multiplicative chains of concentration ratios.

50. A major conceptual limitation of radioecological models is that many of the parameters involved (e.g. concentration ratios) have to be established empirically. Experience gained during recent decades has amply demonstrated that numerical values of many of these parameters may vary by several orders of magnitude; this has been well documented, for example, for plant–soil relationships of radiocaesium and radiostrontium concentrations [F7, F8, N4]. While for the purposes of screening or environmental protection as may be established by the ICRP or required by a national regulator, representative parameter values can be selected that ensure that the model assessments are conservative, obvious difficulties exist if a realistic assessment of exposures in specific ecosystems is needed.

51. Dynamic radioecological models [M4, S13, W3] are applied if the time dependence of exposures that result from varying or instantaneous releases has to be taken into account. Examples of their use include the assessment of the time-dependent radionuclide concentrations in the environment, such as those resulting from accidental radionuclide releases varying over time, and the simulation of seasonal effects, which are of major importance in terrestrial environments during the first year following deposition of radionuclides after an accidental release [M7].

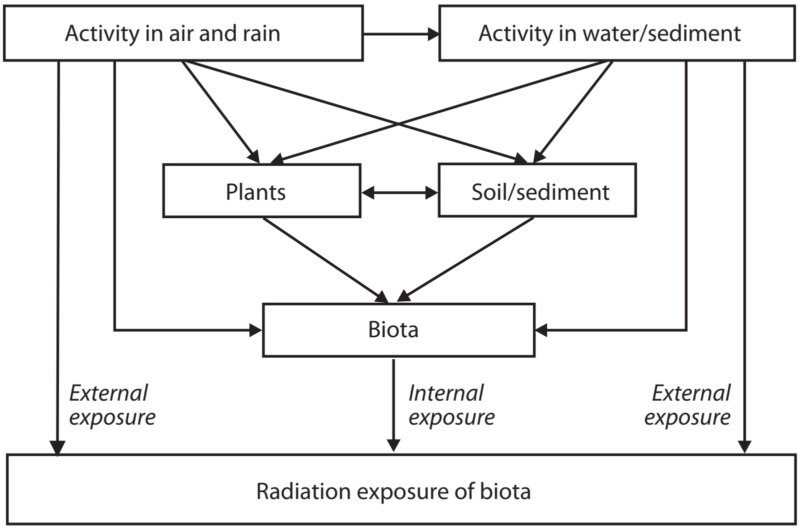
52. Research models are characterized by a high degree of complexity and longer computation times, and presently are limited to simulating a few of the important processes in analyses of environmental pathways for radionuclides [C7, P9]. Currently, therefore, they do not offer an alternative to equilibrium and dynamic radioecological models for environmental assessments, although they do constitute an important tool for improving understanding of the sources of variability observed empirically.

53. The scope of this annex is limited to providing a broad overview of the approach to estimating radiation exposure and subsequent doses to non-human biota. The reader interested in these topics is referred to the extensive literature. Exposure assessments are generally based on equilibrium models. However, for case studies at specific locations contaminated by accidental releases of radionuclides, information on the levels of exposure of local biota taken from the literature is sometimes based on simulations using dynamic radioecological models.

3. Transfer of radionuclides in the environment and resulting exposures

54. The major pathways of radiation exposure of biota in the environment are summarized in figure II. In this schematic representation, the physical components of the terrestrial environment are air, soil and sediment; the biological components include plants, invertebrates, and vertebrates (mammals, birds, reptiles, and land-based amphibians). The physical components of the freshwater aquatic environment include streams, rivers, lakes and sediments; the biological components are phytoplankton, zooplankton, macroinvertebrates, sessile aquatic plants and vertebrates (fish, water-based amphibians and some aquatic mammals). In a marine environment, the physical components include tidal zones, coastal waters and marine sediments; and the biological components include phytoplankton, zooplankton, macroinvertebrates, sessile aquatic plants, and vertebrates (fish and marine mammals), molluscs, crustaceans and marine birds. The terrestrial and aquatic environments are not totally separate. Some birds and terrestrial mammals eat fish and shellfish; moose and waterfowl feed on aquatic plants; and terrestrial animals ingest drinking water from the aquatic environment.

Figure II. Major environmental transfer routes for evaluating radiation exposure of biota



55. The total radiation dose received by an organism (or some organ or tissue of the organism) is the sum of the contributions from both external and internal exposure. External exposure results from complex non-linear interactions of various factors, such as the levels of the radionuclides in the habitat, the geometrical relationships between the radiation source and the target, the shielding properties of the materials in the environment, the size of the organism and the radionuclide-specific decay properties (characterized by the type and energy of the radiations emitted and their emission probabilities).

56. Internal exposure is determined by the activity concentrations of the radionuclides in the organism, the size of the organism, the radionuclide distributions within the organism and the specific decay properties of the radionuclides. In addition, the relative biological effectivenesses (RBE) of alpha, beta and gamma radiation need to be taken into account in assessing the consequences of the exposure.

B. Transfer of radionuclides in the terrestrial environment

57. Radioactive material released into the atmosphere is dispersed and transported by the wind. Exposures of biota are calculated from the activity concentrations of radionuclides in the environmental media, such as air, soils and vegetation, and in the organisms under consideration. The principal processes involved in the transport of radionuclides in the terrestrial environment include dry deposition, wet deposition, interception by vegetation, loss of radionuclides from plants due to weathering, resuspension, the systemic transport of radionuclides within plants, uptake from soil, run-off to water bodies and the transfer to animals. This section discusses the factors that affect the behaviour of radionuclides in a terrestrial environment and the uptake of radionuclides from the environment to plants and animals.

1. Dry deposition

58. Dry deposition per unit time is proportional to the near-surface concentration of the material in air. Usually, the dry deposition of a radionuclide from the atmosphere to soil and vegetation is expressed in terms of the deposition velocity, v_g (m/s), which is defined as the ratio of the activity deposition rate per unit area and the local activity concentration in air of the radionuclide at a reference height. This empirical quantity depends on a variety of factors such as the size of any associated particles, the characteristics of the surface–air interface, the meteorological conditions and the chemical form of the radionuclide.

59. Typical estimates of deposition velocities for grass and forests are summarized in table 3. These values are used for the calculation of the exposures of biota resulting from the atmospheric release of radionuclides.

Table 3. Typical estimates of deposition velocities for grass and forest [P14, R11]

Chemical/physical form	*Deposition velocity (m/s)*			
	Grass	*Forest*[a]		
		Crown	*Trunk*	*Soil*
Particles, 0.1–1 μm	0.001	0.005	0.000 5	0.000 8–0.003
Elemental iodine	0.01	0.05	0.005	0.006–0.02
Methyl iodide	0.000 1	0.000 5	0.000 05	0.000 08–0.000 3

[a] Coniferous trees and deciduous trees with fully developed foliage.

2. Interception of radionuclides deposited from the air

60. Interception defines the fraction of radioactivity deposited by wet and dry deposition processes that is initially retained by the plant. There are several possible ways to quantify the interception of deposited radionuclides. The simplest is the interception fraction, *f*, which is defined as the ratio of the activity initially retained by the standing vegetation, $A_{i,}$ immediately subsequent to the deposition event to the total activity deposited. A full description of the interception process is beyond the scope of this annex and the reader interested in this topic is referred to the extensive literature (e.g. see reference [H26]).

61. Radioactive material in air can be washed out by rain and snow. A fraction of the radionuclides deposited with precipitation is retained by the vegetation, and the rest falls through the canopy to the ground. Although the radioactive material retained eventually transfers to soil through weathering and is retained only temporarily by vegetation, the fraction initially intercepted is important owing to the fact that the concentration of radioactive material will be at its highest at this time. Interception of wet deposits is the result of a complex interaction of the amount of rainfall, the chemical and physical form of the deposit and the actual stage of development of the plant [M4] and thus, interception fractions for a single event may vary from 0 to 1.

62. To account for its dependence on biomass in some models, the interception of wet deposited activity is modelled as a function of the biomass density, according to the approach of Chamberlain [C8]. The chemical form is a key factor; since the plant surface is negatively charged, the absorption of anions is less effective than that of cations [H6, H7, K4, M4, P11]. Differences between plants seem to be of minor importance compared to those between radionuclides, e.g. the interception of polyvalent cations is higher than that for anions by as much as a factor of 8 [H5]. However, in general, for the estimation of interception following the routine discharge of radioactive material, very simple approaches are used in the models [P10]. Anspaugh [A22] suggested a default value for the interception fraction of the order of 0.3 for all elements, plants and precipitation events for routine discharges of radionuclides.

3. Weathering

63. Following deposition on vegetation, radionuclides are removed by wind and rain. In addition, the increase of biomass during growth leads to a reduction in the activity concentration. Since growth is subject to seasonal variations, the post-deposition reduction of the activity concentration of radionuclides in plants depends on the season. These processes of reduction in the activity concentration of radionuclides in plants occur simultaneously after deposition. As it is difficult to quantify the exact contribution of each process, the net reduction in the activity concentration with time is usually called “weathering” and expressed by the empirical weathering half-time, T_w.

64. The chemical form of the contaminant seems to be of minor importance in weathering. After the Chernobyl accident, the median weathering half-times observed for iodine and caesium on grass were approximately 8 and 10 days, respectively [K5]. Shorter half-times were observed primarily in regions with fast growing vegetation, while longer half-times were found in Scandinavia, where the growth rates were lower because of the later spring in the area [K5]. In general, longer weathering half-times are observed for slowly growing or dormant vegetation [M8].

65. In forests, weathering is more complex because of the canopy structure, which comprises several vegetation layers, such as crown, trunk and understorey vegetation. Radionuclides lost from the crown may be retained by the understorey vegetation, thus reducing the overall loss rate of radionuclides from vegetation to soil.

4. Distribution of radionuclides within plants

66. The currently available dosimetric models for the assessment of the exposure of biota do not take into account heterogeneous radionuclide distributions within plants. Hence, any information on these distributions cannot currently be used in the assessment.

5. Uptake of radionuclides from soil

67. Soil is the main reservoir for long-lived radionuclides deposited on terrestrial ecosystems. The behaviour of radionuclides in

soils controls their migration in soil, the possible transport to groundwater, and the long-term radionuclide concentration in vegetation and thus the exposure of soil organisms. As for all minerals, the uptake of radionuclides by plants mainly takes place via dissolution from soil. The concentration of radionuclides in soil solutions is the result of complex physical–chemical interactions with the soil matrix, with ion exchange being the dominant mechanism. Ion exchange by its very nature is a competitive mechanism. The concentrations and composition of the major competing elements present in soil thus are of primary importance in determining the distribution of radionuclides between soil, soil solution and plant roots (which are able to influence the microspace in their vicinity in order to provide and maintain conditions that favour the uptake of nutrients) [E6].

68. The physical chemistry of sorption and desorption of radionuclides in the soil–soil solution system and their possible uptake by plants are the result of complex interactions between soil type, pH, redox potential, sorption capacity, clay content, content of organic matter and soil management practice. Although these factors are qualitatively known, they are difficult either to quantify or to integrate into a universal model applicable to a wide range of soil conditions. Consequently, the approaches used include classifying the transfer according to soil types (e.g. peat, sand, loam and clay) and other physical and chemical parameters. In addition, various biological factors should be considered, especially whether or not the radionuclide is an essential element.

69. For the quantification of the root uptake of radionuclides, empirically derived (aggregated and greatly simplified) parameters—soil–plant transfer factors or concentration ratios—are usually applied despite their inherent limitations [E6]. In this case, these parameters are the ratios of the activity concentrations in the plant to those in the soil within the uppermost layer of a standardized thickness. Transfer factors were originally defined for agricultural ecosystems within which radionuclides are distributed homogeneously within the rooting depth of agricultural plants because of ploughing.

70. The aggregated transfer factor is defined as the activity concentration of a radionuclide in a material (Bq/kg) divided by the total deposition—activity per unit area (Bq/m^2)—at equilibrium. The concept of aggregated transfer factors was developed as a simplification of detailed physical and chemical processes to a single value, inter alia, to avoid difficulties with determining radionuclide concentrations in soils with a multi-layered structure, such as in forests.

71. Alternatively, concentration ratios that relate to the activity concentrations of radionuclides in specific soil horizons exploited by the mycelium or the root system were proposed in the late 1980s and proved to be useful, especially in connection with the prediction of the transfer of ^{137}Cs to fungi [G4, R8, Y1, Y4, Y5].

72. Illustrative ranges of soil–plant transfer factors for a number of elements are summarized in table 4 [T11]. This table shows that the uptake of caesium from soil usually does not result in a simple proportional accumulation in plants. Radiocaesium is effectively sorbed by micaceous clay minerals that are present in almost all soils in varying amounts. A detailed compilation of soil–plant transfer factors including data for specific plant groups, plant organs and soil types can be found elsewhere [I14].

Table 4. Typical ranges of soil–plant transfer factors [T11]

Element	*Concentration ratio Bq/kg plant (d.m.) per Bq/kg soil (d.m.)*	*Aggregated transfer factor*[a] *Bq/kg plant (d.m.) per Bq/m^2 soil*
Sr	0.01–1	4×10^{-5}–4×10^{-3}
Cs	0.001–0.1	4×10^{-6}–4×10^{-4}
Cs[b]	0.1–10	4×10^{-4}–4×10^{-2}
I	0.001–1	4×10^{-6}–4×10^{-3}
Tc	0.1–10	4×10^{-4}–4×10^{-2}
Pb	0.001–0.01	4×10^{-6}–4×10^{-5}
Ra	0.001–0.1	4×10^{-6}–4×10^{-4}
U	0.001–0.1	4×10^{-6}–4×10^{-4}
Np	0.001–0.1	4×10^{-6}–4×10^{-4}
Pu	10^{-5}–10^{-3}	4×10^{-8}–4×10^{-6}
Am	10^{-5}–10^{-3}	4×10^{-8}–4×10^{-6}
Cm	10^{-5}–10^{-3}	4×10^{-8}–4×10^{-6}

[a] Calculated from the concentration ratio assuming a mass density for dry matter (d.m.) in the soil rooting zone of 280 kg/m^2 taking account of the mass of the soil within the rooting zone.

[b] Observed range in natural and semi-natural ecosystems on acid sandy soils poor in potassium.

73. Caesium uptake is particularly high from organic soils with a low pH and pronounced potassium deficits [F11]. Such soils are frequently found in the Russian Federation, Belarus and Ukraine, as well as in Scandinavia, the upland areas of the UK and the alpine areas of Europe. For organic matter, the cation exchange capacity decreases with increasing acidity owing to the saturation of carboxyl groups with hydrogen ions. Furthermore, the availability of caesium for uptake is enhanced in soils that are poor in potassium. Additionally, the clay content of organic soils is low and this prevents strong sorption and leads to persistently high caesium levels in plants [A7, F12, F13, K6]. Another important aspect is that the bioavailability of radionuclides and their uptake after deposition may change with time. This was observed in areas close to the site of the Chernobyl accident and was caused by the degradation of fuel particles, the fixation of caesium within the soil and changes in the sorption strength of the soil for caesium [N5, S14, S15].

74. In recent years, a number of experiments have been performed to determine soil–plant transfer factors for tropical and subtropical environments [C9, F11, R6, T12, T13, U24, U25, W12, W13]. The anaerobic soil conditions in flooded paddy fields change the solubility of some elements, such as I and Tc, and thus possibly their soil–plant transfer factors [M25, T26, Y3]. In general, however, the results do not indicate any systematic impact of climatic conditions on the transfer of radionuclides from soil to plants, although the numbers of data are still small. Further data on the tropical and subtropical environments are therefore needed [M25].

75. In forest ecosystems, the transfer of radionuclides from soil to plants and fungal fruit bodies depends on the depth profile of the radionuclides and the vertical distribution of fine roots and fungal mycelia in soil. At least in the case of fungi, the use of transfer factors referring explicitly to the soil layer exploited by fungal mycelia seems to be the best approach for quantifying the uptake to radionuclides, balancing overall simplicity with mechanistic considerations of the dynamic processes [S37]. However, the concentrations of radionuclides in understorey vegetation, trees and fungal fruit bodies can be estimated roughly in a simplified manner using aggregated transfer factors. The ranges of aggregated transfer factors given in table 5 summarize the available observations.

Table 5. Typical ranges of aggregated transfer factors for ^{137}Cs from soil to vegetation and fungal fruit bodies in forest ecosystems [A8, B27, G7, I16, I17, K15, L7, Z1]

Data are given on a dry weight basis unless otherwise noted

Species or genus	*TF_{agg} (Bq/kg organism (d.m.) per Bq/m^2 soil)*
Fungal fruit bodies	
Agaricus	0.002–0.007
Amanita	0.008–5
Armillaria	0.001–0.2
Boletus	0.001–10
Cantharellus	0.01–2
Clitocybe	0.01–2
Collybia	0.03–0.3
Coprinus	0.004[a]
Cortinarius	0.02–10
Hydnum	3[a]
Hygrophorus	0.2–7
Laccaria	0.4–10
Lactarius	0.006–5
Leccinum	0.005–0.9
Lepista	0.002[a]
Lycoperdon	0.009–0.5
Macrolepiota	0.000 7–0.1
Paxillus	0.01–5
Ramaria	0.05–0.6
Rozites	0.08–10
Russula	0.04–5
Sarcodon	0.3–0.4
Suillus	0.02–2
Tuber	0.000 3–0.008[b]
Xerocomus	0.002–7

Species or genus	*TF_{agg} (Bq/kg organism (d.m.) per Bq/m^2 soil)*
Understorey vegetation	
Rubus chamaemorus (cloudberry), fruit	0.002–0.2
Vaccinium vitis-idaea (lingonberry), fruit	0.03–0.07
Vaccinium myrtillus (bilberry), fruit	0.02–0.1
Rubus idaeus (raspberry), fruit	0.001–0.004
Fragaria vesca (strawberry), fruit	0.004–0.01
Rubus fruticosus (blackberry), fruit	0.006–0.05
Green parts of understorey vegetation, including the stems of berry plants	0.001–1
Trees	
Fagus sp. (beech)	
Bole wood	0.001–0.002
Leaves	0.002–0.003
Picea sp. (spruce)	
Bole wood	0.000 3–0.002
Needles	0.000 6–0.02
Pinus sp. (pine)	
Bole wood	0.000 2–0.003
Needles	0.001–0.04
Quercus sp. (oak)	
Bole wood	0.002–0.004
Leaves	0.008–0.01
Betula sp. (birch)	
Bole wood	0.000 03–0.001
Leaves	0.000 3–0.04
Populus sp. (aspen)	
Bole wood	0.000 5–0.002
Leaves	0.008[a]
Alnus sp. (alder)	
Bole wood	0.001[a]
Leaves	0.008[a]

[a] Only a single value available.

[b] Data are given on a fresh weight basis and refer to the top 10 cm of soil.

76. Fungi are able to accumulate radiocaesium in their fruit bodies [G14, H8]. Some species exhibit activity levels that exceed those of green plants by more than one order of magnitude. On average, the radiocaesium levels in symbiotic fungi are higher than those in saprophytic species [R7, Y4, Y5].

77. Radionuclides in growing wood originate from two sources: the initial atmospheric deposits that enter the plant by foliar absorption, and root uptake from the soil. Their relative contributions depend on the type of tree (coniferous versus deciduous) and the age [B20, E7, G5, H9], the season at the time of deposition and the time elapsed after deposition, with root uptake being the dominant pathway for growing wood in the long term. Transfer factors or concentration ratios that are calculated on the basis of the total content of radionuclides in wood inevitably include both uptake processes and therefore are likely to overestimate root uptake (table 5) [G5].

6. Migration in soil

78. Vertical migration of radionuclides in the soil column is driven by various transport mechanisms, such as convection, dispersion, diffusion and bioturbation. The long-term consequences of downward migration differ considerably, however, depending on the dominant mechanism. For convective-driven migration, for example, the radionuclide input due to the Chernobyl accident moves down the soil as a marked peak and shows broadening with time as a result of dispersive mixing. Convective transport of radionuclides usually dominates in soils showing high hydraulic conductivities, e.g. sandy soils. For further discussion of the importance of downward migration of radionuclides in soil and forest litters, see section III and the references cited.

79. For diffusive transport, the concentration is always at a maximum at the surface with a close to exponential decrease with depth. For this type of transport, which is typical in

soils of low hydraulic conductivity, the bulk of the radionuclides deposited from the atmosphere thus remains within the rooting zone of plants.

80. Agricultural practices have a major impact on radionuclide behaviour. Depending on the intensity and type of soil cultivation, mechanical redistribution of radionuclides may occur. This causes, in arable soils, a rather uniform distribution of radionuclides in the tilled horizon. Fertilization shifts the ratio of radionuclide to nutrient concentrations in soil and soil solution and thus may influence plant root uptake of the radionuclides [E6].

81. Some investigations indicate [B21, S16] that element-independent transport mechanisms, such as the transport of radionuclides attached to clay particles or soil colloids, may play a relevant role in determining the migration rate of radionuclides in soil. Furthermore, the activity of soil animals that cause a turnover of soil, e.g. earthworms, cannot be neglected. The authors of references [B21, S16] suggest that a value of 100 years for the default residence half-time for the upper 25 cm layer is adequate for all elements with low mobility, such as radium, lead, uranium, plutonium and americium. Iodine under aerobic conditions is strongly bound to organic matter and therefore a residence half-time of 100 years can also be assumed [K7]. On the other hand, iodine can be released from soil to soil solution under anaerobic conditions, such as in a flooded paddy field [M25].

82. The situation with forest soil is more complex owing to the more pronounced soil horizons. Radionuclides deposited directly onto forest soil or washed from the canopy and understorey vegetation initially infiltrate the soil rather rapidly. They are therefore initially assigned to a labile pool. In the long term, they will become immobilized through fungal or microbial activity or by mineral constituents of the soil. The radionuclides in the non-labile pool may be available for root uptake, e.g. via symbiotic fungi, but are assumed not to be leached to deeper soil layers. The rate of downward migration is correspondingly reduced considerably over time, and, in the organic horizons, is determined mainly by the rates of decomposition of the organic material, and litter accumulation. Subsequently, downward migration of radionuclides is rather slow and partially offset by upward translocation by fungal mycelia and roots [R4]. Fungal and microbiological activity is likely to contribute substantially to the long-term retention of radionuclides, notably radiocaesium, in organic layers of forest soil. In this phase, radiocaesium is well mixed and almost equilibrated with stable caesium within the biologically connected compartments [Y6]. When radionuclides reach the mineral horizons of forest soil, essentially the same processes may occur as in arable soils, e.g. radiocaesium can be fixed by micaceous clay minerals.

7. Resuspension

83. Resuspension refers to the removal of deposited material from the ground to atmosphere as a result of wind, traffic, soil cultivation and other activities. Potentially, resuspension is a persistent source of radionuclides in air subsequent to their deposition on the ground. Furthermore, it may lead to redistribution of radionuclides and their deposition onto clean surfaces. Resuspension is influenced by a variety of factors, such as the time since deposition, meteorological conditions, surface characteristics and human activities. For biota, resuspension is of low importance. For animals living in the soil, it is not relevant. The contribution of resuspension to the activity concentration of radionuclides in plants in humid ecosystems usually is negligible compared to that of dry deposition and interception [G6, H10].

8. Transfer to animals

84. The transfer of radionuclides to animals is usually estimated using element-dependent concentration ratios or transfer factors. The transfer factor is defined either as the ratio of the activity concentration in an organism or tissue and the intake rate under equilibrium conditions, or as the ratio of the activity concentration in an organism or tissue and the deposition density (activity per unit area). It is only applicable to an intake of a radionuclide by adult animals that is constant over long periods. To account for time-dependent (dynamic) intakes, one or more biological half-lives are considered [M4].

85. In recent decades, many data have been accumulated on the transfer factors for domestic animals. They depend on animal mass, performance level, feeding regimes and feed components. However, these data are not generally applicable to estimating activity concentrations in biota, since they were determined in order to estimate activity concentrations in animal products for human food (such as meat, milk and eggs) while this annex is concerned with the estimation of activity concentrations in whole animals. Furthermore, the application of transfer factors presumes knowledge of the feed intake as well as the activity concentrations of the feed components. It has been demonstrated that highly contaminated feed components may determine the activity levels of game, even if consumed in low quantities. The seasonal peak activity concentration of ^{137}Cs in roe deer, for example, has been attributed to the ingestion of mushrooms [Z1]. Fungal fruit bodies can show radiocaesium levels exceeding those of green plants by one order of magnitude or more. Wild boar ingest deer truffle (*Elaphomyces granulatus*), a preferred “delicacy”, which dominates the radiocaesium uptake, despite being only a few per cent of the boar’s total diet [F14, P12]. However, the relevant data are not available for wild animals in general.

86. In most cases, the activity concentrations of radionuclides in game are calculated in a simplified manner using aggregated transfer factors. This transfer factor neither takes into account the time-dependent intake rates nor can reproduce the time-dependent activity concentrations in game. Values for aggregated transfer factors for different species are compiled in table 6.

Table 6. Aggregated transfer factors (soil-to-game) for ^{137}Cs [A9, I16, J3, K8, S19, Z1]
Data are given on a fresh mass basis unless otherwise noted

Species	*TF_{agg} (Bq/kg organism (dry mass) per Bq/m^2 soil (dry mass))*	
	Default value	*Range of literature data*
Alces alces (moose)	0.02	0.006–0.03
Capreolus capreolus (roe deer)	0.05	0.001–0.2
Cervus elaphus (red deer)	0.03	0.02–0.04
Lepus arcticus (arctic hare)	0.03	0.009–0.1
Lepus capensis (brown hare)	0.004	0.002–0.05
Lynx lynx (lynx)	0.3	0.01–10[a]
Game except roe deer	0.02	

[a] Data are given on a dry weight basis.

87. Table 7 summarizes the equilibrium concentration ratios for the reference organisms considered. The values are "order-of-magnitude" estimates based on the compilation in reference [F4]. Some of the original values were given as aggregated transfer factors and have been converted to concentration ratios. At least in temperate environments, concentration ratios are higher in forest and semi-natural ecosystems than in agricultural systems, because of their often lower nutrient supply and pH values. Furthermore, the high content of organic matter in forests is accompanied by high concentrations of fulvic and humic acids, which act as complexing agents and increase the mobility of cationic radionuclides in soil.

88. The nominal values of transfer factors provided in table 7 have been suggested for use [E10, F4], in the absence of site-specific information, to estimate the exposure rates for biota after the release of radionuclides to atmosphere and their subsequent transfer to soil. As such, these transfer factors were intended to be applied for screening purposes to obtain an order of magnitude estimate, but they may not be appropriate for application to specific sites.

Table 7. Nominal values of transfer factors for reference organisms (adapted from [E10, F4])

Element	*Transfer factors (Bq/kg (fresh weight) per Bq/kg soil)*							
	Earthworm	*Rat*	*Deer*	*Duck*	*Frog*	*Bee*	*Grass*	*Pine tree*
H	150	150	150	150	150	150	150	150
Cl	0.2	7	7	7	7	0.3	20	1
Sr	0.01	2	2	0.6	1	0.06	0.2	0.5
Tc	0.4	0.4	0.4	0.4	0.4	0.4	20	0.3
I	0.2	0.4	0.4	0.4	0.4	0.3	0.1	0.1
Cs	0.09	3	3	0.8	0.6	0.06	0.7	0.2
Np	0.1	0.04	0.04	0.04	0.04	0.1	0.02	0.3
Pu	0.03	0.02	0.02	0.02	0.02	0.06	0.01	0.03
Am	0.1	0.04	0.04	0.04	0.04	0.1	0.005	0.000 1
Pb	0.03	0.04	0.04	0.06	0.1	0.06	0.07	0.08
Ra	0.09	0.03	0.03	0.04	0.04	0.04	0.04	0.000 7
Th	0.009	0.000 1	0.000 1	0.000 4	0.000 4	0.009	0.04	0.001
U	0.009	0.000 1	0.000 1	0.000 5	0.000 5	0.009	0.02	0.007

C. Transfer to freshwater organisms

89. Radionuclides can enter water bodies as a result of discharges to the aquatic environment (e.g. directly from a nuclear facility), by deposition of airborne radioactive material onto the water surface and by run-off of material deposited onto soil. For a point source of emission into a swiftly flowing stream, the flow rate of the stream can be divided by the flow rate of the effluent discharge to obtain the dilution factor. A certain mixing distance must be assumed, which could vary from a few tens of metres for a small stream to a few kilometres for a large river. Beyond the

mixing distance, a uniform concentration of the radionuclide in water can be assumed. Suspended material may be deposited as sediment. The deposited material may become locked in the sediments and, over time, migrate to deeper sediments or be redissolved by physical and biological processes and re-enter the water column. Dissolved or finely suspended material may be transported over large distances, being progressively diluted by water from other streams and rivers, eventually reaching the oceans.

90. The movement of radionuclides in rivers is often modelled using the diffusion–transport equation and the behaviour of radionuclides in the "water column–river bed sediment" system is often assessed using compartment models [M23]. At present, although the structures of the models have not been subjected to significant revisions, the scope of the transfers modelled (physical, chemical and biological) and of the associated radionuclide specific parameters has been considerably enlarged. For instance, the previous state-of-the-art publication of the IAEA, "Handbook of parameter values for the prediction of radionuclide transfer in temperate environments" [I16], listed solely values of water–sediment partition coefficients and concentration factors for edible portions of fish. The most recent version also incorporated equations and parameters for representing transfer by wash-off from watersheds of deposited radionuclides, interaction between liquid and solid phases, migration to and from sediments, and transfers to freshwater biota [I14].

91. The mixing of radionuclides discharged into a lake or pond is much slower than is the case for rivers. As a first approximation, a uniform radionuclide concentration throughout the pond could be assumed, with a dilution factor equal to the pond outflow rate divided by the effluent input rate. In a large lake or coastal environment, a uniform concentration would never be reached. Plume models have been developed for lake-shore environments analogous to atmospheric transport models. The lake-shore environment is often complicated by thermal layering within the water column, which impedes vertical mixing. Moreover, removal of material from the water column via sedimentation is an important long-term process which results in an approximately exponential decline with time of the radionuclide concentrations present in the water column.

92. Sedimentation and attachment to suspended particulates are the main processes influencing the residence times of radionuclides in freshwater. Fractions of dissolved and of particle-bound radionuclides are usually determined by the distribution coefficient, K_d, which is defined as the ratio of the radionuclide concentration in water and the concentration of the radionuclide attached to particulate matter, under equilibrium conditions. Values of K_d are element-dependent. Low K_d values and concentrations of suspended matter indicate high dissolved fractions, whereas high K_d values and suspended load values indicate a considerable sorption of radionuclides by particles and favour sedimentation. Once deposited, radionuclides may migrate down within the sediment or may become involved in resuspension processes. These processes may create additional sources or sinks with potential impact on the long-term behaviour. The distribution coefficients for various elements in freshwater are given in table 8.

Table 8. Distribution coefficients K_d in freshwater ecosystems [I14]

Element	*K_d (m^3/kg)*	
	Geometric mean	*Geometric standard deviation*
Be	42	3.6
Mn	130	12
Co	43	9.5
Sr	0.18	4.6
Ru	32	1.9
Ag	85	2.3
Sb	5	3.8
I	4.4	14
Cs	8.5	6.7
Ba	2	3.6
Ce	220	2.8
Th	180	21
Ra	7.4	3.1
Pu	240	6.6
Am	850	3.7

93. Aquatic organisms may be directly irradiated by radionuclides present in their habitats (e.g. water, sediment). They may also take up radionuclides from water and/or the food chain and incorporate them into their tissues. External irradiation of most aquatic organisms, with the exception of burrowing invertebrates and benthic organisms, is limited by the shielding provided by the surrounding water or sediment.

94. Considerable attention has been focused on fish because they are at a higher trophic level in aquatic food chains and serve as food for humans and predators. Polikarpov [P2] has given concentration ratios, CR, (CR here is the ratio of the activity concentration in fish expressed in units of Bq/kg and that in water expressed in units of Bq/L, under equilibrium conditions) for ^{137}Cs ranging from 500 to 9,500 L/kg for freshwater fish, compared to values of 3 to 25 L/kg for marine fish. The lower values for marine fish were thought to be as a result of the competition for uptake from potassium and other cations. Freshwater amphibians can also show high values of CR (1,000 to 8,000 L/kg) in the aqueous environment.

95. Table 9 gives values of CR for ^{137}Cs in fish in Canadian lakes in the Northwest Territories [L5] and for the upper Great Lakes [T15]. High trophic level fish such as trout, pike and cisco show an especially high accumulation of radiocaesium.

Table 9. Concentration ratios for ^{137}Cs in freshwater fish

Species	*Concentration ratio (L/kg)*	
	NWT Lakes [L5]	*Great Lakes [T15]*
Burbot	800	
Lake whitefish	400–1 000	
Round whitefish	1 000–1 800	
Sucker	700	1 500–2 500
Chub		1 900
Alewife		1 800–2 300
Bullhead		2 300
Cisco	1 600–5 000	
Pike		2 500–5 500
Lake trout	3 000–6 000	6 100

96. Swanson [S20] has summarized concentration ratios for water to fish tissues for the naturally occurring radionuclides of uranium, ^{226}Ra, ^{210}Pb, and ^{228}Th (table 10).

Table 10. Concentration ratios for natural radionuclides in freshwater fish [S20]

Element/ radionuclide	*Concentration ratio (L/kg)*					
	Bone	*Flesh*	*Liver*	*Kidney*	*Gonad*	*Gut*
U	20–800	0.1–25	$<$0.04–0.5	0.1–0.5	0.01–0.35	0.05–0.5
^{226}Ra	35–1 800	1–60	1–45	3–30	5–115	7–45
^{210}Pb	100–2 500	4–100	3–420	6–780	10–150	11–206
^{228}Th	15–160	4–32	4–36	5–46	13–50	23–50

D. Transfer of radionuclides to marine organisms

97. The main processes that modify the activity concentrations of radionuclides in marine water are *(a)* dilution due to convective and dispersive mixing during transport, driven by local, regional and global currents, *(b)* sedimentation after attachment to suspended particles and *(c)* radioactive decay.

98. For a given continuous discharge rate into a specific section of the marine system, the steady-state concentration of a dissolved radionuclide in water, C_w (Bq/m^3), can be calculated according to:

$$C_w = \frac{A}{V \cdot (\tau^{-1} + \lambda_r)} \cdot \frac{1}{1 + K_d \cdot S} \tag{2}$$

where A is the activity of the radionuclide discharged per unit time to a specific part of the sea (Bq/a), V is the volume of this part (m³), τ is the mean residence time *(a)*, λ_r is the radioactive decay constant (a^{-1}), K_d is the distribution coefficient (m³/kg), and S is the concentration of suspended particles (kg/m). The steady-state activity concentration of the radionuclide in suspended particles, C_s (Bq/kg), is then:

$$C_s = \frac{A}{V \cdot (\tau^{-1} + \lambda_r)} \cdot \frac{K_d}{1 + K_d \cdot S} \tag{3}$$

The distribution coefficients for a number of elements in marine waters are summarized in table 11.

Table 11. Distribution coefficients K_d for open ocean and ocean margins [I20]

Element	*K_d (m^3/kg)*	
	Open ocean	*Ocean margins*
H	0.001	0.001
Cl	0.001	0.000 3
Sr	0.2	0.008
Tc	0.1	0.1
I	0.2	0.07
Cs	2	4
Pb	1×10^4	1×10^2
Ra	4	2
Th	5×10^3	3×10^3
U	0.2	1
Np	1×10^2	1
Pu	2×10^3	1×10^2
Am	2×10^3	2×10^3

99. A value of 3 years was given in reference [U3] for the mean residence time, *t*, in a specified part of the marine system, for all radionuclides in coastal waters with the exception of ^{239}Pu, for which a value of 3.5 years was assumed. These values took account of radionuclide losses from water to sediment. From simulations of the transport of radionuclides discharged from the reprocessing plants at Sellafield and La Hague through the North Atlantic and its marginal seas, the mean residence times given in table 12 were estimated using the North Atlantic–Arctic Ocean Sea Ice Model (NAOSIM) [I21].

Table 12. Residence times in different parts of the North Atlantic according to the NAOSIM model

Part of ocean	*Volume (km^3)*	*Mean residence time (a)*
North Sea	41 000	2.5 ± 0.36
Norwegian Sea	59 000	0.37 ± 0.11
Barents Sea	220 000	2.4 ± 0.24
Kara Sea	38 000	4.5 ± 1.2
Central Nordic Seas	44 000	0.52 ± 0.18

100. As for freshwater aquatic biota, activity concentrations of radionuclides in marine biota can be estimated using a concentration ratio approach. Concentration ratios for various elements in marine biota are compiled in table 13. For most elements, these data are based on concentrations in muscle (fish) and soft tissue (crustaceans). For the bone seeking elements such as strontium, however, the entries in table 13 are based on whole body concentrations.

Table 13. Concentration ratios for marine biota [I20]

Element	*Concentration factors (L/kg fresh weight)*		
	Fish	*Macroalgae*	*Crustaceans*
H	1	1	1
Cl	0.06	0.05	0.06
Sr	3	10	10
Tc	80	30 000	1 000
I	9	10 000	100
Cs	100	50	30
Np	1	50	100
Pu	100	4 000	200
Am	100	8 000	400
Pb	200	1 000	9 000
Ra	100	100	100
Th	600	200	1 000
U	1	100	10

E. Evaluating doses to biota

1. Fraction of radiation absorbed by organism

101. Radionuclides distributed in the environment lead to external exposure of an organism living in or close to a medium that contains radionuclides. The external exposure of biota is the result of complex and non-linear interactions of various factors:

- The geometrical relation between the source of the radiation and the target;
- The activity levels of the radionuclides in the environment;
- The materials in the environment and their shielding properties;
- The radionuclide-specific decay properties characterized by the radiation type, the energies emitted and their emission probabilities; and
- The habitat and size of the organism.

102. The geometric relationship between the radiation source and the exposed organism is an important factor in relation to the absorbed dose rate incurred. The intensity of the radiation field around a source decreases with distance and is influenced by the material between the radiation source and the target. The number of possible source target configurations is infinite; therefore, a number of limited and representative situations need to be selected for detailed consideration.

103. The exposure due to radionuclides incorporated into the organism is determined by the activity concentrations in the organism, the size of the organism, and the type and the energy of the emitted radiation. A key quantity for estimating internal doses is the absorbed fraction of energy, $\phi(E)$, which is defined as the fraction of energy emitted by a radiation source that is absorbed within the target tissue, organ or organism. In the simplest case, the organism is assumed to be in an infinite homogeneous medium and to have a uniform activity concentration throughout its body. The densities of the medium and the organism's body are assumed to be identical. Under these conditions, both internal (D_{int}) and external (D_{ext}) dose conversion coefficients (DCCs; the DCC is defined as either the absorbed dose or the absorbed dose rate, according to the circumstances, per unit activity concentration of the relevant radionuclide in the organism or medium) for monoenergetic radiation can be expressed as a function of the absorbed fraction [N1, V2]:

$$D_{int} = E \cdot \phi(E) \quad \text{and} \quad D_{ext} = E \cdot \left(1 - \phi(E)\right) \qquad (4)$$

104. Absorbed fractions for photon and electron sources uniformly distributed in soft-tissue spherical bodies immersed in an infinite water medium have been systematically calculated by Monte Carlo simulation [U17]. The calculations covered a particle energy range of 10 keV to 5 MeV, a range for the mass of the body from 10^{-6} to 10^{3} kg, and shapes from spheres to ellipsoids with varying degrees of non-sphericity. Figures III and IV show, respectively, the results for electrons and photons.

Figure III. Absorbed fraction, $\phi(E)$, for electrons of different energy uniformly distributed in spheres of different mass in a water medium

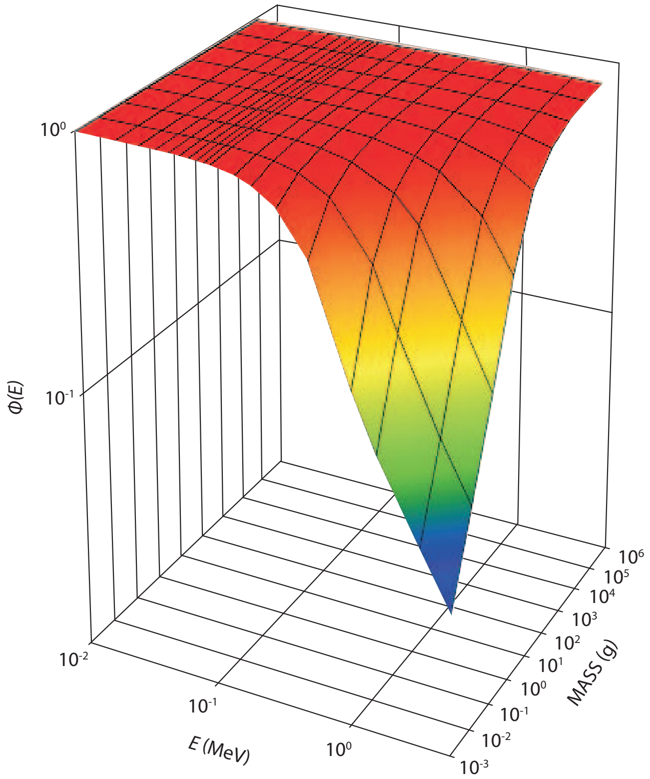
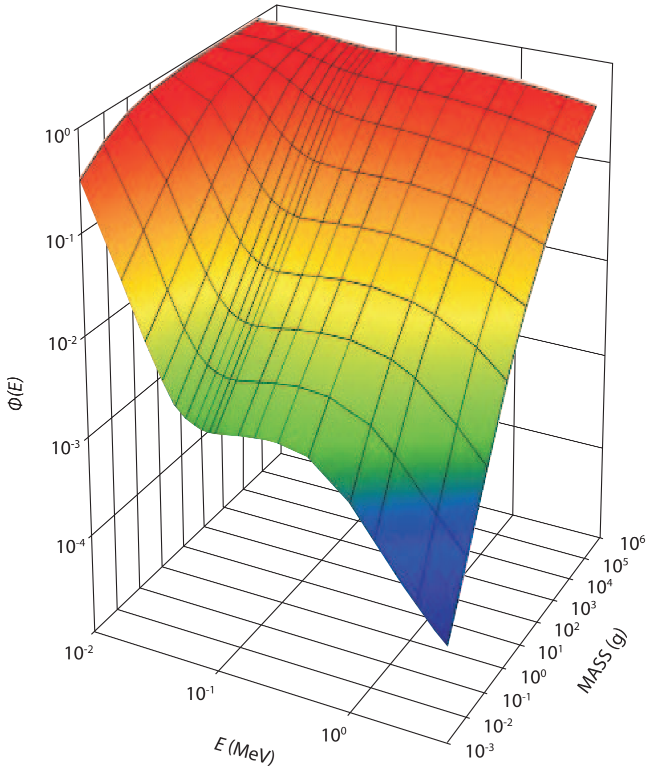


Figure IV. Absorbed fraction, $\phi(E)$, for photons of different energy uniformly distributed in spheres of different mass in a water medium



105. For electron energies below 100 keV, the absorbed fraction is close to unity, even for very small organisms. The mean free path of electrons in living tissue increases from 160 µm for 100 keV electrons to 5 mm for 1 MeV electrons. Thus, even above 100 keV, the absorbed fraction is close to unity if the diameter of the target is much greater than the range of the electron. Only for very small targets and high energies does the absorbed fraction become considerably smaller than 0.5.

106. The mean free path of photons is considerably longer than that of electrons. The absorbed fractions cover a range from nearly unity for low photon energies and large organisms to less than 0.0001 for small organisms and high photon energies. Absorption is a non-linear function of target size and energy. The main processes causing absorption of photon energy are the Compton effect, the photoelectric effect and pair production; their contributions to absorption depend on the energy of the emitted photons. As a result, the absorbed fraction of photons in the energy range from 20 to 100 keV decreases by a factor of 10–15 for small organisms, but is relatively constant for photons with energies between 100 keV and 1 MeV. Beyond energies of 1 MeV, the absorbed fraction decreases steeply with energy.

107. The range of alpha particles in living tissue is very short, increasing from 16–130 µm within the energy range of 3–10 MeV. Therefore, with the exception of bacteria, it is assumed for all organisms that all the energy emitted is absorbed. Since the dimensions of bacteria are well below the range of alpha particles, the absorbed fraction is assumed to be zero.

108. Re-scaling factors have been derived from the computed absorbed fractions for spheres to determine the dose coefficients for ellipsoidal shaped organisms, using the mass and proportions of the organism. The relationship between the re-scaling factors and the non-sphericity parameter of the organism's body are described analytically in reference [U17]. Owing to the short range of alpha particles, the internal exposure due to incorporated alpha emitters is independent of the shape of the organism.

109. The approach was also applied to the calculation of the absorbed fractions for non-aquatic animals and their internal exposures. With the use of the absorbed fractions for spheres and the suggested re-scaling and interpolation techniques, a set of internal DCCs has been calculated for all reference animals and plants [U17].

110. The estimation of external exposures of terrestrial reference animals and plants is more complex than that of biota in the aquatic environment. The intrinsically different density and composition of soil, air and organic matter cannot, in general, be adequately taken into account by the application of analytical solutions. Dosimetric models for estimating external doses to biota in the terrestrial environment were developed within the FASSET project [F4, T10]. A key factor for determining external exposure is the geometric

relationship between the radiation source and the exposed organism. A number of limited and representative exposure situations were selected for detailed consideration.

111. Simple three-dimensional phantoms, i.e. ellipsoids and cylinders, were defined as model geometric equivalents of reference organisms based on their average mass and size characteristics. The dimensions ranged from a millimetre to a metre and the respective masses range from 0.2 g to 550 kg. The ellipsoids represented organisms such as woodlouse, earthworm, mouse, mole, snake, fox, deer and cattle. Details of the assumed exposure conditions are given in reference [T10]. The fur and the outer layers of skin consist of non-active tissue, and therefore shield the living organism.

112. Herbaceous vegetation, shrubs and trees were considered as reference plants. Exposure of the meristem and buds was calculated because these organs are characterized by very intensive cell division, which may make them highly radiosensitive.

113. In order to take account of the distribution of radionuclides in the canopy, a distinction was made between alpha, beta and gamma radiation because of their different ranges. For gamma radiation, the whole canopy was considered to have a homogeneous activity concentration. For high-energy beta radiation, the irradiation of the target was also assumed to result from a canopy with a homogeneous activity concentration. However, owing to the much shorter range of alpha and low-energy beta radiation, the irradiation resulting from external deposits on, or internal activity of, the target organ had to be considered explicitly. Because of the very short range of alpha particles in air, only the exposure due to the external deposits on, or internal exposure of, the target needed to be taken into account [T10].

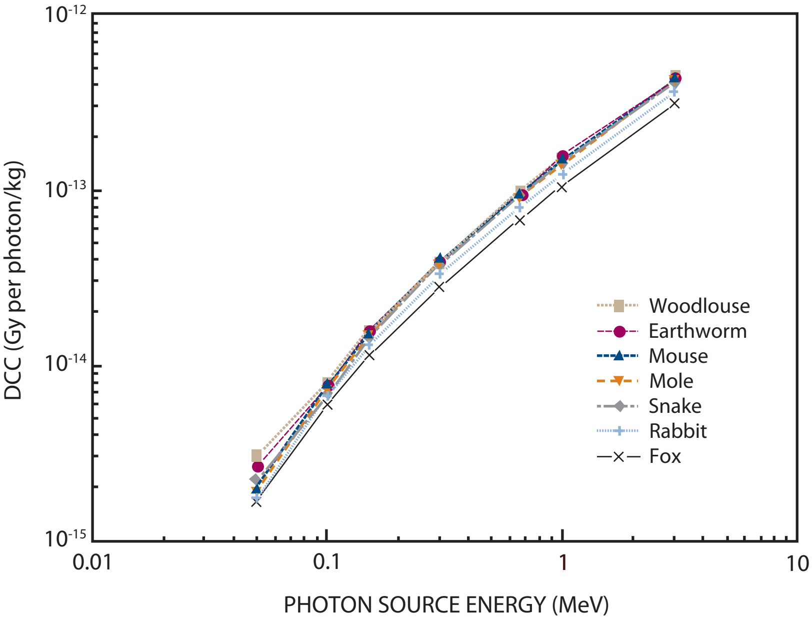
114. The elemental composition and density of the materials involved have an important impact on the radiation transport calculation. All organisms were assumed to be composed of skeletal muscle alone with the characteristics/parameters given in reference [I15]. The DCCs were derived using Monte-Carlo techniques; all relevant processes of radiation transport and interaction with matter were included. For electrons, a thick-target bremsstrahlung model was used instead of an electron-transport simulation. For the calculation of DCCs for a species in the soil, a volume source with uniform activity concentration was assumed. For the calculation of DCCs for a species on the ground, a planar radiation source on top of the soil with a surface roughness of 3 mm and a volume source with a depth of 10 cm were assumed. Calculations were made for monoenergetic gamma energies of 50 keV, 300 keV, 662 keV, 1 MeV and 3 MeV. Data for other energies were obtained by interpolation.

2. Principal relationships for internal and external exposure

(a) External exposure

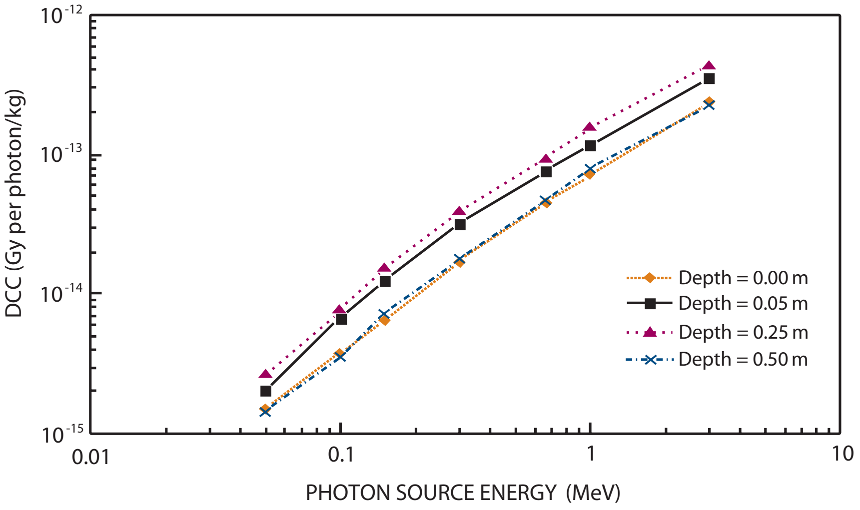
115. Although the simulations cover only a limited number of possible exposure conditions, they allow the relationships between organism size, radiation energy and habitat to be deduced. The DCC (Gy per photon per kg) increases in proportion to the photon energy as illustrated in figure V for a volumetric source with a thickness of 0.5 m and target organisms that live at a depth of 0.25 m. Whereas the DCCs vary by a factor of 200 between photon energies of 50 keV to 3 MeV, the variation between the organisms does not exceed a factor of 2, even for low-energy photons (for high-energy photons, the difference is a factor of only 1.5).

Figure V. Dose conversion coefficients for various soil organisms at a soil depth of 25 cm, for monoenergetic photons from a uniformly distributed source in the upper 50 cm of soil (soil density: 1,600 kg/m³) [F4]



116. The DCC (Gy per photon per kg) for an earthworm as a function of soil depth for monoenergetic photons is shown in figure VI. The upper 50 cm of the soil was assumed to have a homogeneous activity concentration. The maximum DCC was found to be at a depth of 25 cm and the lowest, at depths of 0 cm and 50 cm. The maximum DCC is a factor of 2 higher than the lowest.

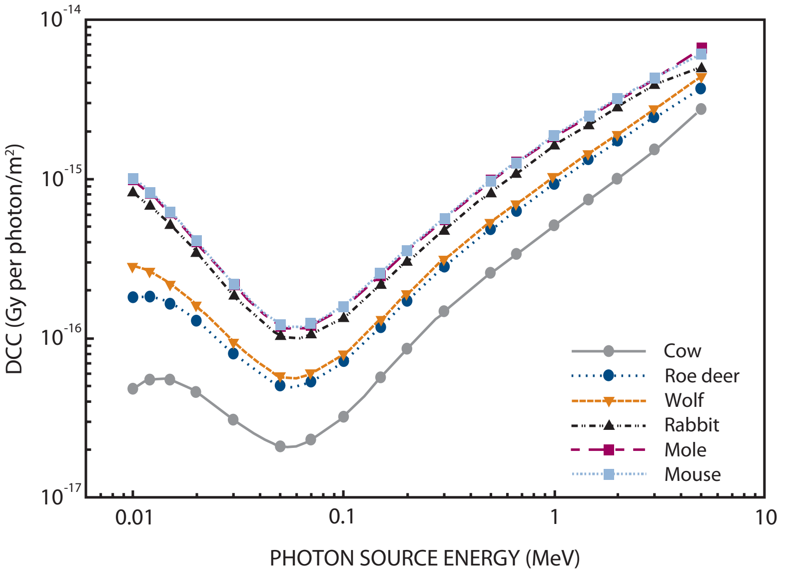
Figure VI. Dose conversion coefficients for an earthworm at various depths in soil, for monoenergetic photons from a uniformly distributed source in the upper 50 cm of the soil (soil density: 1,600 kg/m^3) [F4]



117. The DCC at a depth of 5 cm is only about 20% lower than the maximum. This is because of the relatively short mean free path of photons in soil, which is about 0.2, 2 and 10 cm for photon energies of 20 keV, 100 keV and 3 MeV, respectively. Thus, an organism in soil would be irradiated by photons originating within a surrounding shell of, at most, 10 cm radius.

118. The DCCs (Gy per photon per m^2) for different reference organisms for a planar source on the soil surface are given in figure VII. The DCCs decrease as the photon energy increases from 10 to 100 keV by a factor of about 5 for small animals and 2 for large animals. Above 100 keV, the DCCs gradually increase by approximately two orders of magnitude; the DCCs for small animals are greater than those for large animals owing to the more effective self-shielding in large organisms. Such differences are more pronounced at low energies; for example, the difference between the mouse and the cow is a factor of about 6 for 50 keV photons, whereas it is a factor of 3 for 3 MeV photons.

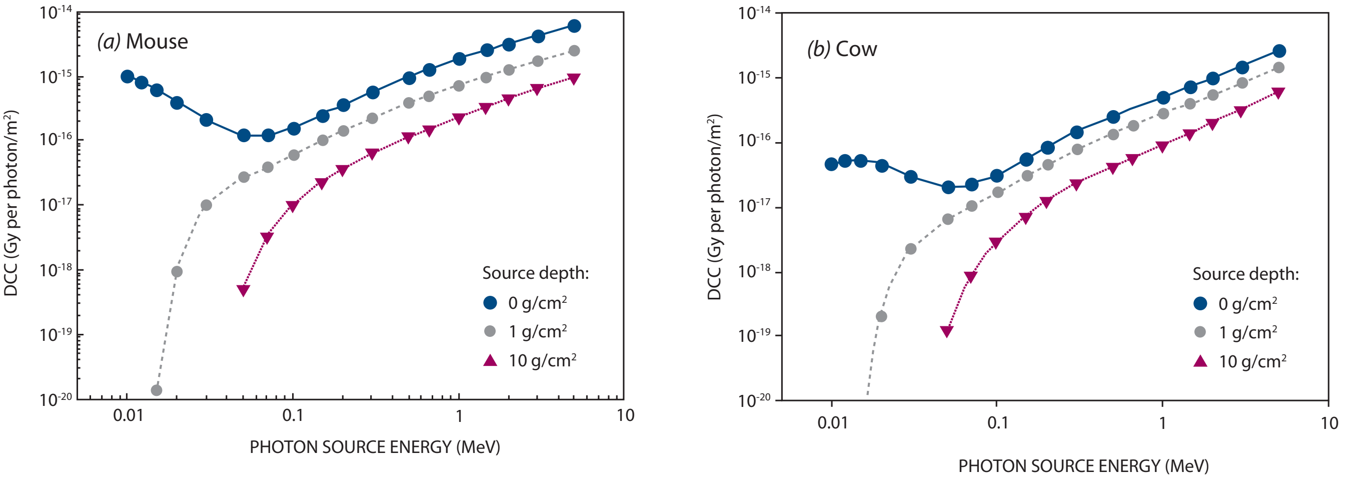
Figure VII. Dose conversion coefficients as a function of the source energy for various reference organisms for a planar source on top of the soil [F4]



119. The DCCs for different animals as a function of the depth of a planar source in the soil are summarized in figure VIII. The results show that the DCCs for low-energy photons for animals living on soil are low. Relatively shallow depths of soil over the planar source suffice to attenuate the photons completely.

Figure VIII. Dose conversion coefficients as a function of the source energy and depth of a planar source in the soil for *(a)* the mouse and *(b)* the cow living on the soil

The source depth quantifies the amount of soil by which the photon source is covered (e.g. the source depth of 10 g/cm^{2} for soil densities of 1.0 and 1.6 g/cm^{2} are equivalent to a depth of the source in the soil of 10 and 6.25 cm, respectively) [F4]



120. The data indicate that the relationship between the DCCs, the size and habitat of the organism and the energy and type of the radiation is complex. Nevertheless, these data provide an appropriate basis for deriving data, either by interpolation or by extrapolation, for other exposure conditions that were not explicitly considered. They were used to derive radionuclide-specific DCCs (μGy/h per Bq/kg) for internal and external exposure of a number of reference organisms, taking into account the type of radiation as well as the energy and intensity of the emission, as specified by the ICRP [I13]. Table 14 summarizes the DCCs (μGy/h per Bq/kg) for external exposure. The data are provided according to the habitat of organisms considered. Animals living in soil were assumed to be at a depth of 25 cm in a soil layer that is homogeneously contaminated by radionuclides to a depth of 50 cm. Above ground organisms were assumed to be irradiated by a source homogeneously distributed in the soil layer to a depth of 10 cm. For the terrestrial organisms, only the contribution of photons was included, whereas for aquatic organisms, exposure due to electrons (including bremsstrahlung) was also implicitly taken into account. This has the effect of causing the DCCs for ^{3}H, ^{90}Sr and ^{135}Cs to appear to be inconsistent: the DCCs for ^{3}H and ^{135}Cs for terrestrial organisms are zero, whereas the values for aquatic organisms are very small. Aquatic organisms are in direct contact with the contaminated medium, whereas electrons emitted from soil are attenuated by the surface roughness of the soil, the air and the fur of terrestrial organisms. So, this apparent inconsistency is of no significant practical consequence.

(b) Internal exposure

121. The DCCs (μGy/h per Bq/kg) for internal exposure are provided in table 15 [U17]. The values are given in terms of weighted absorbed dose rate per unit activity concentration in the organism, assuming homogeneous distribution of the radionuclides. The DCCs have been weighted to take account of the different RBEs of the different qualities of radiation; a factor of 10 to reflect the RBE has been used for alpha radiation and a factor 1 to reflect that for gamma and beta radiation including that from tritium (see the next subsection).

Table 14. Dose conversion coefficients for external exposure of reference organisms [E10, T10, U17]

Radionuclide	Absorbed dose rates per activity concentration (μGy/h per Bq/kg)											
	In soil[a]		On soil[b]						In water[c]			
	Earthworm	Rat	Deer	Duck	Frog	Bee	Grass	Pine tree	Pelagic fish	Benthic fish	Brown seaweed	Crab
^{3}H	0	0	0	0	0	0	0	0	7.9×10^{-12}	7.8×10^{-12}	8.2×10^{-11}	1.0×10^{-11}
^{90}Sr	1.5×10^{-10}	1.2×10^{-10}	4.6×10^{-12}	1.5×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	2.2×10^{-5}	4.9×10^{-5}	2.0×10^{-4}	2.2×10^{-5}
^{99}Tc	0	0	0	0	0	0	0	0	1.2×10^{-7}	1.2×10^{-7}	1.5×10^{-6}	1.4×10^{-7}
^{129}I	3.5×10^{-6}	3.0×10^{-6}	4.0×10^{-7}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	7.7×10^{-6}	9.2×10^{-6}	1.3×10^{-5}	7.9×10^{-6}
^{131}I	1.9×10^{-4}	1.8×10^{-4}	3.7×10^{-5}	7.1×10^{-5}	7.7×10^{-5}	7.8×10^{-5}	7.8×10^{-5}	7.8×10^{-5}	1.9×10^{-4}	2.0×10^{-4}	2.3×10^{-4}	1.9×10^{-4}
^{134}Cs	8.3×10^{-4}	7.8×10^{-4}	1.6×10^{-4}	2.9×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	7.6×10^{-4}	8.0×10^{-4}	8.9×10^{-4}	7.6×10^{-4}
^{135}Cs	0	0	0	0	0	0	0	0	4.5×10^{-8}	4.5×10^{-8}	4.3×10^{-7}	5.2×10^{-8}
^{137}Cs	3.0×10^{-4}	2.8×10^{-4}	5.6×10^{-5}	1.1×10^{-4}	1.1×10^{-4}	1.2×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	2.7×10^{-4}	2.9×10^{-4}	3.4×10^{-4}	2.8×10^{-4}
^{210}Pb	6.0×10^{-7}	5.2×10^{-7}	7.7×10^{-8}	2.6×10^{-7}	2.8×10^{-7}	2.9×10^{-7}	2.9×10^{-7}	2.9×10^{-7}	2.7×10^{-6}	4.7×10^{-6}	4.7×10^{-5}	3.0×10^{-6}
^{226}Ra	9.0×10^{-4}	8.5×10^{-4}	1.8×10^{-4}	3.2×10^{-4}	3.4×10^{-4}	3.5×10^{-4}	3.4×10^{-4}	3.4×10^{-4}	9.1×10^{-4}	9.6×10^{-4}	1.1×10^{-3}	9.1×10^{-4}
^{232}Th	1.4×10^{-7}	1.2×10^{-7}	1.3×10^{-8}	3.9×10^{-8}	4.3×10^{-8}	4.4×10^{-8}	4.3×10^{-8}	4.3×10^{-8}	1.5×10^{-7}	1.8×10^{-7}	5.0×10^{-7}	1.6×10^{-7}
^{238}U	1.2×10^{-7}	1.0×10^{-7}	1.0×10^{-8}	4.3×10^{-8}	4.8×10^{-8}	5.0×10^{-8}	4.9×10^{-8}	4.9×10^{-8}	1.0×10^{-7}	1.3×10^{-7}	5.1×10^{-7}	1.1×10^{-7}
^{237}Np	7.6×10^{-6}	7.0×10^{-6}	1.4×10^{-6}	3.3×10^{-6}	3.6×10^{-6}	3.6×10^{-6}	3.6×10^{-6}	3.6×10^{-6}	1.2×10^{-5}	1.3×10^{-5}	1.8×10^{-5}	1.3×10^{-5}
^{239}Pu	8.5×10^{-8}	7.2×10^{-8}	9.5×10^{-9}	3.0×10^{-8}	3.3×10^{-8}	3.3×10^{-8}	3.3×10^{-8}	3.3×10^{-8}	8.2×10^{-8}	1.0×10^{-7}	3.0×10^{-7}	8.7×10^{-8}
^{240}Pu	1.6×10^{-7}	1.3×10^{-7}	1.4×10^{-8}	5.4×10^{-8}	6.0×10^{-8}	6.2×10^{-8}	6.1×10^{-8}	6.1×10^{-8}	1.4×10^{-7}	1.9×10^{-7}	6.8×10^{-7}	1.6×10^{-7}
^{241}Am	6.1×10^{-6}	5.5×10^{-6}	9.2×10^{-7}	2.4×10^{-6}	2.6×10^{-6}	2.6×10^{-6}	2.6×10^{-6}	2.6×10^{-6}	1.1×10^{-5}	1.2×10^{-5}	1.7×10^{-5}	1.1×10^{-5}

[a] Organisms are assumed to live at 25 cm depth of a soil with radionuclides distributed homogeneously to a depth of 50 cm.
[b] Organisms are assumed to live on a soil layer with radionuclides distributed homogenously to a depth of 10 cm.
[c] Organisms are assumed to be immersed in water.

Table 15. Weighted dose conversion coefficients for internal exposure of reference organisms [T10, U20]

Radionuclide	*Weighted absorbed dose rates per activity concentration (μGy/h per Bq/kg)*[a,b]											
	Earthworm	*Rat*	*Deer*	*Duck*	*Frog*	*Bee*	*Grass*	*Pine tree*	*Pelagic fish*	*Benthic fish*	*Brown seaweed*	*Crab*
^{3}H	3.3×10^{-6}											
^{36}Cl	1.5×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	1.6×10^{-4}
^{90}Sr	5.3×10^{-4}	6.2×10^{-4}	6.5×10^{-4}	6.3×10^{-4}	5.9×10^{-4}	4.4×10^{-4}	5.1×10^{-4}	6.5×10^{-4}	6.3×10^{-4}	6.0×10^{-4}	4.5×10^{-4}	6.3×10^{-4}
^{99}Tc	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.7×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.7×10^{-5}	5.8×10^{-5}
^{129}I	3.8×10^{-5}	4.2×10^{-4}	5.0×10^{-5}	4.4×10^{-5}	3.9×10^{-5}	3.7×10^{-5}	3.8×10^{-5}	5.0×10^{-5}	4.3×10^{-5}	4.2×10^{-5}	3.8×10^{-5}	4.3×10^{-5}
^{131}I	1.1×10^{-4}	1.4×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	1.2×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	2.5×10^{-4}	1.4×10^{-4}	1.3×10^{-4}	1.0×10^{-4}	1.4×10^{-4}
^{134}Cs	1.1×10^{-4}	1.9×10^{-4}	7.1×10^{-4}	2.5×10^{-4}	1.4×10^{-4}	9.9×10^{-5}	1.1×10^{-4}	6.5×10^{-4}	2.3×10^{-4}	1.9×10^{-4}	9.7×10^{-5}	2.3×10^{-4}
^{135}Cs	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.8×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.8×10^{-5}	3.9×10^{-5}
^{137}Cs	1.5×10^{-4}	1.8×10^{-4}	3.7×10^{-4}	2.0×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	3.5×10^{-4}	1.9×10^{-4}	1.8×10^{-4}	1.3×10^{-4}	1.9×10^{-4}
^{210}Pb	2.3×10^{-4}	2.4×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	2.4×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	2.4×10^{-4}	2.0×10^{-4}	2.5×10^{-4}
^{226}Ra	1.3×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.4×10^{-1}
^{232}Th	2.3×10^{-2}											
^{238}U	2.4×10^{-2}											
^{237}Np	2.7×10^{-2}											
^{239}Pu	3.0×10^{-2}											
^{240}Pu	3.0×10^{-2}											
^{241}Am	3.2×10^{-2}											

[a] Assumes a homogeneous activity distribution in the organism.

[b] Assumes an RBE of 10 for alpha and 1 for beta.

(c) Relative biological effectiveness

122. The effects of radiation exposure on biota depend not only on the absorbed dose, but also on the type or quality of the radiation. For example, alpha particles and neutrons can produce observable damage at much lower absorbed doses than beta or gamma radiation. Thus, the absorbed dose (in gray) is often multiplied by a factor in order to account for the RBE of the quality of the radiation.

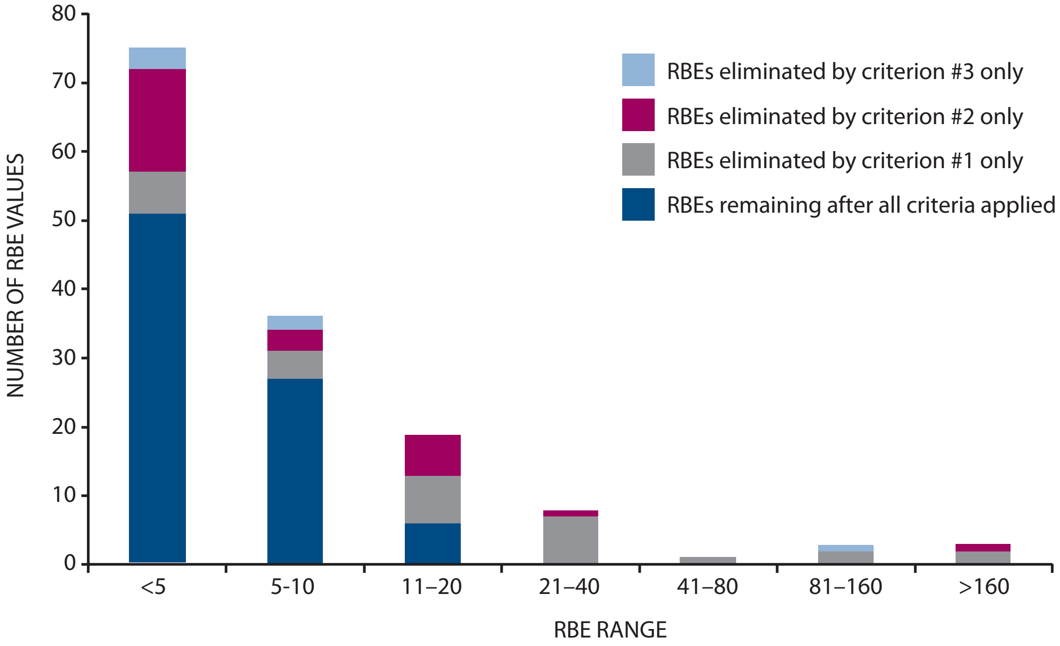
123. A number of authors have evaluated the data on the RBE of different types of radiation [A1, C1, E2, F4, T7, U4, U26]. Nominal values for the factor to reflect the RBE of alpha particles derived from these reviews are summarized in table 16. The experimental values of RBE are specific to the endpoint studied, the biological, environmental and exposure conditions (e.g. reference radiation, dose rate, and dose) amongst other factors. Thus, as noted in a FASSET report [F4], it is difficult to develop a generally valid factor to reflect the RBE for different radiation qualities for use in an environmental risk assessment. The ACRP [A1] and FASSET [F4] have therefore proposed ranges of values for general application. Both selected a factor of 10 to reflect the RBE for alpha particles, the ACRP, citing references [K2, T7, U4], referring to it as a notional central value, and FASSET as a value "to illustrate" the impact of the RBE for an internally deposited alpha emitter.

Table 16. Modifying factors to reflect the RBE of alpha radiation for deterministic effects on non-human biota (relative to low-LET radiation)

Source	*Nominal value*	*Comment*
[N1]	1	Built-in conservatism in dose model
[I4]	20	Numerically the same as the radiation weighting factor used in the protection of humans
[B22]	2–10	Non-stochastic effect of neutrons and heavy ions
[U4]	5	Average for deterministic effects
[T7]	10	Deterministic population-relevant endpoints
[C1]	20	Likely to be conservative for deterministic effects
[E3]	40	Includes studies with high RBE values
[E12]	<35	Based on concentrations in the whole body
[A1]	5–20 (10)	5–10 deterministic effects (cell-killing, reproductive) 10–20 cancer, chromosome abnormalities 10 nominal central value
[F4]	5–50 (10)	10 to illustrate the effect of the alpha RBE
[K19]	<7 to <35	Upper bound of estimate of RBE

124. Chambers et al. [C5] reported a review of the literature on experimentally determined RBEs for internally deposited alpha-emitting radionuclides. The relevance of each experimental result in selecting a factor to reflect the RBE for alpha particles was judged on the basis of pre-established criteria. They recommended a nominal factor of 5 to reflect the RBE for alpha particles for population-relevant deterministic and stochastic endpoints but, to reflect the limitations in the experimental data, they also suggested uncertainty ranges of 1–10 and 1–20 for population-relevant deterministic and stochastic endpoints, respectively. The data developed by Chambers et al. [C5] after application of their evaluation criteria are summarized in figure IX. Three evaluation criteria were used in reference [C5]. Criterion 1 required the dosimetric conditions to be sufficiently well defined and not peculiar to the source of radiation. Criterion 2 required the dose–effect relationships to be sufficiently well known so that the results from the dose rates used experimentally can be applied to effects that may occur with environmental dose rates. Criterion 3 required the experimental uncertainties to be discussed by the authors of the original studies.

Figure IX. Application of the criteria to the distribution of RBEs (all endpoints) [C5]



125. Knowles [K19] reported on experimental studies on groups of zebra fish that were exposed from an early age to different dose rates of gamma and alpha radiation (the latter was from ^{210}Po). Among the gamma-irradiated fish, only those in the highest dose-rate group (7,400 mGy/h) showed radiation-related damage. No groups of alpha-irradiated fish showed evidence of radiation-induced reduction in egg production even though autoradiographs showed concentrations of ^{210}Po in the testes and ovaries. Since the highest alpha dose rate (214 mGy/h) showed no effect, comparison with the gamma dose rate of 7,400 mGy/h, which caused egg production to cease, resulted in only upper limits to the RBE. These were calculated to be in the range of <7 to <20 based on ovary concentrations and <35 based on whole body concentrations. The authors suggested that the RBEs derived from their work provide the best available (upper bound) estimates for a population-relevant effect for fish.

126. The ACRP [A1] considered tritium beta radiation because the low velocity of the beta particles (maximum energy = 18.6 keV) results in a relatively high LET over a short path length. It has an LET very similar to that of 70 keV photons, which are representative of the X-rays used in radiobiological research and in diagnostic medicine [M6]. In their review of the effects of tritiated water (HTO) in mammals and fish, Environment Canada in their Priority Substances List (PSL2) [E3] listed tritium RBE values ranging from 1.7 to 3.8, with gamma rays from ^{60}Co or ^{137}Cs being used as the reference radiation. Based on this, they recommended a factor of 3 to reflect the RBE of beta radiation from tritium. Research conducted at Atomic Energy of Canada Ltd. on breast cancers in female rats [G1] and on myeloid leukaemia in male mice indicated an RBE value of 1.2 for tritium, with X-rays being used as the reference radiation. The difference between these values is largely the result of the choice of reference radiation. Sinclair [S8] has shown that, at low doses, X-rays are about twice as effective as gamma rays in producing damage. Hence, the radiation from tritium has an effectiveness for biological damage in the higher part of the range expected for the gamma and X-ray photon energies likely to be experienced in the environment. Citing Straume and Carsten [S9] amongst others, the ACRP concluded that for the dosimetry of non-human species, where the endpoints are usually deterministic in nature, a reasonable average factor to reflect the RBE of beta particles may be 2 with a range of 1–3, depending on the endpoint being assessed [A1].

127. A number of studies suggested that beta radiation with energies below 10 keV has a higher RBE than electrons with energies above 10 keV [M10, S9]. Straume and Carsten [S9] reviewed 33 studies of the RBE of tritium beta particles and found arithmetic means of 1.8 based on X-rays as the reference radiation, and 2.3 with ^{137}Cs or ^{60}Co gamma rays as the reference radiation. Most of these studies related to deterministic effects. Moiseenko et al. [M10] considered an appropriate factor to reflect the RBE of beta particles from tritium (mean beta energy <10 keV) to be between 2 and 3. The UK Health Protection Agency (HPA) [H21] reviewed the RBE studies on tritium beta particles along with a wide variety of experimental studies using X-rays and gamma rays as reference radiations and noted that the RBEs generally ranged from 1 to 2 when compared to orthovoltage X-rays and from 2 to 3 when compared to gamma rays [H21]. Little and Lambert [L9] also reviewed the experimental studies of cancer induction, chromosomal aberration, cell death and various other endpoints and arrived at similar conclusions for the RBE of tritium in water.

128. In order to illustrate the effect of the radiation quality of emissions from internally deposited radionuclides, the FASSET programme recommended the use of a factor of 10 to reflect the RBE of alpha radiation, 3 for low-energy beta radiation ($E < 10$ keV), and 1 for both beta radiation with energies greater than 10 keV and for gamma radiation [F4, L4].

129. The Committee, in its UNSCEAR 1996 Report [U4], recommended a nominal factor of 5 to reflect the RBE for internally deposited alpha emitters. The Committee now recommends a nominal (generic) factor of 10 to reflect the RBE for internally deposited alpha radiation. For beta and gamma radiation, the Committee recommends a nominal (generic) factor of 1 to reflect the RBE. However, it should be understood that the most appropriate factor to reflect the RBE for low-energy (<10 keV) beta radiation remains an open question and ought to be the subject of future research. These recommended values to reflect the RBE are intended to apply on a generic basis across all organisms and endpoints. Where appropriate scientific information specific to a particular organism and endpoint exists, such information is preferred.

(d) Dose rates for internal exposure

130. The dose from unit exposure of the selected reference organisms is estimated from the weighted absorbed dose rate due to external exposure arising from deposits in the ground and that due to internal exposure. Weighted absorbed dose rates to the reference organisms normalized for continuous exposure to 1 Bq/m^3 in air for each radionuclide are given in table 17. These weighted absorbed dose rates were calculated assuming the factors to reflect the RBE recommended by the Committee. Table 18 summarizes the ratios of weighted to non-weighted normalized total doses. The results are particularly sensitive to the choice of factor, especially for radiation from the actinides and tritium. The contributions of weighted internal doses to the total normalized doses are close to or above 90%, which indicates that internal exposure is the dominant pathway.

131. These annual doses took account of external exposure as well as internal exposure via inhalation and ingestion. They are compared with the weighted absorbed doses to biota in table 19. The ranges given in the table for biota reflect the variations between the different reference organisms considered. This comparison has however some inherent limitations. The values for humans are expressed in terms of annual effective dose, whereas the values for biota are in terms of weighted absorbed dose and were estimated assuming a homogeneous distribution of the radionuclide in the organism. Furthermore, the annual effective doses per unit deposition to humans were based on a radiation weighting factor of 20 for alpha particles, whereas the weighted absorbed doses to biota were based on a factor of 10 to reflect the RBE for alpha particles. Further still, the values for humans reflect largely the transfer of radionuclides through agricultural ecosystems, whereas the values for biota are more typical of the transfer in forests and semi-natural ecosystems.

132. Despite these differences, the estimated normalized effective doses to humans and the weighted absorbed doses to biota are about the same order of magnitude, except in the cases of ^{129}I and ^{131}I. These exceptions are probably due to the special importance of radiation exposure of the human thyroid in evaluating effective dose, which has no counterpart in the dosimetry for biota. Thus, apart from these exceptions, the comparison indicates that for similar levels of radionuclides in the environment, the effective doses to humans and the weighted absorbed doses to biota are comparable.

Table 17. Normalized weighted absorbed dose rates per unit activity concentration to various biota from internal exposure

Radionuclide	*Weighted dose rate per unit activity concentration (µGy/h per Bq/m^3)*							
	Earthworm	*Rat*	*Deer*	*Duck*	*Frog*	*Bee*	*Grass*	*Pine tree*
^{3}H	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}
^{36}Cl	5.6×10^{-15}	3.3×10^{-13}	3.3×10^{-13}	3.3×10^{-13}	3.3×10^{-13}	9.3×10^{-15}	5.4×10^{-13}	5.5×10^{-14}
^{90}Sr	6.1×10^{-15}	1.2×10^{-12}	1.3×10^{-12}	7.3×10^{-13}	7.5×10^{-13}	5.1×10^{-14}	1.8×10^{-13}	4.3×10^{-13}
^{99}Tc	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	2.4×10^{-13}	4.8×10^{-15}
^{129}I	2.3×10^{-14}	4.8×10^{-14}	4.9×10^{-14}	4.5×10^{-14}	4.0×10^{-14}	2.9×10^{-14}	1.7×10^{-14}	2.1×10^{-14}
^{131}I	4.6×10^{-16}	1.3×10^{-15}	1.8×10^{-15}	4.2×10^{-16}	3.4×10^{-16}	1.9×10^{-16}	1.6×10^{-15}	2.8×10^{-15}
^{134}Cs	1.7×10^{-13}	2.7×10^{-13}	4.5×10^{-13}	9.7×10^{-14}	8.1×10^{-14}	6.6×10^{-14}	8.7×10^{-14}	1.2×10^{-13}
^{135}Cs	8.3×10^{-15}	2.7×10^{-13}	2.7×10^{-13}	7.1×10^{-14}	5.4×10^{-14}	5.0×10^{-15}	6.7×10^{-14}	1.7×10^{-14}
^{137}Cs	4.7×10^{-13}	4.4×10^{-13}	1.1×10^{-13}	1.9×10^{-13}	2.0×10^{-13}	2.0×10^{-13}	1.9×10^{-13}	2.3×10^{-13}
^{210}Pb	2.9×10^{-14}	9.4×10^{-15}	9.2×10^{-15}	1.2×10^{-14}	1.2×10^{-14}	1.1×10^{-14}	1.3×10^{-14}	8.7×10^{-16}
^{226}Ra	5.0×10^{-12}	2.1×10^{-12}	4.7×10^{-13}	8.9×10^{-13}	9.3×10^{-13}	3.7×10^{-12}	1.5×10^{-11}	1.3×10^{-12}
^{232}Th	4.9×10^{-13}	6.4×10^{-15}	5.6×10^{-15}	2.8×10^{-14}	2.8×10^{-14}	4.9×10^{-13}	8.4×10^{-13}	4.0×10^{-13}
^{238}U	5.8×10^{-12}	2.4×10^{-12}	2.4×10^{-12}	2.4×10^{-12}	2.4×10^{-12}	7.5×10^{-12}	9.9×10^{-13}	1.8×10^{-11}
^{237}Np	1.9×10^{-12}	1.5×10^{-12}	1.5×10^{-12}	1.5×10^{-12}	1.5×10^{-12}	4.0×10^{-12}	4.1×10^{-12}	4.9×10^{-12}
^{239}Pu	2.1×10^{-12}	1.7×10^{-12}	1.7×10^{-12}	1.7×10^{-12}	1.7×10^{-12}	4.4×10^{-12}	4.5×10^{-12}	5.4×10^{-12}
^{240}Pu	7.2×10^{-12}	2.9×10^{-12}	2.9×10^{-12}	2.9×10^{-12}	2.9×10^{-12}	9.3×10^{-12}	3.9×10^{-12}	3.1×10^{-12}
^{241}Am	8.8×10^{-14}	8.6×10^{-14}	7.6×10^{-14}	7.9×10^{-14}	8.0×10^{-14}	8.0×10^{-14}	3.7×10^{-12}	3.3×10^{-12}

Table 18. Ratio of weighted and unweighted doses

Radionuclide	*Ratio of weighted dose/unweighted dose*[a]							
	Earthworm	*Rat*	*Deer*	*Duck*	*Frog*	*Bee*	*Grass*	*Pine tree*
^{3}H	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{36}Cl	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{90}Sr	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{99}Tc	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{129}I	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{131}I	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{134}Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{135}Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{137}Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{210}Pb	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{226}Ra	2.0	1.0	1.1	1.2	1.1	3.3	7	2
^{232}Th	9.9	7.1	9.5	9.7	9.7	10	10	10
^{238}U	10	10	10	10	10	10	10	10
^{237}Np	9.1	8.9	9.6	9.4	9.3	9.6	9.6	9.7
^{239}Pu	10	10	10	10	10	10	10	10
^{240}Pu	10	10	10	10	10	10	10	10
^{241}Am	4.1	4.3	7.9	6.1	5.9	5.9	10	10

[a] Factors to reflect the RBE: alpha radiation, 10; beta and gamma radiation, 1.

Table 19. Comparison of doses to biota and humans, normalized for unit deposition to terrestrial ecosystems

Radionuclide	*Biota (range)*[a] *Normalized weighted absorbed dose rate ($Gy\ a^{-1}$ per $Bq\ m^{-2}\ a^{-1}$)*		*Humans*[b] *Normalized effective dose rate ($Sv\ a^{-1}$ per $Bq\ m^{-2}\ a^{-1}$)*
	Minimum	*Maximum*	
^{90}Sr	6.2×10^{-9}	1.3×10^{-6}	4.7×10^{-7}
^{99}Tc	4.4×10^{-9}	2.5×10^{-7}	1.8×10^{-8}
^{129}I	1.7×10^{-8}	5.0×10^{-8}	6.3×10^{-7}
^{131}I	2.0×10^{-10}	2.8×10^{-9}	1.0×10^{-7}
^{134}Cs	6.7×10^{-8}	4.6×10^{-7}	1.3×10^{-7}
^{135}Cs	5.1×10^{-9}	2.8×10^{-7}	1.2×10^{-8}
^{137}Cs	1.1×10^{-7}	4.8×10^{-7}	1.3×10^{-7}
^{210}Pb	8.9×10^{-10}	2.9×10^{-8}	2.5×10^{-6}
^{226}Ra	4.8×10^{-7}	1.5×10^{-5}	1.6×10^{-6}
^{232}Th	5.6×10^{-9}	8.5×10^{-7}	1.2×10^{-6}
^{238}U	1.0×10^{-6}	1.8×10^{-5}	6.0×10^{-7}
^{237}Np	1.5×10^{-6}	5.0×10^{-6}	4.9×10^{-7}
^{239}Pu	1.7×10^{-6}	5.5×10^{-6}	6.8×10^{-7}
^{240}Pu	3.0×10^{-6}	9.5×10^{-6}	6.8×10^{-7}
^{241}Am	7.7×10^{-8}	3.8×10^{-6}	5.8×10^{-7}

[a] Range represents the minimum and maximum among the organisms considered.
[b] Calculated according to [I11].

3. Doses to non-human biota

(a) Calculation of doses to biota

133. In terrestrial environments, the most important source of radiation exposure as a consequence of discharges of radionuclides to the environment is due to deposition on soil. Radionuclides present in soil are generally a persistent radiation source for all terrestrial biota. Aquatic organisms are irradiated externally by the activity in water and, in the cases of bottom dwellers and benthic organisms, the activity in sediments, and internally by incorporated radionuclides. The dose rate, D, can be calculated according to:

$$D = \sum_r \left[DCC_{ext,r} \cdot C_{soil,water,r} + DCC_{int,r} \cdot C_{biota,r} \right] \quad (5)$$

where $DCC_{ext,r}$ is the DCC for external exposure to radionuclide r (μGy/h per Bq/kg); $C_{soil,water,r}$ is the activity concentration of radionuclide r in soil or water (Bq/kg); $DCC_{int,r}$ is the DCC for internal exposure to radionuclide r (μGy/h per Bq/kg); and $C_{biota,r}$ is the internal activity concentration of radionuclide r in biota (flora or fauna) (Bq/kg).

(b) Activities in environmental media

134. In the absence of measurements, in order to evaluate equation (5), the activity concentrations, $C_{soil,water,r}$, and $C_{biota,r}$, have to be estimated. Assuming a constant discharge of radionuclides over a period of 50 years, the activity in soil for the last year of that period is calculated as indicated in reference [I11]:

$$C_{s,r} = \frac{D_{tot,r}}{(\lambda_r + \lambda_m) \cdot m_s} \cdot [1 - \exp(-(\lambda_r + \lambda_m) \cdot t_e)] \quad (6)$$

where $C_{s,r}$ is the activity concentration in soil (Bq/kg); $D_{tot,r}$ is the total (wet plus dry) deposition rate to soil (Bq m^{-2} a^{-1}); m_s is the mass of the upper soil layer (kg/m^2); λ_r is the radioactive decay constant (a^{-1}); λ_m is the loss rate from the upper soil layer (a^{-1}); and t_e is the discharge period (50 a).

135. The total deposition is calculated as the sum of dry ($D_{dry,r}$) and wet deposition ($D_{wet,r}$). The activity concentration in flora, $C_{flora,r}$, is estimated by taking into account direct deposition on the foliage and uptake from soil according to reference [I11]:

$$C_{flora,r} = \frac{D_{dry,r} + f_w \cdot D_{wet,r}}{(\lambda_{w,r} + \lambda_r) \cdot b} \cdot [1 - \exp(-(\lambda_{w,r} + \lambda_r) \cdot t_w)] + C_{s,r} \cdot TF_{flora,r} \quad (7)$$

where f_w is the interception fraction (dimensionless); b is the standing biomass (kg/m^2); λ_w is the activity loss rate from plants due to weathering (a^{-1}); t_w is the exposure time (a); and $TF_{flora,r}$ is the transfer factor from soil to flora (Bq/kg flora per Bq/kg soil).

136. The activity concentration in reference fauna is estimated from the soil concentration and the soil–fauna transfer factor as follows:

$$C_{fauna,r} = C_{s,r} \cdot TF_{fauna,r} \quad (8)$$

where $TF_{fauna,r}$ is the soil–fauna transfer factor (Bq/kg fauna per Bq/kg soil).

137. The habitats of the reference fauna are differentiated according to whether the organisms live in or above soil. DCCs for species living in soil are expressed in units of μGy/h per Bq/kg and are based on the assumption that the organism lives in the centre of a slab containing radionuclides uniformly distributed to a depth of 50 cm. For organisms living on soil, it is assumed that radionuclides are homogeneously distributed to a depth of 10 cm; the DCCs in this case have units of μGy/h per Bq/m^2.

138. The estimation of the activity concentration of a radionuclide in aquatic biota ($C_{aqua\ biota}$) is usually obtained from the activity concentration in water (C_{water}) and the concentration factor ($CF_{water–biota}$) according to:

$$C_{aqua\ biota} = C_{water,r} \cdot CF_{water-biota,r} \quad (9)$$

139. As outlined above, the exposure due to incorporated radionuclides is determined by the size and geometry of the organism, the radionuclide distribution, and the type and energy of the emitted radiation. Currently, DCCs are not available for specific target organs in the reference organisms; the DCCs for internal exposure are therefore based on the assumption that the radionuclides are homogeneously distributed throughout the organism [T10].

(c) Doses to marine organisms and to humans due to consumption of marine food

140. As an example of the calculations of exposures of aquatic organisms, the exposures to marine organisms are calculated assuming a radionuclide concentration in water of 1 Bq/m^3 and applying the appropriate concentration factor for water–biota in table 13 and the appropriate DCCs given in tables 14 and 15. The weighted absorbed dose rates to flatfish, crab and brown seaweed are summarized in table 20. For all radionuclides considered, the dose rates to biota are almost completely a result of internal exposure. For comparison, the effective dose rates to an adult human are given assuming an annual fish intake of 20 kg. In general, the effective dose rates to humans are much less than the weighted absorbed dose rates to biota for a unit activity concentration of a radionuclide in marine water.

Table 20. Comparison of doses to non-human biota and humans, normalized to an activity concentration in marine water of 1 Bq/m^3

Radionuclide	*Non-human biota*			*Humans*[a]
	Weighted absorbed dose rate (μGy/h per Bq/m^3)			*Normalized effective dose rate (μSv/h per Bq/m^3)*
	Flatfish	*Crab*	*Macroalgae*	
^{3}H	3.3×10^{-9}	3.3×10^{-9}	3.3×10^{-9}	4.1×10^{-11}
^{36}Cl	9.6×10^{-9}	9.6×10^{-9}	7.0×10^{-9}	1.3×10^{-10}
^{90}Sr	1.8×10^{-6}	6.3×10^{-6}	4.5×10^{-6}	1.9×10^{-7}
^{99}Tc	4.6×10^{-6}	5.8×10^{-5}	1.7×10^{-4}	1.2×10^{-7}
^{129}I	3.8×10^{-7}	4.3×10^{-6}	3.8×10^{-4}	2.3×10^{-6}
^{131}I	1.2×10^{-6}	1.4×10^{-5}	1.0×10^{-3}	4.5×10^{-7}
^{134}Cs	1.9×10^{-5}	6.9×10^{-6}	4.9×10^{-6}	4.3×10^{-6}
^{135}Cs	3.9×10^{-6}	1.2×10^{-6}	1.9×10^{-6}	4.6×10^{-7}
^{137}Cs	1.8×10^{-5}	5.7×10^{-6}	6.5×10^{-6}	3.0×10^{-6}
^{210}Pb	4.8×10^{-5}	2.3×10^{-3}	8.0×10^{-4}	3.2×10^{-4}
^{226}Ra	1.3×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	6.4×10^{-5}
^{232}Th	1.4×10^{-2}	2.3×10^{-2}	4.6×10^{-3}	3.2×10^{-4}
^{238}U	2.4×10^{-5}	2.4×10^{-4}	2.4×10^{-3}	1.0×10^{-7}
^{237}Np	2.7×10^{-3}	2.7×10^{-3}	1.4×10^{-3}	2.5×10^{-5}
^{239}Pu	3.0×10^{-3}	6.0×10^{-3}	1.2×10^{-1}	5.7×10^{-5}
^{240}Pu	3.0×10^{-3}	6.0×10^{-3}	1.2×10^{-1}	5.7×10^{-5}
^{241}Am	3.2×10^{-3}	1.3×10^{-2}	2.5×10^{-1}	4.6×10^{-5}

[a] For an intake of marine fish of 20 kg/a.

4. Conclusions

141. In this section, approaches have been described for the assessment of exposures of flora and fauna to radiation from natural background levels of radionuclides or regulated discharges of radionuclides to the environment. The models cover two major fields. One is concerned with the transport processes of radionuclides from the source to plants and animals, to which approaches may be applied that are similar to those used to assess the exposures of humans. In the terrestrial environment, these are mainly atmospheric dispersion, deposition, interception, weathering and uptake from soil. For discharges to aquatic systems, models can be used that describe dispersion, dilution, sedimentation and uptake by freshwater or marine organisms.

142. There are major differences in the dosimetry involved in the assessment of the exposures of humans and non-human biota. The current approaches for biota rely on the mean activity concentrations in the whole organism rather than on those in distinct organs or tissues. Thus, the calculated absorbed doses are to the whole organism. There is an ongoing discussion about the appropriate factors to be applied in order to account for the different RBEs of the different kinds of radiation involved. Example calculations in this annex show that the estimated weighted absorbed doses from exposure to alpha radiation are sensitive to the value of the factor used. This is relevant to the assessment of doses to biota both as a result of radioactive discharges from a nuclear site and as a result of exposure to radiation from radionuclides that are naturally present in the environment.

143. The estimated doses to biota are compared in this annex with those to humans in accordance with the approach given in reference [U3]. The comparison shows that the weighted absorbed doses to terrestrial non-human biota and the effective doses to humans are generally of a similar order of magnitude, for a given level of environmental contamination by radionuclides. The weighted absorbed doses to marine biota are, in general, considerably higher than the effective doses to humans (for whom an annual consumption of marine fish of 20 kg is assumed for illustrative purposes).

144. The results of the dosimetric calculations presented in this annex are based on stylized models of ecosystems using average values for most of the model parameters. Thus, they do not accurately reflect the variability of ecosystems and the processes present in nature that control the environmental mobility of radionuclides. In addition, the exposures due to the various sources of natural background radiation and their variabilities would have to be included if the results presented in this annex were to be used in a site-specific assessment. As indicated earlier, there are substantial uncertainties associated with the estimation of dose rates to non-human biota, including those associated with the environmental pathways (such as in the values of the transfer factors) and those related to dosimetric issues.

II. SUMMARY OF DOSE–EFFECTS DATA FROM THE UNSCEAR 1996 REPORT

145. In the absence of reports of obvious deleterious effects on other organisms from exposure to environmental radiation, whether of natural origin or due to the controlled discharges of radionuclides to the environment, it had generally been accepted that priority should be given to evaluating the potential consequences for humans (which are among the most radiosensitive mammalian species) and to providing a sound basis for protecting human health. By 1996, this position had, however, been questioned [D1, T1], and at least one situation (namely deep-sea sediments, an environment very remote from man) had been identified where the above accepted priority could be incorrect [I3]. In response to such concerns, the Committee noted that the impact of radiation exposure of non-human biota had been studied in a number of situations [I2, I3, I4, M1, N1, W1, W2] and considered that it was appropriate to conduct an independent review of the matter and to summarize the state of knowledge existing at that time. The UNSCEAR 1996 Report [U4] took account of the earlier reviews and studies and the Committee's summaries of the radiobiological work carried out over the previous 50 years.

146. In its 1996 report, the Committee noted that there was a fundamental difference in the approaches to the protection of humans and non-human biota from the effects of exposure to ionizing radiation. For humans, ethical considerations had made the individual the principal object of protection. This meant, in practice, that any incremental risk to the individual arising from increased radiation exposure was to be constrained below some level that society judged to be acceptable; this level of risk, although small, was not zero [I5]. For non-human biota, the populations of the biota were considered to be important and protection from a significantly increased risk to each population arising from radiation exposure might be the appropriate objective. Exceptions might be populations of small size (rare species) or those reproducing slowly (i.e. with long generation times and/or low fecundity) for which protective measures might be more appropriately targeted at the level of the individual organism. The Committee noted that there could not be any effect at the population level (or at the higher levels of community and ecosystem) if there were no effects on the individual organisms constituting the different populations. It went on to suggest that radiation-induced effects on some members of a population would not necessarily have any significant consequences for the population as a whole.

147. The Committee noted that natural populations of organisms existed in a state of dynamic equilibrium within their communities and environments and that exposure to ionizing radiation was but one of the stresses that may affect this equilibrium. The incremental radiation exposure from human activities could not, therefore, be considered in isolation from other sources of stress, whether natural (e.g. climate, altitude, or volcanic activity) or of human origin (e.g. synthetic chemical toxins, oil discharges, exploitation for food or sport, or habitat destruction). When (as is not uncommon) ionizing radiation and chemicals, both resulting from human activities, acted together on a population, the difficult problem arose of correctly attributing any observed response to a specific cause.

148. The objective of the UNSCEAR 1996 Report on the "Effects of radiation on the environment" [U4] was to summarize and review information on:

- The exposures (actual or potential) of organisms in their natural habitats to the natural background radiation, to radionuclides discharged into the environment in a controlled manner from industrial activities, and to radionuclides released as a consequence of accidents; and
- The responses of plants and animals, both as individuals and as populations, to acute and chronic irradiation.

149. The Committee hoped that its review would assist national and international bodies to select appropriate criteria for the radiological protection of natural populations, communities and ecosystems. The following paragraphs recapitulate the information available to the Committee in 1996.

A. Dosimetry for environmental exposures

150. As discussed in the annex to the UNSCEAR 1996 Report [U4], reliable determination of the dose rate to organisms is essential for assessing the potential or actual impacts of contaminant radionuclides in the environment. The Committee noted that "this simple statement conceals a multitude of difficulties that prevent the easy achievement of that estimation". In practice, it is necessary to make simplifying assumptions, with the degree of simplification depending on the purpose of the assessment. For example, for the purpose of screening, the concept of a single generic biota that represented all plants and animals had been used [A2]. More sophisticated models attempted to account for the dose distributions within reference organisms of assumed shapes and sizes and the fraction of radiation being absorbed within the organism [W2]. The Committee's views on dosimetry for estimating the exposure of biota based on what was known in the UNSCEAR 1996 Report [U4] are summarized below.

151. A dosimetric model is essentially a mathematical construction that allows the energy deposition in a defined target to be estimated from a given radionuclide (source) distribution. The model was often derived using theoretical or empirical functions that described the distribution of dose about a point source [B2, B3, L1, W2]. The dose at a point in the target was then obtained by integrating the point source dose distribution function over the defined radionuclide source, either internal or external to the organism. This

procedure was frequently simplified by using ideal geometries (spheres, ellipsoids, etc.) of appropriate size to represent the target and by assuming that the radionuclide distribution was uniform (over a surface or through a volume) or varied in a way that could be described by a simple mathematical expression (e.g. an exponential decline in radionuclide concentration with depth in soil or sediment). Alternatively, Monte-Carlo calculations had been used to determine the absorbed fractions of energy for a variety of source and target geometries [B4, E2]. These data could be used, either directly or with interpolation (or, to a lesser extent, with extrapolation) for geometries that could represent targets of environmental concern. In principle, these procedures could be adapted for use in estimating doses to terrestrial and aquatic organisms, from both the plant and animal kingdoms, for both internal and external sources of radiation.

152. Dosimetric models had been developed to take account of the radiation type; the specific geometry of the target (e.g. the whole body, the gonads, the developing embryo or the plant meristem); and the source of exposure (e.g. radionuclides accumulated in body tissues, adsorbed onto the body surface or distributed in the underlying soil). Clearly, it was not possible to consider all organisms, and there were limitations in the basic data that were available as input to the models (e.g. the spatial and temporal distributions of radionuclides both within the organism and in the external environment). Additional sources of complexity arose from the behaviour of mobile organisms, particularly some aquatic organisms and many insects, which inhabit different environmental niches at different stages of their life cycles. Thus, the models had to be simplified and generalized without undue loss of the realism that is essential for a valid estimation of dose.

153. The presence of an alpha particle component in the total absorbed dose rate to a tissue in a plant or animal raised the question of how to take account of the probably greater effectiveness of this type (quality) of radiation in producing biological damage. The RBEs of different qualities of radiation had been very critically examined for the purposes of human radiation protection. Each component of the absorbed dose to a tissue or organ was weighted by a factor which took account of the RBE of the radiation involved [I5]. It seemed reasonable to apply a similar approach to the radiation dosimetry for organisms other than man. In practice, however, there were circumstances that altered the detailed application of this approach. In the human case, the major concern had been with the induction of stochastic effects (principally cancer) at low doses and dose rates. For alpha radiation, experimental determinations of the RBE had led to a recommended radiation weighting factor of 20 for the purpose of human radiation protection. In the case of wild animals, however, the Committee assumed that it was likely that deterministic effects were of greater significance. For alpha radiation, the experimental data for animals indicated that a lower factor to reflect the RBE would be more appropriate; the factor to reflect the RBE of beta and gamma radiations would however be numerically the same as the radiation weighting factor used in human radiation protection. On the assumption that mammals are the most sensitive species, these values could be applied to other taxonomic groups.

154. In its 1996 UNSCEAR Report [U4], the Committee assumed that these factors would also apply to effects on plants, although there were no definitive experimental data to support this. In the absence of protection quantities (equivalent and effective dose) for non-human organisms, the absorbed doses from low-LET radiation (beta particles, X-rays and gamma rays) and from high-LET radiation (alpha particles) were assessed and specified separately in the UNSCEAR 1996 Report [U4]. The absorbed doses retained the unit, joule per kilogram (J/kg), with the special name gray (Gy).

155. An IAEA technical report [I4] provided estimates of the dose rates to terrestrial plants due to radionuclides deposited following discharges to the atmosphere. The model, PATHWAY [W3], developed to estimate doses to humans, had been used to derive the equilibrium concentrations of radionuclides in plants and animals for the limiting case in which humans, while living on the land, breathing the air over it and eating the food produced from it, would receive an annual effective dose of 1 mSv. To estimate the dose to plants from internal sources, it was assumed that the energy of alpha and beta particles would be totally absorbed (except for emissions from ^{32}P, which would be 50% absorbed) and that 10% of the gamma-ray energy would be absorbed. An additional degree of conservatism was provided by using estimates of the radionuclide concentrations in plant tissue on a dry weight basis (which are 5–10 times higher than on a wet weight basis) to calculate the absorbed dose rates to living (i.e. “wet”) plant tissue. The results are given in table 21. As these estimates had been made using a radioecological model and a scenario designed for calculating exposures to humans, the calculated exposures of non-human species should be interpreted cautiously.

156. The annex of the UNSCEAR 1996 Report [U4] noted that there have been fewer estimates of the potential exposures of fully terrestrial animals than of animals occupying semi or fully aquatic niches. This was thought to be a reflection of the greater use that had been made of aquatic systems for the discharge of radioactive waste.

157. The annex of the UNSCEAR 1996 Report [U4] suggested that naturally occurring alpha-emitting radionuclides appeared to be the most significant sources of background radiation exposure for the majority of wild organisms.

158. In its 1996 report, the Committee considered that the data on the radiation exposures of non-human biota due to both natural background radiation and contaminant radionuclides were incomplete, more in some areas than in others. The Committee also noted that the aquatic environment was probably the most thoroughly studied environment up to that time [I2, I3, I7, N1, N2, W1], even with the substantial

generalizations that had had to be made, particularly with respect to the range of organisms that could reasonably be considered [I3]. As had been emphasized elsewhere [I3, I6], the limiting factor was not the development of an appropriate dosimetric model for a particular organism but rather the acquisition of essential input data on the temporal and spatial distributions of the radionuclides both external to and within the organism. Although dynamic models had been employed to describe the dispersion and dilution of radionuclides in a water body, related phenomena (e.g. transfers to sediments and biological tissues) were almost always modelled as equilibrium processes, i.e. using simple distribution coefficients and (whole-body) concentration factors. This simplification largely neglected the temporal variations in dose rate due, for example, to short-term fluctuations in discharge rate, differing stages in the life cycle, and behavioural and short-term environmental processes (e.g. seasonality). As a consequence, while the estimated absorbed dose rate might be a reasonable indication of the general magnitude of the actual environmental value, the Committee considered that it did not provide a very secure basis for evaluating total doses over time.

Table 21. Estimated dose rates to organisms from controlled discharges of radionuclides that would each result in an annual dose of 1 mSv to humans residing in the same environment
Table 6 of UNSCEAR 1996 Report [U4]; based on [I4, N1]

Radionuclide	*Dose rate (μGy/h)*		
	Plants[a]	*Animals*[a,b]	*Fish*[c]
^{3}H	5.8	5.8	0.59
^{14}C	18	11	
^{32}P	32	28	4.8
^{60}Co			0.53
^{90}Sr	2.0	0.042	67
^{95}Zr	38	2.0	
^{99}Tc			3.8
^{131}I	1.2	0.058	
^{137}Cs	5.4	3.1	0.72
^{226}Ra[d]			3.6
^{235}U[d]			2.6
^{238}U[d]			4.7
^{239}Pu[d]	0.023	0.000 55	0.49
^{241}Am[d]			0.71

[a] Discharges to atmosphere.
[b] Domestic sheep.
[c] Discharges to water (lakes).
[d] High-LET radiation.

159. The Committee also noted that accident situations were by nature quite different from routine situations, particularly in their potential to produce high dose rates and doses to the environment. It concluded that generalization is difficult because the actual exposure regime depends on the types and quantities of radionuclides released, their initial dispersal and deposition patterns, and their redistribution over time in the environment. Following the accident at the Chernobyl nuclear power plant, large quantities of short-lived radionuclides were released, leading to high dose rates in the local area. Total doses up to 100 Gy were delivered to trees (and, by inference, to most other organisms in the locality) over a period of a few days [K1]. This radiation regime might have been characterized as "acute" in that the doses were delivered in periods that were shorter than or comparable to the time taken for severe damage to become apparent. During this initial (acute) phase, the dose rates declined rapidly as the very short-lived radionuclides decayed. The release following the accident in 1957 in the south-eastern Urals was dominated by ^{144}Ce–^{144}Pr (approximately 66%; $t_{1/2} = 285$ d) and ^{95}Zr–^{95}Nb (approximately 25%; $t_{1/2} = 65$ d). In that case, the dose rates locally were also relatively high during the initial phase (more than 4 mGy/h) but declined more slowly, such that high total doses (causing severe effects, including mortality) could still be accumulated from essentially chronic exposure. Close to the release point, total doses up to 2,000 Gy were experienced [T4]. In the longer term, the exposure regime for the Chernobyl release was dominated by ^{137}Cs ($t_{1/2} = 30$ a) and ^{90}Sr ($t_{1/2} = 28.6$ a), and that for the south-eastern Urals accident area by ^{90}Sr. In both cases, the exposures were chronic and moderately high, with responses other than mortality becoming significant.

160. Radioactive waste discharges to atmosphere, landfills or aquatic systems from man-made practices entail increased radiation exposure of wild organisms. The incremental radiation exposures are chronic (i.e. continuing) at absorbed dose rates of generally no more than 100 μGy/h, but, very exceptionally, they may reach several thousand microgray per hour. The Committee [U4] noted that these additional

radiation exposures may be greater than the normal range of natural background exposures but generally are within the extreme range of background exposures, if the exceptional cases of areas of uranium and thorium mineralization are included. Given that radioactive waste discharged to the environment will normally be dispersed and diluted, dose rates higher than those due to normal natural background exposure are likely to apply to only a small proportion of the individual organisms in any population and the average dose rate to the population would probably be much lower [W8, W9].

B. Effects of radiation exposure on plants and animals

161. Studies of the effects of ionizing radiation exposure on plants and animals were started immediately following the discovery of X-rays and radioactivity (see, for example, reference [A4]). Since 1945, when the first nuclear detonations were conducted, there was widespread concern about the impact of environmental radiation exposures and interest in the environmental behaviour of radioactive materials. As a result, studies using a wide variety of plant and animal species were performed [A4, B5, C3, P1].

162. The Committee, in its 1996 report [U4], noted that the responses of organisms to radiation exposure were varied and may become manifest at all levels of organization, from individual biomolecules to ecosystems. The significance of a given response depended on the criterion of damage adopted, and it was not to be concluded that a response at one level of organization would necessarily produce a consequential, detectable response at a higher level of organization.

163. The Committee also noted that a population might be defined as all members of a population species [U4]. Alternatively, a population might be considered as an aggregate of inter-breeding individuals of a species occupying a specific location in space and time [S5]. The latter definition is perhaps more useful given the Committee's observation that radiation fields, such as those arising from radioactive waste discharges, generally show large spatial variability, not least because of the often discrete nature of the source, and therefore many members of a population might not receive any significant exposure from a particular source. The natural distributions of most species are inhomogeneous because of the variations in physical, chemical and biological conditions under which the individuals of the species are able to survive, i.e. species are geographically restricted. Thus, it is probable that a more limited, and relevant, definition of a population could be developed for the purposes of environmental impact assessment.

164. The following definition (developed for use in population ecology) has been suggested as a useful basis for discussion and progress [I4]: "A population is a biological unit for study, with a number of varying statistics (e.g. number, density, birth rate, death rate, sex ratio, age distribution), and which derives a biological meaning from the fact that some direct or indirect interactions among its members are more important than those between its members and members of other populations" [B6]. Notwithstanding this definition, it has to be understood that a population of a particular species is always linked to its environment. Such a population would (or could) be a self-sustaining unit, independent of other, geographically separate populations of the same species. However, protection of this population would require that increased radiation exposure did not significantly affect the attributes mentioned in the definition on which the population depended for its maintenance within the normal dynamic range of variation dictated by the interactions of natural physical, chemical and biological factors.

165. These attributes, which could be defined only for populations of organisms and might be taken to be indicators of their health, are nevertheless amalgamations of properties that relate to individuals (in no sense was this meant to imply simple addition). The Committee concluded, in effect, that for a response to radiation exposure at the population level (or, indeed, at any higher level of organization) some clearly detectable effect in individual organisms (i.e. at lower levels of organization) would be expected. This clearly implied that the protection of the population (as the ultimate objective) might be achieved by restricting the exposure of individual organisms to the extent that there are no significant radiation effects on those processes necessary for the maintenance of the population. It is therefore necessary to consider the available information on the effects of radiation exposure (mainly at chronic low dose rates) on the relevant processes in individual organisms, to consider how these responses might translate to an impact on the population, and to examine the results of studies of population responses to deliberate experimental irradiation or to exposure in the environment due to controlled or accidental releases of radionuclides.

166. Examination of the population attributes indicated that the individual responses to radiation exposure likely to be significant at the population level are mortality (affecting age distribution, death rate and density), fertility (birth rate), fecundity (birth rate, age distribution, number and density) and the induction of mutations (birth rate and death rate). These individual responses can be traced to events at the cellular level in specific tissues or organs. An extended summary discussing the processes involved was provided in annex J, "Non-stochastic effects of irradiation", of the UNSCEAR 1982 Report [U9]. There was a substantial body of evidence indicating that the most radiosensitive sites are associated with the cell nucleus, specifically the chromosomes, and that, to a lesser extent, damage to intracellular membranes is additionally involved. The end result is that the cells lose their reproductive potential. For most cell types, at moderate doses, death occurs when the cell attempts to divide; death does not, however, always occur at the first post-exposure division: at doses of a few gray, several division cycles might be successfully completed before death eventually occurs. It was also well known that radiosensitivity varies within the cell cycle, with the greatest sensitivities being apparent at mitosis and the commencement

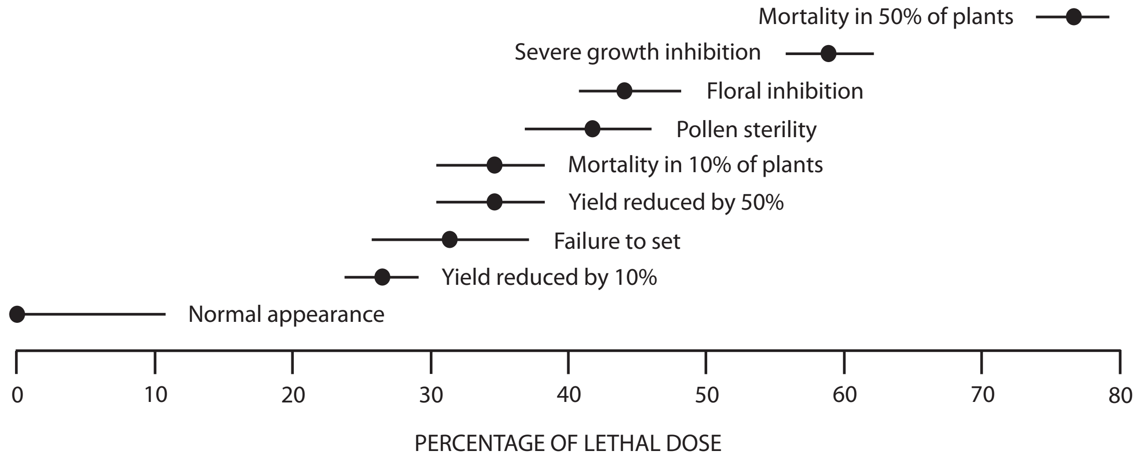
of DNA synthesis [U9]. It followed that the greatest radiosensitivity is likely to be found in cell systems undergoing rapid cell division for either renewal (e.g. spermatogonia) or growth (e.g. plant meristems and the developing embryo); these examples clearly underlie the processes in individual organisms that are important for the maintenance of the population.

167. Fractionation or protraction of exposure to low-LET radiation increases the total dose required to produce a given degree of damage since at low dose rates, the factors responsible for mitigating the response come into play. These include the repair of sublethal damage, the repair of potentially lethal damage, the replacement of killed cells through proliferation of survivors, and other slow repair processes not related to cell repopulation [U9]. Although it was clear to the Committee that repair, in the general sense, is possible, the existence and extent of residual injury was less clear. While such an outcome might be demonstrated for moderate, acute doses, it was not possible to extrapolate these results in order to predict the likely response to low-level exposures extending over a significant fraction of the lifetime of an organism. However, given that genetic mutations might be passed from generation to generation, it was reasonable to suppose that somatic mutations individually consistent with cell survival could occur and accumulate over time until the combined impact might reduce cell viability.

1. Terrestrial plants

168. Radiation injury in plants expresses itself as abnormal shape or appearance, reduced growth or yield, loss of reproductive capacity, wilting and (at high exposures) death [S1]. Acute lethal doses to higher plants ranged from 10 to about 1,000 Gy (approximate mean absorbed doses averaged over the whole plant). The Committee concluded that plants such as mosses, lichens and unicellular species are at one extreme of radiosensitivity being highly resistant to radiation exposure; woody species are at the other extreme being the most sensitive. In 12 species of woody plants assessed 10–14 months after exposure, the lethal doses were found to be in the range of 8–96 Gy [S2]. The pine tree was the most sensitive, experiencing mortality following short-term absorbed doses of about 10 Gy [W5]; growth was severely inhibited at 50–60% of the lethal dose. Floral inhibition was observed at 40–50% of the lethal dose, and failure to set seed at 25–35%. Thus, the capacity of the plant population to maintain itself could be damaged at acute doses lower than those required to cause mortality. Below 10% of the lethal dose, effects were not so apparent and the plants maintained a normal appearance. These general observations for several herbaceous plant species are illustrated in figure X [S3]. Another general relationship was that the dose that reduced survival by 10% (LD_{10}) was roughly equivalent to the dose that reduced the yield by 50% (YD_{50}) [S1].

Figure X. General ranges of response to radiation exposure by herbaceous plants as a percentage of the lethal dose (LD_{100}) [S3]



169. The Committee, in the UNSCEAR 1996 Report [U4], noted that protraction of radiation exposures increased the total doses required to kill plants [S4].

170. A range of sensitivities to radiation exposure was exhibited by the components of plants, ranging from dry seed (least sensitive) to apical meristems (most sensitive). Various crop plants showed different reductions in yield following radiation exposures, with further modifications being caused by external factors (e.g. temperature and humidity).

171. Plant species also varied in their tolerance to chronic radiation exposures. For the more sensitive pine species, dose rates of more than 3 mGy/h over 3–4 years reduced needle growth; in one-year-old saplings, needle length was substantially reduced when subjected to a dose rate of 7 mGy/h over a single growing season. Trunk growth was reduced in mature pine trees by dose rates in the range 0.4–2 mGy/h over a 9-year period. Delayed bud burst and an extended period of leafing out was demonstrated in white oaks chronically exposed to gamma radiation. At dose rates greater than 4 mGy/h, the trees were more susceptible to aphid infestation.

172. In view of the effects on the most sensitive plants evident with chronic exposure at dose rates of 1–3 mGy/h and of some specific changes noted at dose rates of 0.4–2 mGy/h, the Committee [U4] suggested that chronic dose rates at or below 400 µGy/h (10 mGy/d) should have only slight effects on sensitive plants but would be unlikely to produce any significant deleterious effects on the wider range of plants present in natural plant communities.

2. Terrestrial animals

173. The effects of radiation exposure on mammals had been extensively studied in radiobiological experiments using laboratory animals (mice, rats, dogs and monkeys) and domestic livestock (pigs, sheep, goats, burros and cattle) [B7, B8]. Except in the case of exposure involving unusually high doses, radiation damage or lethality in mammals results from disturbances in the haematopoietic system and the gastrointestinal mucosa. These cell self-renewal systems contain stem cells, differentiating cells and functional end cells, with the stem cells being the most radiosensitive and thus having the predominant influence on the radiation response. Symptoms become apparent when end cells are not replaced.

174. Protraction of a given total exposure generally reduces the extent of injury, as it allowed two distinct processes to intervene. First, sublethal damage is reparable at the cellular level, which is particularly important for exposures to low-LET radiation. Secondly, cell proliferation could replace lethally damaged cells and maintain the cell population at a new level, which is determined by the dynamic interaction between the dose rate and the rate of cell death, and by the total reserve proliferative capacity.

175. The Committee noted that at reduced dose rates (protraction of a given total dose) of low-LET radiation, all species showed a gradual increase in LD_{50}, i.e. higher total doses were tolerated. This changing response was attributed to the increasingly effective influence of cellular repair of sublethal damage at the lower dose rates. As the dose rate was further reduced, a sharply increasing trend in the values for the median lethal dose was apparent for mice, pigs, dogs, goats and sheep; the approximate threshold dose rates for this change in response corresponded to the accumulation of an LD_{50} dose within periods ranging from 0.2 days (mouse) to 9 days (goat). This rapid change in LD_{50} with dose rate was interpreted as being the consequence of a shifting balance in the dynamic interaction between the dose-rate-dependent cell loss and the cell proliferation and maturation kinetics in the haematopoietic system; the latter processes are under homeostatic control, i.e. their rate constants can alter in response to radiation-induced cell loss. The data for the burro (donkey) and primates did not show any sharp increase in the median lethal dose at dose rates down to 8.3 mGy/h (LD_{50} in 18 days) and 5.4 mGy/h (LD_{50} in 60 days), respectively. There did not appear to be any data for LD_{50} values at dose rates of less than 4 mGy/h or for exposure periods exceeding 60 days, although studies had been made outside these levels for other purposes.

176. While acknowledging that the numbers of mammalian species that had been (or indeed were likely to be) studied were extremely limited and probably atypical, the Committee noted [U4] that, even taking account of substantial interspecific variability, the available data provided very little evidence that chronic dose rates below 400 µGy/h (approximately 10 mGy/d) to the most exposed members of the population would seriously affect their mortality (and, thus, the death rate in populations of these species) from either deterministic or stochastic responses.

177. The effects of radiation exposure on reproduction had also been much studied, with most of the results suggesting that natality is a more radiosensitive parameter than mortality in species other than man and therefore of more relevance in an environmental context. The Committee considered that the minimum dose required to depress reproduction rates might be less than 10% of the dose required to produce direct mortality [W6].

178. The Committee suggested that damage to the developing mammalian embryo appeared to be a potentially significant criterion for assessing the impact of contaminant radionuclides in the natural environment. Dose rates of 420 µGy/h throughout gestation produced readily detectable reductions in the populations of germ cells in the developing gonads of a number of mammalian species, and the lowest dose rate at which damage had been seen was 10 µGy/h from tritium (as HTO in drinking water) incorporated in female mouse embryos. In addition, dose rates of the order of 420 µGy/h induced reductions in neonatal brain weight, although the significance of this deficit was unknown in functional or behavioural terms. The wider significance of these responses at the population level had not been investigated. Even recognizing that only very limited data were available, the Committee concluded that maximum dose rates of 100 µGy/h (2.4 mGy/d) to pregnant members of a mammalian population were unlikely to have any consequences for the population as a whole from the induction of damage in the developing embryos.

179. The Committee noted that the data on the radiosensitivity of terrestrial animals were dominated by data on mammals, the most sensitive class of organisms. Acute lethal doses ($LD_{50/30}$) were 6–10 Gy for small mammals and 1.5–2.5 Gy for larger animals and domestic livestock. When a total dose of magnitude similar to the $LD_{50/30}$ was delivered over a lifetime—for example, 7 Gy to the mouse (420 µGy/h, or 10 mGy/d)—the average loss of lifespan had been estimated to be about 5% and resulted from the induction of neoplastic disease [U9]. There was substantial inter-species variability, but, in general, little indication that dose rates below about 400 µGy/h to the most exposed individual would seriously affect mortality in the population.

180. The Committee noted that reproductive capacity was more sensitive to the effects of radiation exposure than life expectancy (mortality) and felt that the reproductive rates of mammals might be depressed at doses that were 10% of

those leading to mortality. It also felt that some loss of oocytes might occur at 1% of the lethal dose, but because of excess oocyte production, fecundity should be affected to a lesser extent. Mice, exposed from conception to a dose rate of 800 µGy/h, could be made sterile at 25 weeks. In the most sensitive mammal studied, the beagle dog, a dose rate of 180 µGy/h caused progressive cell depletion and sterility within a few months, but a dose rate of 36 µGy/h over the whole life produced no damaging response. The Committee concluded that a radiation dose rate of less than 40 µGy/h to the most exposed individual in a population (and most probably, therefore a lower mean dose rate to individuals in the population as a whole) would be unlikely to have an impact on the overall reproductive capacity of a mammalian population as a consequence of the effects of radiation exposure on fertility, fecundity or the production of viable offspring.

181. The effects of radiation exposure on birds had been shown to be similar to those on small mammals. Reptiles and invertebrates were less radiosensitive, although physiological differences began to make direct comparisons with other species less appropriate. The chronic exposure of one short-lived species of lizard in enclosures had shown no evident effects when exposed over 5 years at a dose rate of 830 µGy/h. In two longer-lived species of lizard, some individuals had been made sterile after 3.5 years at a dose rate of 630 µGy/h in one species and after 5.5 years at a dose rate of 210 µGy/h in another species. Adult invertebrates were seemingly quite insensitive to the effects of radiation exposure in terms of induced mortality, but the process of gametogenesis, developing eggs and juvenile stages were more sensitive.

3. Aquatic organisms

182. A number of reviews of the studies of the effects of exposure to ionizing radiation on aquatic organisms were available to the Committee [A3, B9, C3, E2, I2, I3, N1, N2, P2, T5, W9] during the preparation of the annex of the UNSCEAR 1996 Report [U4]. Some of these had been prepared specifically to provide a basis for assessing the potential effects of discharges of liquid radioactive effluents on aquatic organisms in their natural environment [I2, I3, N1, N2, W1].

183. Among aquatic organisms, fish were the most sensitive to the effects of radiation exposure; the developing fish embryos were particularly sensitive. The LD_{50} for acute irradiation of marine fish was in the range 10–25 Gy for assessment periods of up to 60 days following exposure. The upper end of the range of LD_{50} for marine invertebrates had been found to be several hundred grays. Embryos, on the other hand, were affected at much lower doses, for example, the $LD_{50/90}$ for salmon embryos was 0.16 Gy [B10].

184. Chronic exposures at dose rates of 10–30 mGy/h had no effect on the mortality of snails, marine scallops, clams and blue crabs. Dose rates somewhat above this range had some effects on food-limited populations of *Daphnia pulex*. Short-term (40 days) exposure of mosquito fish at dose rates in the range 14–54 mGy/h showed no radiation-induced mortality, but, for the closely related guppy, there was some indication that long-term exposure (>470 days) at dose rates above 1.7 mGy/h reduced the normal lifespan, particularly for males.

185. Reproductive effects are a more sensitive indicator of radiation response for aquatic organisms. Chronic dose rates in the range 3.2–17 mGy/h reduced the reproductive capacity in the freshwater snail, *Physa heterostropha*, and in the marine polychaete worms, *Ophriotrocha diadema* and *Neanthes arenaceodentata*. Exposure at a dose rate of 7.3 mGy/h rendered male freshwater fish (*Ameca splendens*) effectively sterile after 50 days, and exposure at a dose rate of 1.7 mGy/h over the lifespan of pairs of guppies (the freshwater fish, *Poecilia reticulata*) significantly reduced the lifetime production of offspring [W7]. It had been concluded that significant effects on fish gonads from chronic radiation exposure would be unlikely at dose rates less than 1 mGy/h [I3, W1]. Overall consideration of the data available led to the conclusion that chronic irradiation at dose rates up to 400 µGy/h to a small proportion of the individuals in an aquatic population (and, therefore, with correspondingly lower average dose rates to the whole population) would not have any detrimental effects at the population level [I4, N1].

C. Effects of radiation exposure on populations of plants and animals

186. The Committee noted in the annex of the UNSCEAR 1996 Report [U4] that one of the difficulties in evaluating the effects of radiation exposure on populations and ecosystems was the determination of the parameters to measure. Typically measured attributes at the population level included numbers of individuals, mortality rate, reproduction rate and mean growth rate. The Committee also noted that measurable changes in populations and communities required rather severe effects to be induced at the cellular and individual organism levels [e.g. W8]. The Committee also noted that genetic or somatic mutations that could be produced by relatively low levels of exposure might have little or no impact on population or community performance because of natural selection [B10, C4, M2, P3, T5] and the convergence of genetic information among adjacent populations [R1, T5].

187. The Committee also noted that the effects of radiation exposure at the population and community levels were manifest as a combination of direct changes due to radiation damage and indirect responses to the direct changes. This seriously complicated the interpretation of the effects of radiation exposure on organisms in the natural environment. The wide range of radiosensitivities of the organisms that make up most natural communities creates a situation where, if doses are such that the sensitive species, but not the more resistant ones, are affected, the latter might gain a significant competitive advantage and increase in abundance or vigour.

This could erroneously be interpreted as a hormetic response; such a response might not however be produced if the resistant species alone were irradiated. This is but one of many examples of indirect response to the direct effects of radiation exposure.

188. Because of the compensation and adjustment possible in animal species, the Committee considered that it is unlikely that radiation exposures causing only minor effects on the most exposed individual would have significant effects on the population. Reproductive changes are a more sensitive indicator of the effects of radiation exposure than mortality, and mammals are the most sensitive animal organisms. On this basis, chronic dose rates of less than 100 µGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal communities. The Committee also concluded that maximum dose rates of 400 µGy/h to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level. These conclusions referred to the effects of low-LET radiation exposure. Where a significant part of the incremental radiation exposure comes from high-LET radiation (alpha particles), the Committee considered that it is necessary to take account of the different RBEs.

D. Effects of major accidents

189. The UNSCEAR 1996 Report [U4] discusses the effects of two accidents in the former Soviet Union (at Chernobyl and at Mayak in the south-eastern Urals) leading to major releases of radioactive material into the environment [A28, G19, I23, I24, K1, K22, K23, N9, S29, S34, S40, T4, T27]. These accidents provided opportunities to observe radiation-related changes in plant and animal communities. The Committee noted however that any major accident is likely to be unique in terms of the quantity and composition of the radioactive material released, the time course of the release, the dispersal and deposition patterns, which are governed by local and regional meteorological or hydrological conditions, and the biochemical and geochemical character of the areas subject to contamination. Where long-lived radionuclides are released, biochemical and geochemical processes would determine the long-term behaviour and redistribution of the radionuclides in the environment. Given this multiplicity of factors, any major nuclear accident would be expected to yield new radioecological information. However, the primary concern following an accidental release of radionuclides is to ensure that the radiation risks to human populations are controlled and minimized. Consequently, the only environmental information likely to be collected is that which is immediately necessary to meet this objective. Such information is unlikely to be sufficient for the purposes of developing a complete radioecological description of the situation. The larger the incident and the greater its potential human impact, the more limited would be the resources available to collect radioecological information, particularly in the early phase following the accident.

190. In particular, the data required to develop estimates of the radiation exposure of wild organisms (i.e. the space and time-dependent variations of the radionuclide concentrations, especially of the short-lived radionuclides both within the organisms and in their external environment immediately following an accident) would not be known. These variations would result in substantial intra-species and inter-species inhomogeneities in exposure and would pose considerable difficulties for establishing a clear and reliable relationship between cause (the accumulated radiation dose) and any observed effect. In practice, it is likely that estimates of the dose rates in the early period following the release would be calculated subsequently from the observed distribution of deposition densities of the longer-lived radionuclides, from a knowledge of the relative quantities of the radionuclides released, and using models of radionuclide behaviour in the environment. Such dose-rate estimates are inevitably imprecise and could be subject to significant systematic error.

191. The highly variable habits and target geometries of the wild organisms are additional complicating factors. These range, for example, from soil bacteria to single-celled algae and protozoa, and include a wide variety of terrestrial and aquatic invertebrates, mammals (ranging from shrews to deer) and large deciduous or evergreen trees. Plants provide a very high surface area to mass ratio (compared with animals) for deposition/adsorption of a radioactive aerosol. Because the leaves, flowers and terminal buds of plants are responsible for energy absorption, growth and reproduction, a coincidence arises between radionuclide accumulation (and hence radiation dose) and potential radiosensitivity. Other examples of coincidence are the surface litter layer and its populations of invertebrate decomposers in terrestrial environments, and surface sediments and benthic organisms in aquatic systems.

192. Depending on the quantities of specific radionuclides released following an accident, the radiation exposures might range from low (a few multiples of the natural background) to high (absorbed doses greater than 1 Gy). Different phases of biological response to the higher total doses might be distinguished. Initially, and, in particular if short-lived radionuclides made up a significant proportion of the release, there might be an acute phase in which total doses sufficient to produce immediate or relatively early detectable biological responses are accumulated. In the intermediate phase, dose rates would decrease owing to the decay of the short-lived radionuclides and possibly, but not necessarily, owing to the redistribution of the longer-lived radionuclides by natural processes. Even in this phase, the slower accumulation of radiation dose might still result in total integrated doses sufficient to prevent recovery of organisms damaged in the initial phase or lead to the appearance of medium-term damage. In the long-term phase, post-irradiation recovery (and adaptation) becomes apparent, provided that the initial and medium-term damage had not been large enough to radically alter the population or community structure.

III. SUMMARY OF DOSE–EFFECTS DATA FROM THE CHERNOBYL ACCIDENT

193. A great deal of scientific information concerning the effects of exposure to ionizing radiation has been developed from studies of non-human biota in the area surrounding the site of the Chernobyl accident. The follow-up studies provided the main source of new information on the effects of radiation exposure on non-human biota since the UNSCEAR 1996 Report [U4]. This area has a temperate climate and flourishing flora and fauna. Much of the new information, originally reported in Russian, has been summarized in a report prepared for the Committee [A5] and by the work of the Chernobyl Forum [E8]. The following discussion of radiation levels and effects on biota observed in the region around the Chernobyl nuclear power plant is based on information presented in reference [E8] and in other recent reviews [G26].

A. Radiation exposure

194. The Chernobyl Forum Expert Group on Environment (EGE) [E8] noted that the effects of the Chernobyl accident should be studied within specific time periods. Three distinct phases of radiation exposure have been identified in the area local to the accident [U4]. In the first 20 days, radiation exposures were essentially acute because of the large quantities of short-lived radionuclides present in the passing cloud (^{99}Mo, ^{132}Te/I, ^{133}Xe, ^{131}I and ^{140}Ba/La). Most of these short-lived, highly radioactive nuclides deposited onto plant and ground surfaces, resulting in gamma radiation dose rates of up to about 20 Gy/d. However, for surface tissues and small biological targets (e.g. mature needles and the growing buds of pine trees) there was a considerable additional dose rate due to the beta radiation from the deposited radionuclides. High doses to the thyroids of vertebrate animals also occurred during the first days/weeks following the accident owing to the inhalation and ingestion of radioactive isotopes of iodine and their radioactive precursors.

195. The second phase of radiation exposure extended through the summer and autumn of 1986, during which time the short-lived radionuclides decayed and the longer-lived radionuclides were transported to different components of the environment by physical, chemical and biological processes. Dominant transportation processes included rain-induced transfer of radionuclides from plant surfaces onto soil, and bioaccumulation through plant tissues. Dose rates at the soil surface declined to much less than 10% of the initial values owing to radioactive decay of the short-lived radionuclides, but damaging total doses were still accumulated. Approximately 80% of the total radiation dose accumulated by plants and animals was received within 3 months of the accident, and over 95% of this was due to beta radiation exposure [E8]. Measurements made with thermoluminescent dosimeters on the soil surface at sites within the 30-km exclusion zone indicated that the ratio of beta to gamma dose was about 26:1, (i.e. 96% of the total dose was due to beta radiation exposure) [P18].

196. The EGE [E8] also defined a third (and continuing) phase of radiation exposure with chronic dose rates less than 1% of the initial values and derived mainly from ^{137}Cs. With time, the decay of the short-lived radionuclides and the migration of much of the remaining ^{137}Cs into the soil meant that the contributions to the total radiation exposure from the beta and gamma radiations tended to become more comparable. Reference [E8] noted that the balance depended on the degree of bioaccumulation of ^{137}Cs in organisms and the behaviour of the organism in relation to the main source of external exposure resulting from the ^{137}Cs in the soil.

B. Effects of radiation exposure on plants

197. The report of the EGE was a great advance on previous publications describing the follow-up work on the effects of the Chernobyl accident. In particular, the report gave considerable attention to evaluating the dosimetry of, and consolidating the information on the effects on non-human biota. Thus, given both the greatly improved quality of the data and the comprehensive nature of the evaluation provided by the EGE, much of the following discussion is adapted from reference [E8].

198. Doses received by plants arising from the deposited radionuclides resulting from the Chernobyl accident were influenced by the physical properties of the various radionuclides (i.e. their half-lives, radiation emissions, etc.), the physiological stage of the plant species at the time of the accident, and the different species-dependent propensities to take up radionuclides into critical plant tissues [E8]. The occurrence of the accident in late April 1986 was thought to have enhanced the damaging effects of the deposition because it coincided with the period of accelerated growth and reproduction of plants.

199. The deposition of beta-emitting radionuclides onto critical plant tissues resulted in their having received a significantly larger dose than animals living in the same environment [P18, P19]. According to reference [G9], large apparent inconsistencies in the dose–response observations occurred when the beta-irradiation component was not appropriately taken into account.

200. Within the 30-km zone around the Chernobyl plant, the doses to plants associated with the deposition of total beta activity (0.7–3.9 GBq/m^2) were sufficient to cause short-term sterility and reduction in productivity of some species [P19]. By August 1986, crops that had been sown prior to the accident began to emerge. Growth and development problems were observed in plants in fields with deposition densities of 0.1–2.6 GBq/m^2 of total beta activity, and with estimated dose rates initially received by the plants having reached 300 mGy/d. Spot necroses on leaves, withered tips of leaves, inhibition of photosynthesis, transpiration and metabolite

synthesis were detected, as well as an increased incidence of chromosome aberrations in meristem cells [S22]. The frequency of various anomalies in winter wheat exceeded 40% in 1986–1987, with some abnormalities apparent for several years afterwards [G12].

201. Coniferous trees were already known to be among the more radiosensitive plants, and the pine forests, 1.5–2 km west of the Chernobyl nuclear power plant, received sufficient doses, more than 80 Gy, at dose rates that exceeded 20 Gy/d, to cause mortality [T18]. The first signs of radiation injury were yellowing and needle death in pine trees in close proximity to the nuclear power plant and appeared during the summer of 1986. The colour of the dead pine stands resulted in the forest being referred to as the "red forest".

202. Tikhomirov and Shcheglov [T18] and Arkhipov et al. [A11] found that mortality rate, reproduction anomalies, stand viability, and re-establishment of pine-tree canopies were dependent on absorbed dose. Acute irradiation of *Pinus silvestris* at doses of 0.5 Gy caused detectable cytogenetic damage; at doses of more than 1 Gy, growth rates were reduced and morphological damage occurred; and, at more than 2 Gy, the reproductive abilities of trees were altered. Doses of less than 0.1 Gy did not cause any visible damage to the trees. Table 23 shows the variation in activity concentration and dose among pine trees within the 30-km zone. The radiosensitivity of spruce trees was observed to be greater than that of pines. At absorbed doses as low as 0.7–1 Gy, spruce trees had malformed needles, buds and shoot growth [K1].

203. About 90% of the absorbed dose to critical parts of the trees was due to beta irradiation from the deposited radionuclides with the remaining 10% from gamma irradiation. Table 22 summarizes the external gamma dose rates and the internal radionuclide concentrations in the conifers around the Chernobyl plant. By 1987, recovery processes were evident in the surviving tree canopies and the forests were re-establishing themselves where the trees had perished [A11]. In the decimated pine stands, a sudden invasion of pests occurred that later spread to adjoining areas. Grassland, with a slow invasion of self-seeding deciduous trees, has now replaced the deceased pine stands. Four distinct zones of radiation-induced damage to conifers were discernable (table 23).

Table 22. Activity concentration in needles of coniferous trees and estimated external gamma dose rates in October 1987 as a function of distance from the Chernobyl nuclear power plant

For azimuth 205 to 260 degrees (adapted from reference [K12])

Distance from NPP (km)	*External exposure rate (μGy/h)*[a]	*Accumulated external dose (mGy)*[a]	*Activity concentration in needles (kBq/kg)*					
			^{144}Ce	*^{106}Ru*	*^{95}Zr*	*^{95}Nb*	*^{134}Cs*	*^{137}Cs*
2	2 500	126 000	13 400	4 100	800	1 500	1 500	4 100
4	120	5 000	150	60	8	15	17	72
16	0.4	14	1.5	0.6	0.1	0.17	0.18	0.55

[a] Based on gamma radiation levels at 1 m height above the soil surface. The values given in the original reference were in mR/h and have been converted assuming 1 mR/h is equivalent to 10 μGy/h.

Table 23. Zones and corresponding damage to coniferous forest in the area around the Chernobyl nuclear power plant (from reference [K1])

Zone and classification	*External gamma dose (Gy)*	*Exposure rate (μGy/h)*[a]	*Internal dose to needles (Gy)*
Conifer death (4 km^2) Complete death of pines Partial damage to deciduous trees	over 80–100	over 5 000	over 100
Sublethal (38 km^2) Death of most growth points Partial death of coniferous trees Morphological changes to deciduous trees	10–20	2 000–5 000	50–100
Medium damage (120 km^2) Suppressed reproductive ability Dried needles, morphological changes	4–5	500–2 000	20–50
Minor damage Disturbances in growth, reproduction and morphology of coniferous trees	0.5–1.2	<200	<10

[a] The values given in the original reference were in mR/h and have been converted assuming 1 mR/h is equivalent to 10 μGy/h.

C. Effects of radiation exposure on soil invertebrates

204. Between 60% and 90% of the initial fallout of radionuclides was captured by the forest canopy and other plants [E8]; however, within weeks to a few months, the processes of wash-off by rain and leaf fall removed most of the initial deposition to the litter and soil layers, where soil and litter invertebrates were exposed to high radiation levels for protracted time periods. The timing of the accident coincided with the most radiosensitive life stages of the soil invertebrates: reproduction and moulting following their winter dormancy [T18]. Within two months after the accident, the numbers of invertebrates in the litter layer of forests 3–7 km from the nuclear power plant were reduced by a factor of 30 [K11], and reproduction was strongly impacted (larvae and nymphs were absent). These effects corresponded to doses of approximately 30 Gy (estimated from TLDs placed in the soil) resulting in mortality of eggs and early-life stages, as well as reproductive failure in adults. However, within a year of the accident, reproduction of invertebrates in the forest litter resumed, due, in part, to the migration of invertebrates from less contaminated sites. After 2–3 years, the ratio of young to adult invertebrates in the litter layer, as well as the total mass of invertebrates per unit area, were no different from those in control sites; however, species diversity remained markedly lower [K11]. As noted in the report of the EGE [E8], this is important since the diversity of invertebrate species within the soil facilitates an analysis of the community-level effects of radiation exposure (i.e. changes in species composition and abundance). For example, only five species of invertebrates were found in 10 soil cores taken from pine stands in July 1986, 3 km from the Chernobyl nuclear power plant, compared to 23 species at a control site 70 km away. The mean density of litter fauna was reduced from 104 individuals per 225 cm^2 core at the control location to 2.2 at the 3-km site. Six species were found in all 10 cores taken from the control site, whereas no one species was found in all 10 cores from the 3-km location [K13]. The number of invertebrate species found in the heavily contaminated sites was only half that of controls in 1993, and complete species diversity did not recover until 1995, almost 10 years after the accident [K11].

205. A fourfold reduction in earthworm numbers was found in arable soils, but no catastrophic mortality in any group of soil invertebrates was observed. The dose to invertebrates in forest litter was 3–10 fold higher than that to those residing in unploughed surface soil since the radionuclides deposited on the surface had not migrated downwards. The result was no reduction in the numbers of soil invertebrates below a depth of 5 cm in the soil as they were shielded by the overlying soil [K11].

206. Although, the researchers were unclear if sterility of invertebrates occurred in the heavily contaminated sites around the Chernobyl nuclear power plant [K11], the 30 Gy cumulative dose reported in the field studies was within the range of experimental doses used to control pest insects by external irradiation. A recent review indicated that most insect, mite and tick families require a sterilization dose of less than 200 Gy [B40], although the sterilization dose for some insects and related arthropods is much lower than this and varies widely. As was found for plants [S2], the radiosensitivity of insects is related to the average interphase nuclear volume [B40].

D. Effects of radiation exposure on farm animals

207. Ruminants, both domestic (cattle, goats and sheep) and wild (elk and deer), generally receive relatively high doses in radioactively contaminated environments, because they consume large amounts of vegetation, and many radionuclides accumulate in their bodies. For example, a single cow consumes about 75 kg of fresh grass each day.

208. In the period shortly after the accident, domestic livestock within the 30-km zone were exposed to high levels of radioactive iodine (^{131}I and ^{133}I with half-lives of 8 days and 21 hours, respectively). This resulted in significant internal and external doses due to beta and gamma radiation exposure (table 24). A dose of about 76 Gy is sufficient to cause harm to the thyroid gland [B23]. Soils of Ukraine and Belarus are naturally low in stable iodine, cobalt and manganese. In conditions of endemic deficiency of stable iodine, the transfer of radioactive iodine from blood to the thyroid gland may be 2–3 times greater than normal [P19]. These conditions accentuated the consequences of the accident.

Table 24. Doses to cattle that stayed in the 30-km zone around the Chernobyl plant from 26 April to 3 May 1986 [K12]

Distance from nuclear power plant (km)	*Surface activity (10^8 Bq/m^2)*	*Absorbed dose (Gy)*		
		Thyroid	*GI tract*	*Whole body internal*
3	8.4	300	2.5	1.4
10	6.1	230	1.8	1.0
14	3.5	260	1.0	0.6
12	2.4	180	0.7	0.4
35	1.2	90	0.4	0.2

209. Depressed thyroid function in cattle was related to the dose received (69% and 82% reductions in function with thyroid doses of 50 Gy and 280 Gy, respectively). The concentration of thyroid hormones in the blood of animals was lower than the physiological norm during the whole lactation period. Radiation damage to the thyroid gland was confirmed by histological studies (i.e. hyperplasia of connective tissue and sometimes adipose tissue, vascular hyperaemia and necrosis of epithelium). Animals with practically no thyroid tissue were observed in Ukraine. Disruptions of the hormonal status in calves born to cows with irradiated thyroid glands were especially pronounced [A12]. Similar effects were observed in cattle evacuated from the Belarusian portion of the 30-km zone [I18].

210. Although most livestock were evacuated from the area after the accident, several hundred cattle were maintained in the more contaminated areas for a 2–4 month period. By autumn 1986, some of these animals had died; others showed impaired immune responses, lowered body temperatures and cardiovascular disorders. Hypothyroidism lasted until 1989, and may have been responsible for reproductive failures in animals that received thyroid doses of more than 180 Gy [I18]. Offspring of highly exposed cows had reduced weight, reduced daily weight gains, and signs of dwarfism. Reproduction returned to normal in the spring of 1989. Haematological parameters were normal for animals kept in areas with ^{137}Cs deposition densities of 0.2–1.4 MBq/m^2 (5–40 Ci/km^2) [A12].

211. No increase in the rates of birth defects were detected above background levels at annual doses below about 0.05 Gy [P17].

E. Effects of radiation exposure on other terrestrial animals

212. Surveys and autopsies of wildlife and of abandoned domestic animals that remained within 10 km of the Chernobyl nuclear power plant were conducted four months after the accident. [K11]. Fifty species of birds were identified, including some rare ones; all appeared normal in appearance and behaviour. No dead birds were found. Swallows and house sparrows were found to be producing progeny that also appeared normal. Forty-five species of mammals from six orders were observed and no unusual appearances or behaviours were noted.

213. In a review of thirty-three studies of the biological consequences of the Chernobyl accident, Møller and Mousseau [M19] commented on various increases in mutations and cytogenetic abnormalities attributed to elevated radiation levels. They noted that the fitness consequences of such increases were largely unknown and cited a study of differences in phenotypes in barn swallows from near Chernobyl and those from relatively uncontaminated control areas [M18]. The authors suggested that mutations with slightly negative fitness effects could have been exported from the contaminated zones and potentially affected unexposed populations. In an exchange of views, Møller et al. [M17, M20] challenged the hypothesis of Smith [S26] that the impacts on barn swallows arose from factors other than radiation exposure, namely the change in habitat and wildlife community arising from changes in agricultural practices resulting from efforts to reduce the spread of radioactively contaminated food. Smith however noted that the most contaminated sites were located within abandoned lands, which had large differences in both land use and ecology from the control sites.

214. Some wildlife and domestic animals were shot and autopsied in August and September 1986. Dogs and chickens showed signs of chronic radiation syndrome (reduced body mass; reduced fat reserves; increased mass of lymph nodes, liver and spleen; haematomas present in liver and spleen; and thickening of the lining of the lower intestine). No eggs were found in the nests of chickens, nor in their ovaries.

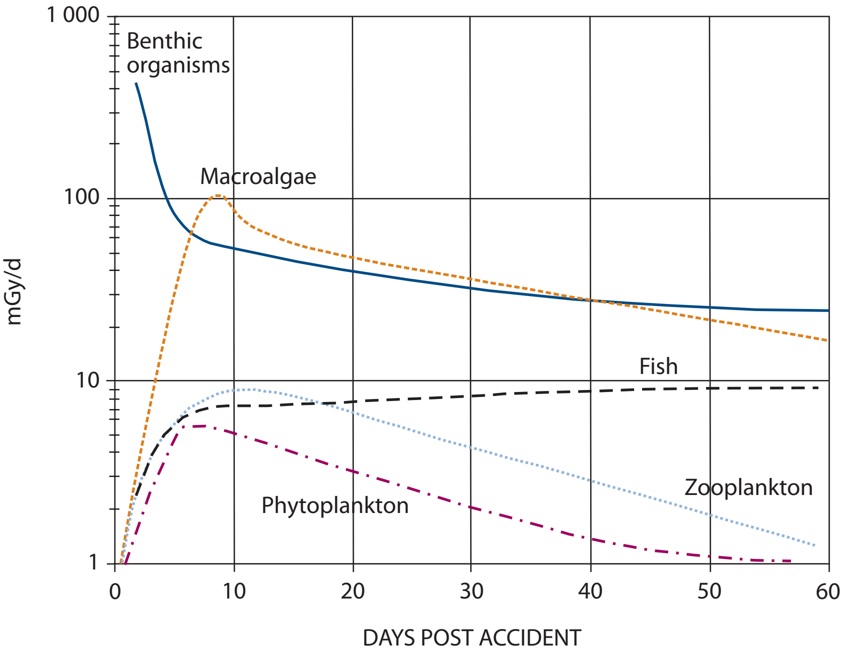
215. During the autumn of 1986, the number of small rodents on highly contaminated research plots decreased by a factor of 2–10. Estimates of absorbed doses during the first five months after the accident ranged from 12–110 Gy for gamma and 580–4,500 Gy for beta irradiation. By the spring of 1987, the numbers of animals were recovering, mainly due to immigration from less affected areas. In 1986 and 1987, the percentage of pre-implantation deaths in rodents in the highly contaminated areas was 2–3 fold greater than that in the controls. Resorption of embryos also increased markedly in rodents from the impacted areas; however, the number of progeny per female did not differ from that of the controls [T16].

F. Effects of radiation exposure on aquatic organisms

216. Cooling water for the Chernobyl nuclear power plant was obtained from a 21.7 km^2 man-made reservoir located to the south-east of the plant site. The cooling reservoir became heavily contaminated following the accident with a total activity of over 6.5 ± 2.7 PBq of a mixture of radionuclides (alpha and beta emitters) in the water and sediments [K14]. Aquatic organisms were exposed to external radiation from the radionuclides in the water, contaminated bottom sediments, and aquatic plants. Internal irradiation occurred as organisms took up radionuclides in their food and water or inadvertently consumed contaminated sediments. The resultant doses to aquatic biota over the first 60 days following the accident are depicted in figure XI.

Figure XI. The dynamics of absorbed dose rate to organisms within the Chernobyl nuclear power plant cooling pond during the first 60 days following the accident

Data are model results based on concentrations of radionuclides in the water column and lake sediments (adapted from reference [K12])



217. The maximum dose rates to aquatic organisms (excluding fish) were reported in the first two weeks after the accident, when short-lived radionuclides (primarily ^{131}I) contributed 60–80% of the dose. During the second week, the contribution of short-lived radionuclides to the doses of aquatic organisms decreased by a factor of two. Maximum dose rates to fish were delayed (see figure XI) owing to the time required for their food webs to become contaminated with longer-lived radionuclides (largely ^{134,137}Cs, ^{144}Ce/Pr, ^{106}Ru/Rh and ^{90}Sr/Y). The dose rates to fish depended on their trophic positions. Non-predatory fish (carp, goldfish and bleak) incurred estimated peak dose rates of 3 mGy/d due to internal exposure in 1986, followed by significant reductions in 1987. Dose rates to predatory fish (perch), however, increased in 1987 and did not start to decline until 1988 [K12]. Accumulated doses were greatest for the first generation of fish born in 1986 and 1987. Bottom-dwelling fish (goldfish, silver bream, bream and carp) that were significantly irradiated by the bottom sediments accumulated total doses of approximately 10 Gy.

218. The reproductive capacity of young silver carp was analysed in 1990 [R10]. The fish were in live boxes within the cooling pond at the time of the accident. By 1988, the fish had reached sexual maturity. Over the entire post-accident period, they received a dose of 7–8 Gy. Biochemical analyses of muscles, liver and gonads indicated no difference from the controls. The amount of fertilized spawn was 94%; 11% of the developing spawn was abnormal. Female fertility was 40% higher than that of the controls, but 8% of the irradiated sires were sterile. The level of fluctuating asymmetry in offspring did not differ from that of the controls, although the level of cytogenetic damage (22.7%) significantly exceeded that of controls (5–7%). In contrast, Pechkurenkov [P20] reported that the number of cells with chromosome aberrations in 1986–1987 in carp, bream flat and silver carp was within the norm. It is worth noting that the cooling pond was subjected not only to radioactive contamination, but also to chemical pollution. Table 25 provides a summary of the recent reviews of the chronic effects of ionizing radiation exposure on the reproduction in fish. The Chernobyl accident data are included.

Table 25. Chronic effects of exposure to ionizing radiation on reproduction in fish

Derived from the FASSET database [C11]

Dose rate (µGy/h)	*Dose rate (mGy/d)*	*Reproductive effects*
0–99	0–2.4	Background dose group, normal cell types, normal damage and normal mortality observed
100–199	2.4–4.8	No data available

Dose rate (µGy/h)	*Dose rate (mGy/d)*	*Reproductive effects*
200–499	4.8–12	Reduced spermatogonia and sperm in tissues
500–999	12–24	Delayed spawning, reduction in testis mass
1 000–1 999	24–48	Mean lifetime fecundity decreased, early onset of infertility
2 000–4 999	48–120	Reduced number of viable offspring Increased number of embryos with abnormalities Increased number of smolts in which sex was undifferentiated Increased brood size reported Increased mortality of embryos
5 000–9 999	120–240	Reduction in number of young fish surviving to 1 month of age Increased vertebral abnormalities
>10 000	>240	Inter-brood time tends to decrease with increasing dose rate Significant reduction in neonatal survival Sterility in adult fish Destruction of germ cells within 50 days in medaka fish High mortality of fry, germ cells not evident Significant decrease in number of male salmon returning to spawn; after 4 years, female salmon had significantly reduced fecundity

G. Genetic effects in animals and plants

219. High quality data on the incidence of radiogenic mutations in plants and animals as a result of the accident are relatively sparse. An increased mutation level was apparent in 1987 in the form of various morphological abnormalities in Canada fleabane, common yarrow and mouse millet. Examples of abnormalities included: unusual branching of stems; doubling the number of racemes; abnormal colour and size of leaves and flowers; and development of "witch's broom" in pine trees. Similar effects within 5 km of the nuclear power plant also appeared in deciduous trees (leaf gigantism, and changes in leaf shapes). Morphological changes were observed at an initial gamma dose rate of 4.2–6.3 mGy/d. At a dose rate of 15.8–31.5 mGy/d, enhancement of vegetative reproduction (in heather) and gigantism of some plant species were observed [A11, K10, T17, T18].

220. Cytogenetic analysis of cells from the root meristem of winter rye and wheat germ of the 1986 harvest demonstrated a dose dependency in the number of aberrant cells. A significant excess over the control level of aberrations was observed at an absorbed dose of 3.1 Gy. Inhibition of mitotic activity occurred at a dose of 1.3 Gy, and germination was reduced at a dose of 12 Gy [G10]. The analysis of three successive generations of winter rye and wheat on the most contaminated plots revealed that the rates of aberrant cells in the intercalary meristem in the second and third generations were higher than in the first.

221. From 1986–1992, mutation dynamics were studied in populations of *Arabidopsis thaliana Heynh.* (L.) within the 30-km zone [A10]. On all study plots during the first 2–3 years after the accident, *Arabidopsis* populations exhibited an increased mutation burden. In later years, the level of lethal mutations declined; nevertheless the mutation rate in 1992 was still 4–8 times higher than the spontaneous level. The dose dependence of the mutation rate was best approximated by a power function with an exponent value of less than one.

222. Zainullin et al. [Z2] observed elevated levels of sex-linked recessive lethal mutations in natural *Drosophila melanogaster* populations living under conditions of increased chronic exposure to radiation resulting from the Chernobyl accident. The mutation levels were increased during 1986–1987 in flies inhabiting the more contaminated areas with initial exposure rates of 2 mGy/h (expressed as 200 mR/h in the original text) and more. During the subsequent two years, mutation frequencies gradually returned to normal.

223. Shevchenko et al. [S21] and Pomerantseva et al. [P16] reported studies of adverse genetic effects in wild mice. These involved mice caught during 1986–1991 within a 30-km radius of the Chernobyl nuclear power plant with different levels of gamma radiation exposure and, during 1992–1993, on a site in the Bryansk Oblast, Russia. The estimated total doses of gamma and beta radiation varied widely; the dose rates reached 3–4 Gy per month in 1986–1987. One endpoint was dominant lethality, measured by embryo mortality in the offspring of wild male mice mated with unexposed female laboratory mice. The dominant lethality rate was elevated for a period of a few weeks following capture in mice sampled at the most contaminated site. At dose rates

of about 2 mGy/h, 2 of 122 captured males produced no offspring and were assumed to be sterile. The remainder showed a period of temporary infertility and reduced testis mass. Fertility and testis mass, however, recovered with time after capture.

224. The frequencies of reciprocal translocations in mouse spermatocytes were consistent with previous studies. A dose-rate-dependent incidence of increased reciprocal translocations (scored in spermatocytes at meiotic metaphase I) was observed in all collected mice. The frequency of mice harbouring recessive lethal mutations decreased with time after the accident [P16]. Radiation-related gene mutation is unlikely to have any adverse effect on populations, at the dose rates that prevail now.

225. Increasing sophistication in the technologies for the detection of molecular and chromosomal damage have allowed researchers on the genetic consequences of the Chernobyl accident to examine endpoints not previously considered [E8]. Most prominent, and controversial, is the technique involving the measurement of mutation frequencies in repeat DNA sequences termed “minisatellite loci” or “expanded simple tandem repeats” (ESTR). These are repeat DNA sequences that are distributed throughout the germline and have a high background (spontaneous) mutation rate. Presently, ESTRs are considered to have no function, although this is a matter of much interest and discussion [B33, C10, I9]. Minisatellite mutations have only rarely been associated with recognizable genetic disease.

226. Although laboratory examination of mutations in mouse ESTR loci show clear evidence of a mutational dose response [D4, F16], the EGE was not aware of any convincing data on elevated levels of minisatellite mutations in plants or animals residing in the contaminated areas having been published in peer-reviewed scientific literature [E8]. In general, quantitative interpretation of the ESTR data is difficult because of conflicting findings, their weak association with genetic disease, dosimetric uncertainties and methodological problems [C10]. This is an area of science that requires additional research.

H. Overall observations on the effects of the Chernobyl accident

227. According to the EGE [E8], prior to the accident, much of the area around the Chernobyl nuclear power plant was covered by 30–40 year old pine stands that, from a successional standpoint, represented mature, stable ecosystems. The high dose rates due to ionizing radiation exposure during the first few weeks following the accident altered the balance in the community and opened niches for immigration of new individuals.

228. The ecological conditions within the 30-km Chernobyl exclusion zone arose from the complex interaction of a number of factors. The highest level of contamination occurred within this zone. As a result of the elevated radiation doses associated with the contamination, human activities such as agriculture, forestry, hunting and fishing within the exclusion zone were stopped [E8]. After the accident, the fields continued to yield agricultural produce for a number of years and, in the absence of active management in the areas that had been evacuated, many animal species, especially rodents and wild boars, consumed the abandoned cereal crops, potatoes and grasses as an additional source of forage [E8]. This was advantageous to these animal species and, along with the special reserve regulations established in the exclusion zone (e.g. a ban on hunting), tended to compensate for the adverse biological effects of radiation exposure and promoted an increase in the populations of wild animals, including game mammals (wild boars, roe deer, red deer, elk, wolves, foxes, hares, beaver, etc.) and bird species (black grouse, ducks, etc.) [G8, S23]. In addition, the Chernobyl exclusion zone has become a breeding area of white-tailed eagles, spotted eagles, eagle owls, cranes and black storks [G9].

229. The high dose rates from ionizing radiation during the first few weeks following the Chernobyl accident affected the balanced community by killing sensitive individuals, altering reproduction rates, destroying some resources (e.g. pine stands), making other resources more available (e.g. soil water), and opening niches for immigration of new and sometimes negative organisms (e.g. negative entofauna). These components and more, were interwoven in a complex web of action and reaction that altered populations and communities of organisms [E8].

230. Overall, the EGE [E8, H25] arrived at a number of general observations from their evaluation of the Chernobyl data, namely that:

- Radiation from radionuclides released as a result of the Chernobyl accident caused numerous acute adverse effects on the biota located in the areas of highest exposure (i.e. up to a distance of a few tens of kilometres from the release point). Beyond the exclusion zone, no acute radiation-induced effects on biota have been reported;
- The environmental response to the increased radiation exposure incurred as a result of the Chernobyl accident was a complex interaction among radiation dose, dose rate and its temporal and spatial variations, as well as the radiosensitivities of the different taxons. Both individual and population effects caused by radiation-induced cell death were observed in plants and animals and included increased mortality of coniferous plants, soil invertebrates and mammals; reproductive losses in plants and animals; and chronic radiation sickness in animals (mammals, birds, etc.);
- No adverse radiation-induced effects were reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy during the first month after the accident (i.e. <10 mGy/d, on average); and

– Following the natural reduction of exposure levels due to radionuclide decay and migration, populations have been recovering from acute radiation effects. By the next growing season following the accident, the population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from the major radiation-induced adverse effects on plants and animals.

231. Fesenko et al. have compared the relative radiological impact on people and non-human biota arising from the Chernobyl accident [F17]. They reviewed the data on reference dose rates for non-human biota (which they refer to as critical exposure doses or CDV_b below which an effect would not be expected). The authors adopted the commonly used endpoints of early mortality, morbidity, reduced reproductive success and deleterious genetic effects. Their values of CDV_b for non-human biota near Chernobyl are summarized in table 26. They noted that coniferous trees were known to be among the most radiosensitive components of the biosphere and indicated that the minimum dose rate at which morphological changes have been seen in the Chernobyl zone was about 1.2 mGy/d. The authors also indicated that this dose rate is about nine times lower than the reference dose rate provided in reference [U4] but suggested that such discrepancies can be explained by the use of generic reference dose rates for all terrestrial plants rather than for specific plants. For herbaceous plants, they suggested a reference dose rate of about 8.2 mGy/d [F17] which is comparable to the value suggested in reference [U4]. For cattle, they suggested a reference dose rate of about 1.6 mGy/d based on data given in references [C16, S36] but go on to indicate that radiation harm to farm animals in the Chernobyl zone was more related to damage to the thyroid from internally deposited radionuclides. Based on the assumption that impairment of reproduction usually occurs at doses about one order of magnitude below the LD_{50} of about 0.8 Gy and on observed reductions in the numbers of invertebrates, the authors [F17] suggested a reference dose rate of about 2.5 mGy/d. Finally, for aquatic systems, the authors [F17] suggested that fish are generally more radiosensitive than plankton and zoobenthos and proposed a reference dose rate of about 1.6 mGy/d.

Table 26. Review of CDV_b for non-human species inhabiting the study area
(adapted from reference [F17])

Non-human species	*CDV_b (mGy/d) cited in [F17]*	*Literature data*
Terrestrial ecosystems		
Coniferous trees (pine)	1.1	1.1 [S35], 2.4 [C16], 10 [U4]
Herbaceous plants (meadow grasses)	8.2	1.1 [S35, S36], 2.4 [C16], 10 [U4]
Herbaceous plants (cereals)	8.2	1.1 [S35, S36], 2.4 [C16], 10 [U4]
Cattle	1.6 (137[a])	1.1 [S36], 2.5 [C16]
Mouse-like rodents	1.1	0.1 [S35], 0.2 [S36], 1 [C16], 1 [U4], 2.7 [B31]
Soil invertebrates	2.5	1.1 [S35, S36], 2.4 [C16], 5.5 [B31]
Aquatic ecosystems		
Phytoplankton	8.2	2.4 [C16], 2.7 [B31]
Zooplankton	6.8	2.4 [C16], 2.7 [B31]
Zoobenthos	2.5	1.6 [C16], 5.5 [B31]
Fish	1.6	0.3 [S35], 0.5 [C16], 0.5 [B31], 10 [U26]

[a] Dose to the thyroid.

232. Another report provided a comprehensive evaluation of the effects of radiation exposure resulting from the Chernobyl accident on non-human biota along with corresponding dosimetry information [G26]. In total, 250 references were evaluated. Of these, some 79 papers were considered to have adequate information on environmental contamination and doses to biota. The review focussed on the assessment of the effects of radiation exposure on plants and animal populations inhabiting the contaminated areas around Chernobyl at the time of, and following, the accident [G26]. As described earlier, the radiation doses associated with the first phase following the Chernobyl accident was a period of short-term quite high radiation dose rates followed by a period with a gradual decline in dose rate. The most severe

environmental effects were associated with the high dose rates. Effects of radiation exposure were seen in both natural and agricultural systems. The authors noted that the effects depended on the radiosensitivity of the dominant species and observed that coniferous trees were one of the most sensitive plant species and mammals were the most radiosensitive animal species [G26]. To date, reference [G26] provides the most comprehensive evaluation of observations of the effects of the Chernobyl accident on non-human biota. The key observations from the review are summarized in table 27, which shows various effects on non-human biota around Chernobyl and the corresponding doses below which such effects were not observed.

233. The reliability of the estimated doses arising from the Chernobyl accident has been examined by the Chernobyl Forum [E8]. Table 27 provides a summary of the information on the effects and associated doses and dose rates from studies of non-human biota around the Chernobyl nuclear power plant. However, given the importance of this topic, a few additional comments are appropriate. The available information indicates that the forest close to the Chernobyl power plant captured much of the radioactive dust following the accident, reducing the spread of radioactive material outside the 10-km zone [A11]. The dose rate within the 10-km zone showed an exponential decay, with the majority of the total dose absorbed by the environment within the first month [A11, K20, S30]. Thus, the Committee has assumed, in table 27, that most (80% or so) of the dose would have been delivered in (about) the first month following the accident. Where appropriate for comparison purposes, a notional daily dose rate was derived by dividing the reported doses by 30.

Table 27. Effects on populations of non-human biota around the Chernobyl power plant [G26]

Species effect	*Estimated minimum doses (or dose rates) at which effect was observed*	*Estimated maximum doses (or dose rates) at which effect was not observed*
Scots pine		
Death of weakened trees	8–12 Gy [A11, K20]	5 Gy
Mass death of young cones and anthers	10–12 Gy [S29]	5 Gy
35–40 years old, mass yellowing of needles	8–12 Gy [K20]	5 Gy
Inhibition of reproductive capacity (reduced number of seeds per cone and increased fraction of hollow seeds)	1–5 Gy [F10]	0.5 Gy
Morphological disturbances one year after accident	0.1–1.0 Gy [A11]	0.05 Gy
Significant increase in cytogenetic effects in seedlings and needles	0.5 Gy [F10]	0.05 Gy
Frequency of mutations of enzyme loci in seed endosperm	0.07 Gy [F10]	0.01 Gy
Spruce		
10–15 years old. Death of trees	4–5 Gy [K20]	1 Gy
25 years old. Dying-off of young sprouts. Mortality of much of the trees within 2–3 years	8–10 Gy [K21]	5 Gy
40 years old. Noticeable reduction in sprout mass	2.5–3 Gy [K21]	1 Gy
Mass yellowing of needles	3.5–5 Gy [K21]	2 Gy
Herbaceous plants		
Reduced density of plants and species diversity in following year	17 mGy/d [S30]	10 mGy/d
Morphological changes	4.2–6.3 mGy/d [S30]	2 mGy/d
Enhanced vegetative reproduction and gigantism of some herbaceous species	16–30 mGy/d [S30]	10 mGy/d
Sterility of seeds	40 Gy – vetch; 10 Gy – dandelion and arabidopsis [S30]	5 Gy
Decrease in the number of peas in pods of wild vetch, increase in both fraction of sterile pods and fraction of embryonic lethalities	0.4 mGy/d [S31]	0.1 mGy/d
Soil fauna		
Drastic decrease in the population density and species composition of forest litter mesofauna	Dose absorbed on the soil surface 9 Gy [K13]	1 Gy

Species effect	*Estimated minimum doses (or dose rates) at which effect was observed*	*Estimated maximum doses (or dose rates) at which effect was not observed*
Amphibians (brown frogs)		
Increased yield of chromosome aberrations and damage severity in aberrant cells	Dose rate, mGy/d: 0.01 from ^{90}Sr to bone tissue, 0.038 from other sources to the whole body, 0.013 from external γ-radiation exposure [E18, E19]	0.01 mGy/d
Hydrobionts		
Silver carp. Higher occurrence of reproduction system alterations, reduced viability of progeny	9–11 Gy for 5 years [B19, M21]	1 Gy/a
Small mammals		
Inhibition of reproductive capacity (the significantly reduced testis mass as well as irreversible or temporary sterility in some males)	Absorbed gonad doses of 3 Gy per month [P16]	1 Gy/a
Pathological changes in haemopoietic system, liver, adrenals and thyroid	Absorbed dose from external γ-radiation exposure from the moment of accident till animal catching in autumn 1986 was 1 Gy. Contribution of β-radiation was 2–5 times higher than γ and incorporated radionuclides by 1–2 orders lower than from external [E20, M22]	0.5 Gy
A dose-dependent increase in the frequencies of chromosome aberrations in bone marrow cells and embryonic losses in bank voles, high frequency of polyploid cells and genome mutations	Whole-body absorbed dose rate in 1986: approximately 6–600 μGy/d [R17]	5 μGy/d
Cattle		
Destruction of thyroid, chronic radiation disease	Doses absorbed by thyroid $>$200 Gy, with dose to the whole body being no more than 0.2 Gy [A24, B16]	20 Gy to thyroid[a]

[a] Effect in the early days after the accident was mainly determined by ^{131}I action and depended greatly on content of stable iodine in animal ration.

IV. EFFECTS OF RADIATION EXPOSURE ON NON-HUMAN BIOTA

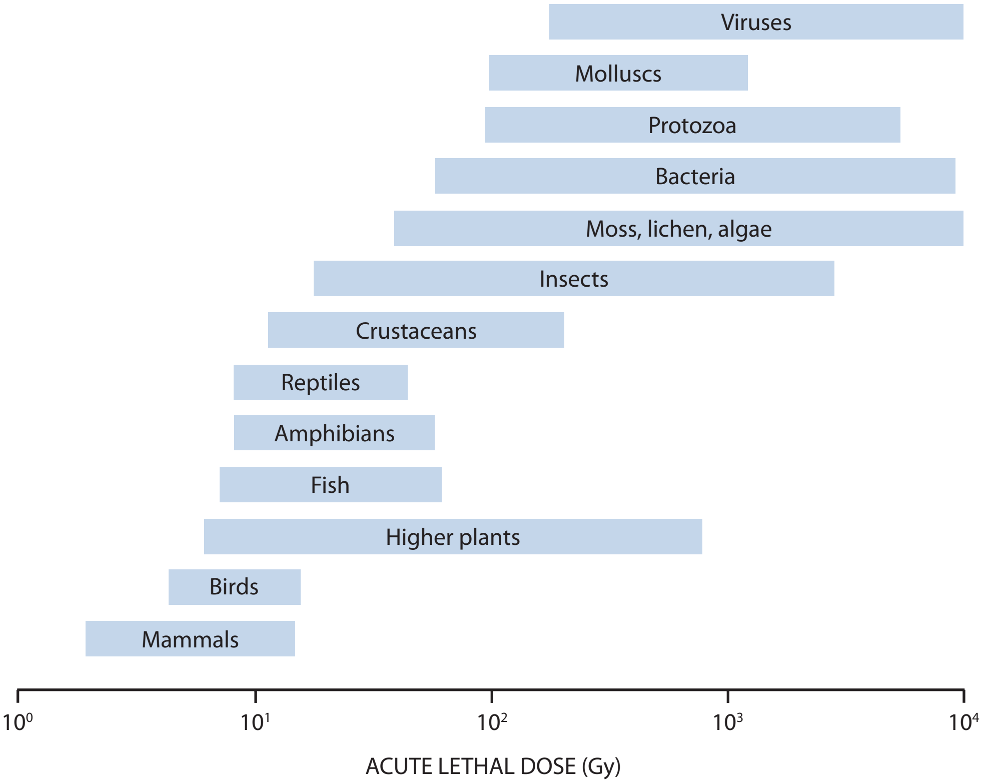
234. This chapter provides an overview of the independent evaluations of the published literature on the effects of radiation exposure on non-human biota, briefly considers the relevant observations from case studies where dose rates to non-human biota have been estimated and compared to reference dose rates (from, for example, reference [U4]), and extracts additional key observations from the post-1996 literature.

A. Overall conclusions of the UNSCEAR 1996 Report

235. The main observations from the Committee's 1996 evaluation [U4] are described in chapter III of this annex. The Committee, while emphasizing that only limited data were available for consideration, concluded that the production of viable offspring through gametogenesis and reproduction is a more radiosensitive population attribute than the induction of individual mortality.

236. The Committee also noted that there was a wide dose range over which organisms were sensitive to the lethal effects of radiation exposure. A schematic representation of the Committee's qualitative assessment of the overall sensitivities of various taxa to an acute dose of radiation is shown in figure XII [U4].

Figure XII. Approximate acute lethal dose ranges for various taxonomic groups [S12, W6]
Reproduction of figure VII of reference [U4]



237. Overall, the Committee judged that for the most sensitive plant species, the effects of chronic radiation exposure were noteworthy at dose rates of 1–3 mGy/h. It suggested that chronic dose rates of less than 400 µGy/h (10 mGy/d) would have effects, although slight, on sensitive plants but would be unlikely to have significant deleterious effects on the wider range of plants present in natural plant communities.

238. The Committee concluded that “for the most sensitive animal species, mammals, there is little indication that dose rates of 400 µGy/h to the most exposed individual would seriously affect mortality in the population. For dose rates of up to an order of magnitude less (40–100 µGy/h), the same statement could be made with respect to reproductive effects. For aquatic organisms, the general conclusion was that maximum dose rates of 400 µGy/h to a small proportion of the individuals and therefore, a lower average dose rate to the remaining organisms, would not have any detrimental effects at the population level. The radiation doses necessary to produce a significant deleterious effect are very difficult to estimate because of long-term recovery (including natural regeneration and the migration of individuals from surrounding less affected areas), compensatory behaviour and the many confounding factors present in natural plant and animal communities in both terrestrial and aquatic environments”.

B. Evaluations since 1996

239. Since the UNSCEAR 1996 Report [U4], several national and international authorities have reviewed the available literature on the effects of ionizing radiation exposure on non-human biota [C1, E1, F5, W11, W17]. This section provides a short discussion of the recent work relevant to this annex.

1. United States Department of Energy

240. The United States DOE has conducted a considerable amount of work in developing a graded approach to radioecological risk assessments [H1, H2, J1, U26]. In developing their approach, the DOE considered a number of issues relevant to the re-evaluation, including assessment endpoints, effort levels and dosimetry. The DOE noted that radioecological risk assessments focused on population relevant endpoints, such as reproduction, and cited guidance from national and international organizations [I4, N1, U4]. The DOE went on to adopt screening dose rates corresponding to expected safe levels of exposure of populations of biota based on reviews of the data on the acute and chronic radiation effects of exposure to a dose rate of

10 mGy/d to populations of aquatic animals, 10 mGy/d to populations of terrestrial plants and 1 mGy/d to populations of terrestrial animals [I4, N1, R2, U4]. The DOE indicated that, if the dose rate to the most exposed individual in the population does not exceed the expected safe dose rate, the population should also be protected [B18].

2. Canada

241. In response to requirements under the Canadian Environmental Protection Act (CEPA), 1999 [C6], Environment Canada and Health Canada carried out an assessment of the impact of the discharge of radionuclides from nuclear facilities on non-human biota for all aspects of the uranium fuel chain, from mining and milling to power generation and waste management [E5].

242. The approach used in reference [E5] for ecological risk assessment required identifying "chronic toxicity values" (CTVs) from which "estimated no-effects values" (ENEVs) were derived using appropriate application factors [E2]. The application factor was intended to address the uncertainties related to differences between observed effects on endpoints and the success of organisms in the field. An application factor (safety factor) of 1 was used to estimate ENEVs for radiation exposure. The CTVs for the various taxonomic groups reported in reference [E5] were based on measures of effect applicable to the survival of populations of sensitive species and on chronic exposures. In assessing radiological risks, Environment Canada and Health Canada [E5] used factors of 1 for gamma and beta radiation and 40 for alpha radiation to account for the differences in the RBEs of the different types of radiation. The ENEVs used by Environment Canada and Health Canada are summarized in table 28 and were based on detailed evaluations of the published literature [I4, R2, U4] as well as on evaluations specifically carried out in support of the assessment [E4, H3, M3].

Table 28. Summary of "estimated no-effects values" (ENEVs) used to assess the potential toxicity of exposure of non-human biota to radiation near Canadian nuclear facilities [E2]

Taxa	*ENEV (Gy/a)*[a]
Fish[b]	0.2
Benthic invertebrates	2
Algae	1
Macrophytes	1
Mammals	1
Terrestrial plants	1
Terrestrial invertebrates	2

[a] In all cases, the application factor used to convert the CTV to an ENEV was 1.

[b] The assessment given in reference [E2], citing the lack of data for Canadian fish, referred to effects on carp (species different from those found in Canada) in the Chernobyl cooling pond, and acknowledged that the ENEV for fish may be conservative.

243. The (former) Advisory Committee on Radiological Protection (ACRP) to the Canadian Nuclear Safety Commission also reviewed the available information relevant to the protection of non-human biota [A1]. The ACRP considered that the ultimate goal of "ecological protection" is to ensure that communities and populations of organisms can thrive and that all the component parts will be self-sustaining. Similar to the DOE [H1], the ACRP [A1] reported the generic dose-rate criteria summarized in table 29 for the effects of ionizing radiation exposure on biota, which were based on reviews by national and international authorities, including UNSCEAR [U4], the NCRP [N1] and the IAEA [I4]. The ACRP also suggested that overall, dose-rate criteria in the range of 1–10 mGy/d were generally protective of populations of non-human biota and, given current knowledge (and the associated uncertainties), that perhaps a single nominal dose-rate criterion of about 3 mGy/d might be suitable on a broad basis for assessing risks to non-human biota.

Table 29. Generic dose-rate criteria for biota [A1]

Biota	*IAEA [I4]*	*NCRP [N1]*	*UNSCEAR 1996 Report [U4]*
Terrestrial plants	10 mGy/d (4 Gy/a)	—	10 mGy/d (4 Gy/a)
Terrestrial animals	1 mGy/d (0.4 Gy/a)	—	—
mortality		—	10 mGy/d (4 Gy/a)
reproduction		—	1 mGy/d (0.4 Gy/a)
Aquatic organisms		10 mGy/d (4 Gy/a)	10 mGy/d (4 Gy/a)

244. The ACRP [A1] noted that radionuclides incorporated in biota are not uniformly distributed and that some radionuclides tend to concentrate in certain tissues or organs but that for dosimetric calculations, radionuclides were often assumed to be distributed uniformly throughout the organism. This assumption can result in underestimation of the doses to specific tissues for those radionuclides that concentrate in these tissues (for example, bone-seeking radionuclides in fish). The ACRP emphasized that, in practice, simplifying assumptions have to be made especially for demonstrating compliance with regulatory standards or criteria and that the degree of simplification will depend on the purpose of the application [A1]. For screening purposes, the concept of a single “generic” biota, which represents all plants and animals irrespective of size, shape and composition, has been used [A2] while somewhat more sophisticated models took account of the dose distributions within reference organisms of assumed shapes and sizes and the fractions of radiation energies absorbed in the organisms [W2]. The ACRP also recognized that it is impractical to address organisms individually and recommended the use of reference biota, typically developed in terms of simple physical shapes and dimensions for the purpose of dosimetry [B14, I2, N1, P7].

3. FASSET

245. The group working on the Framework for Assessment of Environmental Impact (FASSET) [F1, F4, F6, L4] reported on a wide range of issues relevant to the protection of non-human biota from ionizing radiation, including dosimetric information and data on the effects of radiation on non-human biota. The FASSET project developed a database (FASSET Radiation Effects Database—FRED) on the effects of radiation exposure on non-human biota under four broad effects categories, referred to by FASSET as “umbrella effects”. These included:

- Morbidity (including growth rate, effects on the immune system, and the behavioural consequences of damage to the central nervous system from radiation exposure of the developing embryo);
- Mortality (including the stochastic effect of somatic mutation and its possible consequence for cancer induction, as well as deterministic effects in particular tissues or organs that would change the age-dependent death rate);
- Reduced reproductive success (including fertility and fecundity); and
- Mutation (induced in germ and somatic cells).

246. Table 30 gives an overview of the quality and quantity of the available data within the FRED, based on a simplified categorization (ecosystem type, exposure duration and irradiation pathway). The data on effects are strongly weighted in favour of terrestrial ecosystems (73% of all data) and, for each ecosystem, the available data appear to be biased roughly 2:1 in favour of data of acute effects and an external gamma radiation exposure situation. As a consequence, the data on chronic effects are limited and largely dominated by external gamma radiation exposure conditions experimentally obtained using gamma sources (frequently either ^{137}Cs or ^{60}Co); thus, mathematical modelling such as that described in section I is needed to estimate doses for comparison with reference dose rates [G3, G15].

247. Real et al. [R9] summarized the available information from the FRED on the effects of continuous low dose-rate irradiation of plants, fish and mammals. The effects observed on plants, fish and mammals are shown in tables 31, 32 and 33, respectively. Each of these tables provides a brief description of the effect, the corresponding endpoint and the dose rate resulting in the effect. Table 34 provides an overall summary of the data on chronic effects of radiation exposure as provided by reference [R9].

Table 30. Allocation of the data on effects within the FRED database to freshwater, terrestrial and marine ecosystems, and to the radiation exposure regimes (duration and irradiation pathways) [G3]

Ecosystem (number of references)	*Total number of data (%)*	*Number of data for each exposure duration*			*Number of data for each exposure irradiation pathway*		
		Type	*Total number*	*%*	*External*	*Internal*	*Other*[a]
Terrestrial (579)	19 983 (72.6)	Acute	12 273	61.4	11 564	288	421
		Chronic	6 795	34.0	3 449	344	3 002
		Transitory[b]	913	4.57	670	40	203
		Not stated	2	0.03	0	0	2
Freshwater (195)	6 067 (22.0)	Acute	4 526	74.6	4 058	97	371
		Chronic	1 484	24.5	970	20	494
		Transitory	54	0.89	12	2	40
		Not stated	3	0.01	0	0	3

Ecosystem (number of references)	*Total number of data (%)*	*Number of data for each exposure duration*			*Number of data for each exposure irradiation pathway*		
		Type	*Total number*	*%*	*External*	*Internal*	*Other*[a]
Marine (45)	1 470 (5.4)	Acute	1 116	75.9	995	58	63
		Chronic	353	24.1	286	0	67
		Transitory	0	0	0	0	0
		Not stated	1	0	0	0	1

[a] "Other" means that the experiment reported in the literature was devoted to the study of the effects involved by mixed irradiation pathways, and/or not well characterized to be used for the present analysis.

[b] "Transitory" means in between "acute" and "chronic" in terms of exposure duration.

Table 31. Effects of chronic irradiation on plants [R9]

Dose rate (μGy/h)	*Species*	*Radiation*	*Effects described*	*Endpoint*	*Reference*
100–1 000	Pine	Gamma	Reduced trunk growth of mature trees	Morbidity	[W4]
			Death of some conifers; little changes in populations	Morbidity	[A6]
$(1–5) \times 10^{3}$	Pine	Gamma	Reduced canopy cover of individual conifers; whole canopy remains constant	Morbidity	[A6]
			Decreased stem growth of saplings	Morbidity	[A23]
			Reduced photosynthetic capacity of pines and thus growth	Morbidity	[B11]
$(5–10) \times 10^{3}$	Pine	Gamma	Death of all conifers within 2–3 years	Mortality	[A6]
$(1–2) \times 10^{4}$	Pine	Gamma	Reduced seed production and germination	Reproduction	[W11]
			Morphological changes in leaves of some plants	Morbidity	[W11]
			Withered crowns	Morbidity	[W11]
	Birch	Gamma	Underdeveloped leaves	Morbidity	[W11]
$>2 \times 10^{4}$	Herbaceous	Gamma	Reduced reproductive potential	Reproduction	[U4]
	Birch	Gamma	Death of trees	Mortality	[A6, W11]
	Grasses	Gamma	Death of grasses and forbs	Mortality	[W11]
$>1 \times 10^{5}$	Plants	Gamma	Death of all higher plants	Mortality	[A6, W11]
$>1 \times 10^{6}$	Lichen	Gamma	Reduced diversity of lichen communities after one year exposure	Mortality	[B13, W18]

Table 32. Effects of chronic irradiation on fish [R9]

Dose rate (μGy/h)	*Species*	*Radiation*	*Effects described*	*Endpoint*	*Reference*
$(1–10) \times 10^{2}$	Plaice, Medaka, Roach	Gamma	Reduction in testis mass and sperm production. Lower fecundity. Delayed spawning	Reproduction	[H11, K16, N1]
$(1–5) \times 10^{3}$	Plaice, Eelpout, Medaka, Guppy, Rainbow trout	Gamma or beta	Reduction in testis mass and sperm content. Severe depletion of spermatogonia. Reduced fertility or complete infertility. Reduced fecundity. Reduced male courtship activity. Reduced immune response	Reproduction Morbidity	[E10, G20, H11, H16, K16, K17, P5, W7]
$(5–10) \times 10^{3}$	Medaka	Gamma	Depletion of spermatogonia	Reproduction	[H11]
$(1–5) \times 10^{4}$	Medaka, Guppy	Gamma	Sterility. Reduction in larval survival. Increase in vertebral anomalies	Reproduction	[H17, W7]
$>5 \times 10^{4}$	Guppy	Gamma	No impact on offspring survival following parental irradiation	Mortality	[W7]

Table 33. Effects of chronic irradiation on mammals [R9]

Dose rate (µGy/h)	*Species*	*Radiation*	*Effects described*	*Endpoint*	*Reference*
$<10^2$	Mouse Rat	Gamma	No detrimental effects have been described	Morbidity Mortality Reproduction	[C17, P8] [C17, U21] [L2, Y2]
$(1–10) \times 10^2$	Dog	Gamma	Life shortening	Mortality	[C18]
	Mouse	Gamma	Life shortening	Mortality	[M13]
	Mouse	Neutrons	Life shortening	Mortality	[M13]
	Pig	Gamma	Prenatal irradiation decreased the number of primitive stem germ cells and the ovary and testis weight	Reproduction	[E14, E15]
	Rat	Gamma	Reduction in number of A1 spermatogonia	Reproduction	[E16]
	Mouse	Beta	Irradiation from conception to 14 days of age decreased the number of primary oocytes	Reproduction	[D2]
	Mouse	Gamma	Reduction of mean number of litters per female; higher mortality between birth and weaning; reduction in number of primary oocytes	Reproduction	[S6]
			Irradiation during three consecutive generations increased the % of sterile mice and the % of early deaths and decreased the mean litter size	Reproduction	[M14, M15]
			Field study. Increased % of sterile pairs; reduced mean offspring sired and weaned	Reproduction	[L3]
	Reindeer	Gamma	Natural forest. Increased number of chromosomal aberrations	Mutation	[R3]
$(1–5) \times 10^3$	Goat	Gamma	Life shortening	Mortality	[H18]
	Mouse	Gamma	Increased mortality ratio (the effect was dependent on the mice strain used); decreased mean after survival	Mortality	[G25, T2]
	Mouse	Neutrons	Life shortening	Mortality	[U21]
	Goat	Gamma	Reduced number of liveborn per female in the third generation and reduced total sperm production	Reproduction	[H19]
	Mouse	Gamma	Irradiation during the 2nd week after birth reduced the fertility and the litter size	Reproduction	[R5]
			Irradiation during 4–90 days reduced the fertility span, the germ cells per ovary and the testis weight	Reproduction	[M16, R12, R13]
	Rat	Beta	Prenatal irradiation reduced the litter size and increased the % of resorptions	Reproduction	[L2, L6]
	Rat	Gamma	Reduced number of spermatogonia and testis weight	Reproduction	[P15, P21]
			Prenatal irradiation reduced the number of germ cells in females and males	Reproduction	[E14]
	Mouse	Gamma	Increased mutation frequency at seven specific loci in mouse spermatogonia	Mutation	[R14]
$(5–10) \times 10^3$	Sheep	Beta	Reduction in the number of leukocytes in peripheral blood	Morbidity	[B15]
	Rat	Gamma	Reduced brain weight and cingulum volume	Morbidity	[R15]
	Mouse	Gamma	Life shortening after exposures of 68 days or longer	Mortality	[S7, S24]
			Increased paternal expanded simple tandem repeat (ESTR) mutation rate and paternal mutation per offspring band at loci MMS10 plus Ms6-hm plus Hm-2	Mutation	[D3, D5]
$>10^4$	Dog	Beta	Reduced survival	Mortality	[R16]
	Mouse	Gamma	Increased mortality ratio (dependent on the strain used)	Mortality	[G25]
	Rat	Gamma	Prenatal irradiation reduced the length and weight of embryos and increased the % mortality	Reproduction	[C19]
			Reduction in ovary and testis weight	Reproduction	[E17]

Table 34. Overall summary of data on the effects of chronic irradiation for plants, fish and mammals, based on the FASSET Radiation Effects Database (FRED) [R9]

Wildlife group	*Morbidity*	*Mortality*	*Reproductive capacity*	*Mutation*
Plant	Plant growth begins to be affected at more than 100 μGy/h. Continued exposure at 21 μGy/h for 8 years increases the sensitivity in pines	50% mortality at 8 years at ~1 000 μGy/h in pines	A field study indicated a decrease in seed weight of a herb at 5.5 μGy/h	The mutation rate in microsatellite DNA increased at ~40 μGy/h
Fish	One experiment, but not another, indicates effects on the immune system at 8.3 μGy/h	Too few data to draw conclusions	One study showing effects on gametogenesis at 230 μGy/h. Otherwise effects at more than 1 000 μGy/h	Radiation exposure increases the mutation rate
Mammals	Rat growth not affected at 16 μGy/h but affected at more than 3 000 μGy/h. Some blood parameters affected at 180–850 μGy/h. No effect on thyroid function at 8 000 μGy/h	No effect on mouse lifespan at 460 μGy/h, but significant reductions above ~1 000 μGy/h in the mouse, goat and dog	Threshold for effects at ~100 μGy/h, with clear effects at more than 1 000 μGy/h	Too few data to draw conclusions. One of nine references gives an LOEDR of 420 μGy/h for mice

248. Real et al. [R9] noted that plant morphology (size, shape and density of plant stands) can alter the exposure and the resulting radiation dose. They also noted that plants with exposed meristems or buds can receive higher doses to the critical tissues than those plants that grow and reproduce underground or are protected by thick scales.

249. Real et al. [R9] concluded that chronic exposures up to 4×10^3 μGy/h to developing fish embryos will not result in significant effects on growth. Furthermore, they considered that the available data suggest that dose rates of less than 4×10^3 μGy/h at any life stage would not be expected to affect survival. However, they felt that the limited amount of data further suggests that genetic damage caused by chronic irradiation is likely to occur at all dose rates and that the radiosensitivity for this damage is similar to that of other vertebrates.

250. There are a large number of data on mammals available within the FRED; therefore, Real et al. [R9] had to be selective in summarizing the information. Altogether, the authors considered 183 references for mammals, which provided more than 3,000 data points on effects. The authors concluded that chronic radiation dose rates lower than 10^3 μGy/h do not result in irreversible effects on mortality, morbidity and reproduction. A dose rate of 100 μGy/h (i.e. 2.4 mGy/d) had been described for reproductive capacity impairment; however, the detrimental effects observed were reversible [R9]. The authors indicated that the majority of the work had been conducted using mice and rats and that it would be beneficial to have additional information on the effects of chronic radiation exposure on other species.

251. An overall summary of the effects due to chronic exposure of plants, fish and mammals identified by FASSET was reported in reference [R9] for the different endpoint classifications (morbidity, mortality, reproductive capacity and mutation) provided in table 34. The authors concluded that the amount of available information on the effects of low dose rates (less than about 100 μGy/h) for continuous radiation exposure is reasonable for both plants and animals and that for chronic exposure conditions "the reviewed effects data give few indications for readily observable effects at chronic dose rates below 100 μGy/h". However, they advised that "using this information for establishing environmentally 'safe levels' of radiation should be done with caution, considering that the database contains large information gaps for environmentally relevant dose rates and ecologically important wildlife groups" [F5, R9].

4. ERICA

252. The project on Environmental Risks from Ionizing Contaminants: Assessment and Management (ERICA) carried out under the European Commission's 6th Framework Programme was the successor of the FASSET project. Extensive quality assurance of the data was carried out and this led to the development of an expanded effects database (referred to as FREDERICA). A database on the effects of chronic radiation exposure of fish, which was developed in the project on Environmental Protection from Ionising Contaminants in the Arctic (EPIC) [S25] was subsequently incorporated into the FREDERICA effects database [C12].

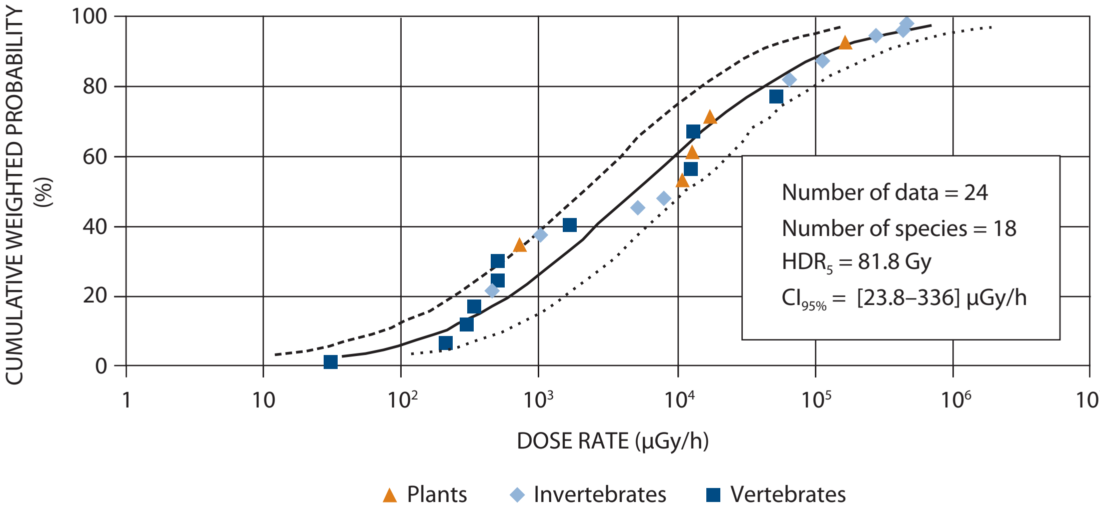
253. The ERICA integrated approach adopted an Ecological Risk Assessment tiered methodology that required values of the risk assessment screening dose rates for risk characterization within Tiers 1 and 2. The screening values used within Tiers 1 and 2 were derived on the basis of data taken from the FRED and compared from some key data from the EPIC project (making thus the best use of the FREDERICA database) [C12]. The method applied follows recommendations of the European Commission for the estimation of Predicted

No-Effect Concentration (PNEC) for chemicals [E11]. A three-step methodology was used. First, a coherent data subset was extracted from each experiment, covering endpoints related to mortality, morbidity and reproduction. Next, a systematic mathematical treatment was applied to reconstruct dose-rate–effect relationships and to estimate critical toxicity endpoints. For chronic exposure, the critical toxicity endpoint was the estimated Effect Dose Rate (EDR_{10}, expressed in µGy/h), the dose rate that gives rise to a 10% change in observed effect. The final step of the method consisted in using these estimated critical toxicity data to derive a Predicted No-Effect Dose Rate (PNEDR) by means of the species sensitivity distribution method (SSD) [E11, G15, G27].

254. The SSD method was used to estimate the Hazardous Dose Rate (HDR_5), the dose rate at which 95% of the species in the aquatic/terrestrial ecosystem are protected. After separate analyses of the data available for different ecosystems, the authors [G15] concluded there was no statistical justification for attempting to derive ecosystem-specific screening dose rates and all data were therefore analysed together as a generic ecosystem. The resultant HDR_5 was 82 µGy/h (with 95th percentile confidence intervals of 23.8 and 336 µGy/h). To derive the final dose rate for screening (i.e. PNEDR), a safety factor (*SF*) of 5 was used to allow for any remaining extrapolation and the resultant number rounded down to the nearest one significant figure. Based on this approach, the authors suggested a reference dose rate for incremental exposure of 10 µGy/h for “screening for potential radiological effects”. The methodology and process used to derive this screening value are documented within references [G3, G11, G15] where the value is shown to be similar to that derived using alternative methods to SSD (figure XIII).

Figure XIII. Species sensitivity distributions for generic ecosystems and chronic external gamma irradiation conditions

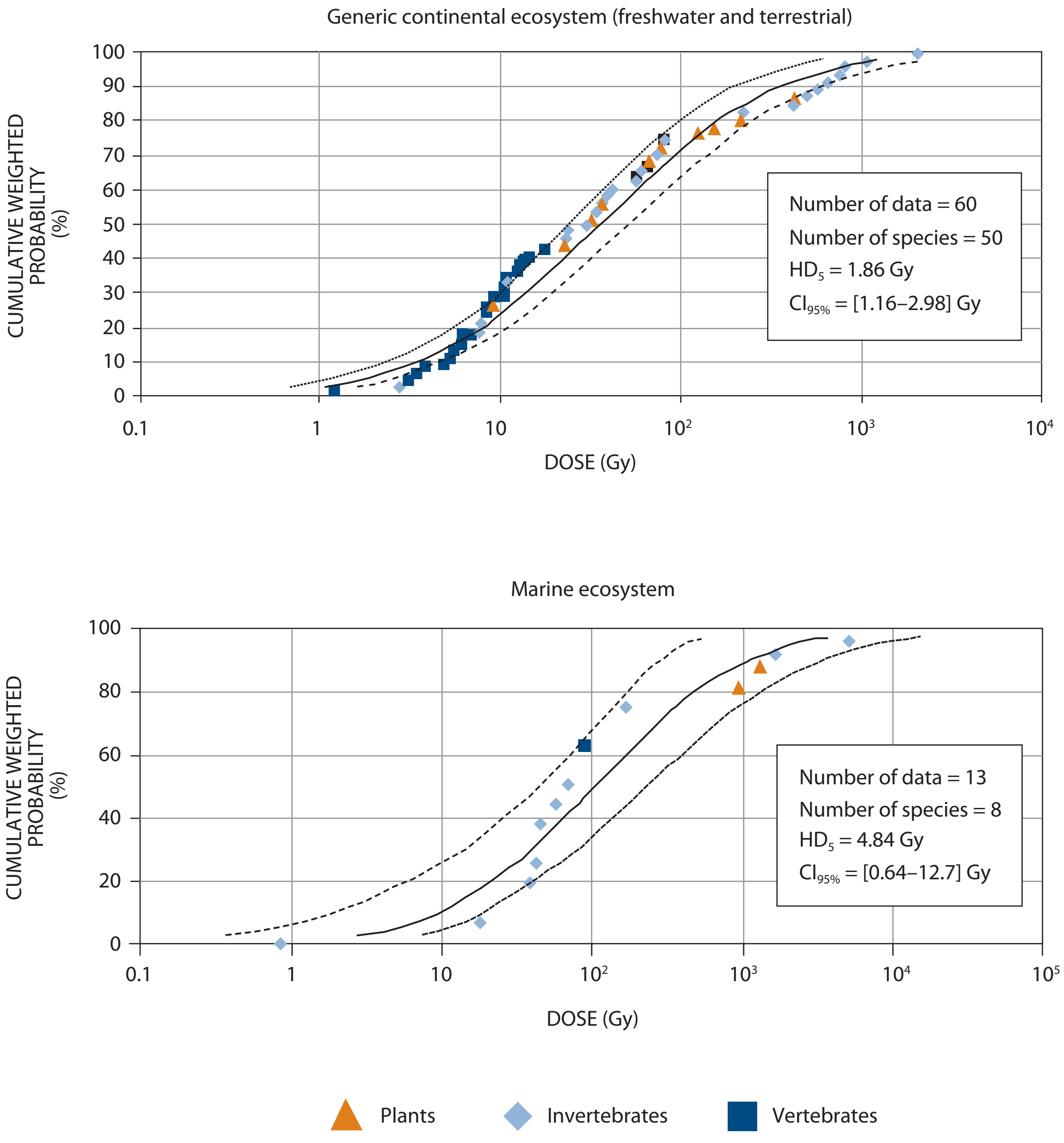
The log-normal distribution with its associated 95% confidence interval is fitted to geometric means per effect category for each species calculated on critical ecotoxicity data (*EDR_{10}*) [G3]



255. At the ecosystem level, the value of the ERICA integrated approach screening dose rate lies in the range giving rise to minor effects [F5, G3, G15, G27]. The authors suggested that such effects are not expected to be directly relevant at higher organizational levels, such as the structure and functioning of ecosystems.

256. The same method was also applied to acute exposure conditions to guide interpretation of accidental situations; however, in this case, the authors [G11, G15] did find a difference between marine ecosystems compared to terrestrial and freshwater ecosystems. The values derived from an SSD analysis on the set of Effect Doses giving a 50% change in observed effect (ED_{50}) for limiting the potentially affected fraction to 5% of the species under acute external gamma irradiation conditions varied from about 1 to 5.5 Gy, according to the ecosystems type, with associated 95% confidence intervals covering less than one order of magnitude (see figure XIV). To derive screening values, an *SF* of 5 was applied and the results rounded down to the nearest one significant figure. This resulted in Predicted No-Effect Doses (PNED) of 900 mGy for marine ecosystems and 300 mGy for terrestrial and freshwater ecosystems [G3, G15, G27].

Figure XIV. Species sensitivity distributions for generic ecosystems and acute external gamma irradiation conditions
The log-normal distribution with its associated 95% confidence interval is fitted to geometric means per effect category for each species calculated on critical ecotoxicity data (*ED*$_{50}$) [G3]



257. Dose rates below which no significant effects are expected at various levels of organization (population, wildlife group or ecosystem) were compared by different organizations/authors [G3, G15], and are summarized in table 35. The selection was mainly based on observations of effects and expert judgement. The approach using SSD provides an alternative methodology for assessing radiation risks by deriving, for the first time for radioactive substances, protection thresholds using a rational and transparent process based on the approach adopted for chemicals in Europe [G15].

Table 35. Dose-rate values proposed by various organizations/programmes to support effect analysis for chronic exposure to radiation [G3, G11]

Targeted protected level as described in the source	*Method/justification of the value*	*Dose rate (µGy/h)*	*Source reference*
Terrestrial ecosystems			
Generic ecosystems	SSD-95% species protected plus *SF* of 5 SSD giving an HDR_5 of 81.8 µGy/h divided by an *SF* of 5 and rounded down	10	[G3]
Generic ecosystems	SF method: *SF* of 10 applied to the lowest critical radiotoxicity value EDR_{10}	0.6	[G3]
Plants	Background	0.02–0.7	[U4]
Plants	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Plants	Review based on NCRP 1991; IAEA 1992; UNSCEAR 1996	400	[O1, U26]
Plants	Critical review for screening purpose from IAEA 1992	400	[E12]
Organisms	Background – external irradiation and non-weighted	0.01–0.1	[G21]
Animals	Background	0.01–0.44	[U4]
Animals	Review based on NCRP 1991; IAEA 1992; UNSCEAR 1996	40	[O1, U26]
Animals	Critical review for screening purpose from IAEA 1992	40	[E13]
Small mammals	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Invertebrates	Review, *SF* on the lowest critical radiotoxicity value	220	[B31, E5]
Vertebrates and cytogenetic effects	Review contaminated environments	4–20	[S28]
Vertebrates and effects on morbidity	Review contaminated environments	20–80	[S28]
Vertebrates and effects on reproduction	Review contaminated environments	80–200	[S28]
Aquatic ecosystems			
Generic freshwater ecosystems	SSD-95% species protected plus *SF* of 5 SSD giving an HDR_5 of 81.8 µGy/h divided by an *SF* of 5 and rounded down	10	This annex
Generic freshwater ecosystems	SF method: *SF* of 50 applied to the lowest critical radiotoxicity value EDR_{10}	10	This annex
Generic marine ecosystems	SSD-95% species protected plus *SF* of 5 SSD giving an HDR_5 of 81.8 µGy/h divided by an *SF* of 5 and rounded down	10	[G3]
Generic marine ecosystems	SF method: *SF* of 50 applied to the lowest critical radiotoxicity value EDR_{10}	3.7	[G3]
Freshwater organisms	Background	0.022–0.18	[U4]
Freshwater organisms	Background–external irradiation and non-weighted	0.02–6	[B32]
Aquatic algae/macrophytes	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Aquatic animals	Review based on NCRP 1991; IAEA 1992; UNSCEAR 1996	400	[O1, U26]
Freshwater and coastal marine organisms	Critical review for screening purpose from IAEA 1992	400	[E12]
Amphibians/reptiles	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Benthic invertebrates	Review, *SF* on the lowest critical radiotoxicity value	220	[B31, E5]
Fish	Review, *SF* on the lowest critical radiotoxicity value	20	[B31, E5]
Marine organisms	Background–external irradiation and non-weighted	0.03–1	[B32]
Marine mammals	Critical review for screening purpose from IAEA 1992	40	[E13]
Deep ocean organisms	Critical review for screening purpose from IAEA 1992	1 000	[E13]
Aquatic and terrestrial flora and fauna	Review concluded that few indications of readily observable effects at chronic dose rates below	<100	[F5]

258. As indicated elsewhere in this annex, few new data on the effects of ionizing radiation exposure on non-human biota have been developed since 1996. In all the recent literature reviews [C1, F5, G16, R9, W11]), the specificities of the environmental situations of interest (chronic low-level exposure regimes) consistently emphasized the importance of all reproductive parameters to the population within a given ecosystem to the structure and functioning of that ecosystem. These reviews clearly argued for the need of a research programme to acquire specific data related to chronic low-level exposure and the effects on reproductive capacity in such a way as to be able to shift from observations on individual organisms to observations on populations. A brief summary of the data on effects from the FRED is given in table 36 along with assigned weight ratios based on the numbers of data sets available related to acute versus chronic exposure and, for chronic exposure data, to external versus internal exposure and reproductive endpoints. The extrapolation on the basis of the existing knowledge will become increasingly critical as the relative weights increase. In reviewing these data, Garnier-Laplace et al. [G16] concluded that operationally for any site-specific risk assessment, the present state-of-the-art on extrapolation issues allows the relative magnitudes of the various sources of uncertainty to be ordered as follows: one species to another > acute to chronic = external to internal = mixture of stressors > individual to population > ecosystem structure to function.

Table 36. Brief overview of the data on effects from FRED (adapted from reference [G16])

Wildlife group	*Number of data*	*Weight data ratio*		
		All data: acute/chronic	*Chronic data: (external)/(internal+mixed)*	
			All endpoints	*Reproduction*
Aquatic plants	616	2.7	4.1	0/0[a]
Aquatic invertebrates	542	1.2	4.1	8.3
Amphibians	749	1.3	0.02	0/0
Bacteria	171	0.5	2.4	0/0
Birds	1 732	3.4	3.4	5.5
Crustaceans	850	3.7	180	20/0
Fish	2 802	2.8	1.0	0.8
Fungi	120	0/120	120	0/0
Insects	1 237	5.2	5.4	0.8
Mammals	4 112	2.5	4.7	3.3
Molluscs	484	2.4	1.7	0.4
Moss/lichen	44	0/44	0.5	0/0
Plants	11 984	1.6	0.7	0.5
Reptiles	271	6.7	0/35	0/0
Soil fauna	398	1.6	0.15	0/0
Zooplankton	111	4.3	21/0	9/0

[a] (number of data devoted to reproduction endpoints and chronic external irradiation) / (number of data devoted to reproduction endpoints and chronic internal or mixed irradiation): for example, 0/0 means that no data exist.

5. Observations from recent literature

259. The European Commission (EC) has been supporting research on the effects of ionizing radiation exposure on non-human biota for the past several years. This included the development of the FRED. More recently, the ERICA project conducted a review of the quality of the data in the FRED and merged the FRED with the Russian EPIC database to form a new database, FREDERICA, with several hundred additional references [C12]. This database includes references to over 1,200 papers that focus on the effects of radiation exposure on non-human biota and is a valuable source of information. General information on the new data on effects or new interpretations of the data on effects is provided in the previous section. Additional observations from the literature identified in the ERICA database as well as the open literature are provided in the following section in an attempt to supplement the previous information in several areas of current interest.

(a) Terrestrial biota

260. Hingston et al. have described the effects of low doses of ionizing radiation on terrestrial invertebrates and reported experiments on earthworms (*Eisena fetida)* and woodlice *(Porcellioscaber)* [H23]. Both species were continuously exposed to gamma radiation from a ^{137}Cs source over a range of dose rates with total exposures for each experimental group

of 0.5–20 Gy delivered over a total of 14 and 16 weeks, respectively. The investigators considered a number of endpoints relevant to reproduction, growth and mortality. They reported on the results for woodlice [H23]. They found no deleterious effects for the endpoints studied up to a maximum dose rate of approximately 8 mGy/h (192 mGy/d); the woodlice were unaffected by the doses given. However, they noted that the results may, in part, have reflected the laboratory conditions, i.e. an environment protected from predation. Hertel-Aas et al. reported the results from a study of the reproductive capacity (numbers of cocoons, hatchability, etc.) of earthworms exposed chronically to gamma radiation [H22]. In this study, earthworms (*Eisena fetida*) were exposed over two generations to gamma radiation from a ^{60}Co source at five dose rates, from 0.18–43 mGy/h. The lowest dose rates at which an effect was observed was 4 mGy/h and 11 mGy/h in F_0 and F_1 worms, respectively. The experiments also suggested a possible acclimatization in F_1 worms.

261. Tanaka et al. [T3, T25] discussed the effects of chronic exposure of mice (SPF B6C3F1) to gamma rays at low dose rates. Mice of both sexes were divided into 4 groups, one of which was not irradiated and the other three which were irradiated. The exposed mice were irradiated at dose rates of 0.05, 1.1 and 21 mGy/d for about 400 days using a ^{137}Cs source. All mice were maintained until natural death, after which pathology was performed to identify the cause of death. Females exposed to 1.1 mGy/d and both sexes exposed to 21 mGy/d had significantly shortened lifespans compared to non-exposed mice. The mean survival times of mice of both sexes exposed to 0.05 and 1.1 mGy/d were shorter than for non-exposed mice but not significantly so.

(b) Aquatic and marine biota

262. The great majority of the data on aquatic invertebrates in the FRED concern the effects of chronic irradiation on crustaceans. The data indicate that observable impacts at dose rates up to 10^3 mGy/h are unlikely and that a dose rate of ~10^4 mGy/h is probably the lower limit for the onset of significant effects. However, effects were apparent in the embryonic development of the goose barnacle (*Pollicipes polymerus*) following a 32-day exposure to tritiated water at dose rates of 0.7, 6.5 and 64 mGy/h [F5].

263. Concerning the effects of internal radiation exposure on crustaceans, recent data exist on daphnids which were chronically exposed internally to alpha radiation from ^{241}Am under experimental conditions at dose rates up to 990 µGy/h [A19]. These authors reported that exposure to dose rates of 110 µGy/h or higher resulted in a significant (15%) reduction in body mass. Daphnids also showed increased respiratory demand after 23 days at the highest dose rate, suggesting increased metabolic cost of maintenance resulting from the need to cope with the stress from alpha irradiation. Fecundity remained unchanged over the 23-day period, but individual masses of eggs and neonates were significantly smaller compared to the control. This suggested that increased metabolic expenditure in chronically alpha-irradiated daphnids came at the expense of their energy investment per offspring. As a consequence, neonates showed significantly reduced resistance to starvation at every dose rate compared to the control.

264. Gilbin et al. [G22] reported effects on *Daphnia magna* of external gamma radiation exposure at dose rates ranging from 0.4–31 mGy/h over a 23-day period (i.e. 5 broods). Gamma radiation exposure caused no significant change in somatic growth. The mass-specific respiration rate was significantly lower at dose rates of 31 mGy/h than for the control. Broods were deposited earlier and fecundity was 20% lower at the highest dose rate than for the control. The combination of decreased fecundity and unchanged individual offspring mass resulted in a smaller total mass of eggs produced per daphnid at dose rates of 4.2 and 31 mGy/h than for the control. A decreased resistance of neonates to starvation was observed at every dose rate.

265. Alonzo et al. [A27] tested the chronic effects of internal alpha irradiation on *Daphnia magna* respiration, somatic growth and reproduction over three successive generations. They showed that the toxicological effects of internal alpha irradiation on life-history traits of *Daphnia magna* increased across generations. A 70-day experiment was performed with *Daphnia magna* exposed to waterborne ^{241}Am corresponding to average dose rates of 0.3, 1.5 and 15 mGy/h. In the first generation (F_0), a reduction in body length (5%) and the dry mass of females (16%) and eggs (8%) was observed after 23 days of exposure, while mortality and fecundity remained unaffected. New cohorts were started with neonates of broods 1 and 5, to examine the potential consequences of the reduced mass of the offspring for subsequently exposed generations. At the highest dose rate, an early mortality of 38–90% affected juveniles while survivors showed delayed reproduction and reduced fecundity in F_1 and F_2. At dose rates of 0.3 and 1.5 mGy/h, the mortality of daphnids in generation F_1 ranged from 31–38%. Reproduction was affected through a reduction in the proportion of breeding females occurring in the first offspring generation at a dose rate of 1.5 mGy/h (to 62% of total daphnids) and in the second generation at 0.3 mGy/h (to 69% of total daphnids). Oxygen consumption remained significantly higher at dose rates ≥0.3 mGy/h than for the control in almost every generation. Body size and mass continued decreasing in relation to dose rate, with a significant reduction in mass ranging from 15% at a dose rate of 0.3 mGy/h to 27% at 15 mGy/h in the second offspring generation.

266. Dose rates above 0.1 mGy/h to developing mollusc embryos affected the incidence of developmental abnormalities but not the subsequent overall survival of the resulting larvae. Significant detrimental effects are to be expected at dose rates greater than 1 mGy/h [F5]. Recently, Jha et al. [J4] exposed mussels (*Mytilus edulis*) to a series of concentrations of HTO equivalent to a dose rate ranging from 12–485 µGy/h for 96 hours. The study revealed a dose-dependent increase in the response for both the micronuclei test and the comet assay. Dose rates below 500 µGy/h induced genetic damage in the haemocytes. For the same species but another life stage (i.e. one-hour-old embryos exposed during 12 to 24 hours to a range of HTO doses between 0.02 and 21.41 mGy), Hagger et al. [H13] found that the embryo–larvae showed dose or concentration-dependent effects for mortality, developmental

abnormalities and induction of sister chromatid exchanges. However, they reported that there was a lack of a clear dose response for chromosomal aberrations and proliferative-rate index.

267. For annelids, Knowles and Greenwood [K3] exposed *Ophryotrocha diadema* to beta radiation at a dose rate of 7.3 mGy/h and observed that the number of eggs surviving to the larval stage was reduced, but did not affect egg production. This is in contrast to previous studies related to gamma irradiation where egg production is reduced but not the number becoming larvae.

268. Kryshev and Sazykina [K18] reported an evaluation of the radioecological effects on aquatic organisms exposed to high levels of radioactive contamination in lakes affected by the Mayak reprocessing facility, in lakes affected by the Kyshtym accident, in the cooling pond of the Chernobyl nuclear power plant (NPP) and in the littoral area downstream of the Leningrad NPP. The authors reported doses based on the concentrations of radionuclides in water, sediments and fish and indicated that the highest dose rates, up to 300–800 mGy/d, were to organisms in the lakes affected by the Mayak complex. They also noted that the biota in the Mayak lakes were exposed to chemical contamination in addition to radiation but commented that the fish population had retained its viability for the period of observation of 30 years. The lowest dose rates were for the Leningrad NPP, where the authors noted that, typically, aquatic organisms were exposed to background levels of radiation. However, the dose rates to aquatic organisms in the liquid radioactive-waste canal of the Leningrad NPP were elevated. Here, the authors noted an increased asymmetry of the soft rays of the pectoral fins of roach and suggested that this was due to the combined effects of exposure to radiation and elevated temperature. The overall observations from this study are summarized in table 37.

Table 37. Radioecological effects in water bodies exposed to radioactive contamination
(adapted from reference [K18])

Water body (period of assessment) species under study	*Dose rate assessment (μGy/d)*	*Brief description of the effects*
Southern Urals [K24, K25, K26]		
Lake Karachai (1951–1952) Techa River (1951–1951)	300 000–800 000 30–2 000	Total death of lake ecosystem Mass death of fish in the upper reaches of the river
Cooling pond of the Chernobyl NPP [B19, K12, K28] (1986–1992): Silver carp *Hypophthalmichthys molitrix*	0.2–3	Increased anomalies of the reproductive system; disturbances in the state of sexual cells to 47–90%; sterility of gonads
Waste channel of the Leningrad NPP [K27, R18] (1980–1983) Roach *Rutilus rutilus*	0.007–2	Increase by a factor of 2.3 in the variance of fluctuating asymmetry of the number of soft rays of pectoral fins at different sides of the body of roach

269. Real et al. [R9] in their review of the information in the FRED observed that the developing embryos of fish that were subjected to chronic exposures at dose rates up to 4 mGy/h will not result in significant effects on subsequent growth. They also noted conflicting results for the effects of radiation exposure of the immune system: for rainbow trout irradiated as embryos, there was a threshold at dose rates between 8.3–83 µGy/h from exposure to beta radiation from tritium, while there was no effect at a dose rate of 9 mGy/h from exposure to radiation from ^{137}Cs. According to the authors [R9], the limited data available on mortality effects of chronic irradiation indicated that dose rates less than 4 mGy/h at any life stage were unlikely to affect survival and that there was little consistent, significant evidence for any effects on reproductive capacity at dose rates of less than 0.2 mGy/h. Finally, the authors [R9] suggested, based on a very limited amount of data, that chronic irradiation-induced genetic damage probably occurs at all dose rates and that radiosensitivity for this damage is similar to that of other vertebrates.

270. An interesting recent study has been performed with zebrafish larvae by Jarvis and Knowles [J5]. Gamma radiation was delivered externally from sealed sources (^{137}Cs) at a dose rate ranging from 0.3–7.4 mGy/h. The alkaline comet assay was used to assess DNA damage on larvae (5–6 days post laying, 2 days post hatching), exposed for 24 hours to dose rates of 0.4, 1.2 or 7.2 mGy/h and for 1 hour to 0.4 or 1.2 mGy/h. Entire larvae were macerated and their cells embedded in agarose gel. Larvae exposed at dose rates of 7.2 or 1.2 mGy/h for 24 hours (total dose of 173 and 29 mGy, respectively) showed a significant increase in the percentage of DNA in the comet tail. The same observation was made for larvae exposed at the same rates for 1 hour (total dose of 7.2 and 1.2 mGy, respectively). The increase in tail movement was not correlated to the exposure time, indicating that DNA damage was repaired with time. No information was available on DNA repair in long-term irradiated or contaminated fish. It must be noted that for a similar dose rate (1 mGy/h), no effect on reproduction in adults after exposure of more than 12 months could be observed [E12].

(c) Genotoxicity

271. Data on genotoxicity are summarized in table 38. Knowles [K16] irradiated plaice under laboratory-controlled conditions using sealed ^{137}Cs sources to investigate potential genotoxic effects. No effect on the coefficient of variation (CV) of the DNA content, aneuploidy or polyploidy, measured by flow cytometry (FC), was observed even for the maximum exposure period (197 days) and maximum dose rate (1 mGy/h).

Table 38. Genotoxicity in aquatic species exposed to radionuclides in the laboratory or in situ [A13]

Species (life stage)	*Type of exposure*	*Dose rate, dose or internal concentration*	*Exposure duration*	*Assay (parameter)*	*Effect LOEDR (μGy/h) (LNOEDR or LOED)*	*Reference*
Zebrafish (*D. rerio*), larvae (2 d)	Lab in vivo, external, ^{137}Cs	400, 1 200, 7 200 μGy/h	1 hour; 24 hours	Alkaline comet (tail moment)	+ 1 200 μGy/h	[J5]
Pond slider (*T. scripta*) Snapping turtle (*C. serpentina*), adults	In situ, (White Oak Lake) external + internal, ^{235}U, ^{239,240}Pu, ^{137}Cs, ^{60}Co, ^{90}Sr, Hg, HAP, PCB	External dose rate: 50 μGy/h[a]	n.d.	Alkaline and neutral unwinding (hepatocytes)	+ 50 μGy/h	[M5]
Mosquitofish (*G. affinis*), adults	In situ, (Oak Ridge) external + internal, ^{235}U, ^{239,240}Pu, ^{137}Cs, ^{60}Co, ^{90}Sr, Hg, HAP, PCB	External dose rate: 50 μGy/h	49 years	Agarose gel electrophoresis (hepatocytes, erythrocytes)	+ 50 μGy/h	[T21]
Channel catfish (*I. Punctatus*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 μGy/h[b]	n.d.	Alkaline unwinding (hepatocytes, gill cells, erythrocytes)	=	[S18]
Largemouth bass (*M. salmoides*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 μGy/h[c]	n.d.	Alkaline unwinding (hepatocytes, gill cells, erythrocytes)	=	[S17]
Marine polychaete worm *(N. arenaceodentata*), larvae	Lab in vivo, external, ^{60}Co	400–25 000 Gy/h	12 hours 24 hours	SCE	+ 400 μGy/h	[H15]
Midge *(C. tentans)*, larvae	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	260 μGy/h	Lifetime	CA	+++ : inversion + : deletion 260 μGy/h	[B34]
Marine polychaete worm *(N. arenaceodentata*), larvae	Lab in vivo, external, ^{60}Co	3 000 μGy/h (24 d) 6 000 μGy/h (48 d)	24 days 48 days	CA (metaphase)	+ 3 000 μGy/h + 6 000 μGy/h	[P4]
Slider turtle (*T. scripta*), fibroblasts and lymphocytes	Lab, external, ^{137}Cs	1 000 μGy/h to >100 Gy/h	n.d.	CA (symmetrical translocations)	230 000 μGy/h (LNOEDR)	[H14, U18]
18 different fish species	Various conditions (literature review)	Background 5 × 10^{-3} to 0.5 μGy/h[d]	n.d.	MN per 1 000 erythrocytes	+ Mean [min; max] : 3 [0; 13] 5 × 10^{-3} to 0.5 μGy/h	[G23]
Plaice, (*P. platessa*), adult	Lab, in vivo, external, ^{137}Cs	240–1 000 μGy/h	197 days	MN per 1 000 erythrocytes	=	[K16]
Pike (*E. lucius*), perch (*P. fluviatis*), roach (*R. rutilus*) and bream (*A. brama*)	In situ, Swedish lake, Chernobyl fallout 1988, external + internal, ^{137}Cs	10 000 Bq/kg d.w. ^{137}Cs 10 μGy/h[d]	n.d.	MN per 1 000 erythrocytes	=	[A20]
Pike (*E. lucius*), perch (*P. fluviatis*), roach (*R. rutilus*) and bream (*A. brama*)	In situ, Swedish lake, Chernobyl fallout 1988, external + internal, ^{137}Cs	18 000 Bq/kg d.w. ^{137}Cs Ext. dose rate : 10 μGy/h[d]	n.d.	MN per 1 000 erythrocytes	=	[A21]
Pike *(E. lucius)*, adults	In situ, Siberian (Tomsk-7) nuclear site	57 000 μGy/h[d] 1 200 Bq/kg w.w.	n.d.	MN per 1 000 erythrocytes	++ 57 000 μGy/h	[I22]

Species (life stage)	*Type of exposure*	*Dose rate, dose or internal concentration*	*Exposure duration*	*Assay (parameter)*	*Effect LOEDR (µGy/h) (LNOEDR or LOED)*	*Reference*
Channel catfish (*I. Punctatus*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h[b]	n.d.	MN per 1 000 erythrocytes	-	[S18]
Plaice, (*P. platessa*), adult	Lab, in vivo, external, ^{137}Cs	240–1 000 µGy/h	197 days	FC (DNA CV, aneuploidy, polyploidy)	=	[K16]
Largemouth bass (*M. salmoides*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h[c]	n.d.	FC erythrocytes (DNA CV, aneuploidy and CV distribution)	= : aneuploidy + : CV + : CV distribution 80 µGy/h	[L8]
Crucian carp (*Carassius carassius*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h[b]	n.d.	FC (DNA CV, aneuploidy)	= : aneuploidy + : CV 125 µGy/h	[L10]
Crucian carp (*Carassius carassius*), carp (*Cyprinus carpio*), tench (*Tinca tinca*), channel catfish (*I. punctatus*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h[b]	n.d.	FC whole blood, erythrocytes, leukocytes (DNA CV, aneuploidy, cell proliferation)	= : aneuploidy + : CV blood & erythrocytes ++ : CV leukocytes + : cell proliferation 125 µGy/h	[D8]
Slider turtles (*P. scripta*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h[c]	n.d.	FC erythrocytes (DNA CV and aneuploidy)	= : aneuploidy + : CV 80 µGy/h	[B35]
Slider turtles (*P. scripta*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h[c]	n.d.	FC erythrocytes (DNA CV and aneuploidy)	= : aneuploidy + : CV 80 µGy/h	[L11]
Mallard (*A. platyrhynchos*), ducklings	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h[c]	9 months	FC erythrocytes (DNA CV, aneuploidy and cell proliferation)	= : aneuploidy = : cell proliferation + : CV 80 µGy/h	[G24]

Symbols and abbreviations: Dose rates are either those indicated in the article or those taken from other studies ([a] from reference [T21]; [b] from reference [K9]; [c] from reference [H14]; [d] from reference [T6]). SCE : sister chromatid exchange; CA : chromosomal aberration; MN : micronuclei; FC : flow cytometry. Effect description: + : increase; ++ : strong increase (>3 fold the value of the control group); +++ : very strong increase; = : no significant response; - : decrease; -- : strong decrease (>3 fold the value of the control group). LOEDR (µGy/h) : Lowest Observed Effect Dose Rate; LNOEDR (µGy/h) : Lowest No Observed Effect Dose Rate; LOED (µGy) : Lowest Observed Effect Dose. By default, the endpoint is LOEDR. If not available, LNOEDR or LOED are given.

272. To date, experiments have failed to demonstrate a clear correlation between micronucleus (MN) induction and the ^{137}Cs concentration in fish muscle. Al-Sabti [A20] collected blood samples from pike, perch, roach and bream in Swedish lakes contaminated by Chernobyl fallout. Even if the ^{137}Cs concentrations in the muscle were high, up to 18 kBq kg^{-1} (dry weight), and MN induction significant, they were not correlated and the highest MN frequency (42 per 1,000 erythrocytes) was observed in the control lake. A similar observation was made in another study on Swedish lakes [A21]. In another in-situ study conducted by Sugg et al. [S18] on catfish from the Chernobyl area, the highest MN frequency (6 per 1,000 erythrocytes) was found in fish from the control site, although alkaline unwinding assay showed an increase (non-significant) of single-strand breaks (SBs) in the cooling pond. The authors hypothesized that other pollutants might have been present in the control lake or that the fish might have displayed an adaptive behaviour and increased defence mechanisms against ionizing radiation exposure. On the other hand, Ilyinskikh et al. [I22] found a positive correlation between the ^{137}Cs concentration in pike muscle (up to 1.2 kBq/kg wet weight) and the frequency of micronucleated erythrocytes, for fish caught in Siberian nuclear facilities. A positive correlation was also found between micronuclei frequency and age.

273. Gustavino et al. [G23] exposed carp to acute doses of X-rays (250 kV, 6 mA, 0.75 Gy/min). They found a dose and time-dependent response of MN to irradiation, the peak being 21 days after treatment. The lowest dose tested, for which there was a significant MN induction, was 0.1 Gy. It is interesting to remark that the baseline of micronuclei induction ranges over 2–3 orders of magnitude between different fish species. In the medaka (*Oryzias latipes*), an X-ray dose of 4 Gy (0.5 Gy/min) increased the frequency of MN to approximately 7 per 1,000 gill cells. Knowles [K16] irradiated plaice using ^{137}Cs sealed sources. He did not observe any MN induction, even for the highest dose tested (1 mGy/h over 197 days, total dose of 4.6 Gy). The lack of sensitivity of this assay for fish could be linked to its application to non-dividing cell populations or to dividing cell populations in which the kinetics of cell division are not well understood or controlled.

274. Ulsh et al. [U18, U19] used the fluorescence in situ hydridization (FISH) technique in a study involving slider turtles. They showed for *Trachemys scripta* fibroblasts and lymphocytes, that the dose rate below which no reduction in effect per unit dose was observed with further dose protraction was about 230 mGy/h. Interestingly, they also showed that this species had a much lower spontaneous background of symmetrical translocations in lymphocytes than humans (30-fold less), which makes it a sensitive species for the study of low doses and dose rates.

275. Theodorakis and Shugart [T21, T22] found different allele frequencies for mosquitofish populations exposed to radionuclides within the Oak Ridge nuclear site compared to fish in reference lakes. They showed that heterozygotes for the allozyme locus nucleoside phosphorylase (NP), an enzyme involved in nucleoside synthesis, were more prevalent in fish in the radionuclide-contaminated sites and, moreover, that they had fewer DNA strand breaks than the homozygotes. Finally, they showed that NP heterozygotes had a greater fecundity than homozygotes.

276. Genetic adaptation, i.e. the genetic basis for resistance, can be evaluated in populations exposed to a contaminant. The individuals that are not resistant are naturally eliminated, while tolerant individuals can be bred. Subsequently, F_1 and F_2 generations can be tested for resistance. If tolerance persists or increases in F_1 and F_2 generations, then the response can be said to be genetic. Further analyses can be conducted using molecular techniques to investigate thoroughly the mechanisms involved. Such experiments have been scarcely performed, probably because they are costly and time consuming. In a series of papers, Theodorakis et al. used such an integrated approach, and demonstrated the effects of contaminants (mostly radionuclide) on genetic patterns [T20, T21, T22, T23]. The bacterium *Escherichia coli* population became radioresistant after daily X-irradiation over many generations [E21], and it was shown that the most radioresistant strain isolated from this population has the mutation(s) in genes involved in inducible DNA repair [E9].

(d) Effects of acute exposure

277. For primary producers, the information is still rather limited (only 10 papers in the FRED), mainly describing morphological changes and growth inhibition for green microalgae at high doses (approximately 100–1,000 Gy). Chromosome aberration at doses from 1–5 Gy was evident in the macroalgae *Nitella flagelliformis* (as discussed in reference [F5]).

278. From the information in the FRED, acute doses up to 1 Gy have no significant effects on species representative of annelid, mollusc and crustaceans. Acute doses as low as 0.5 Gy can significantly decrease the percentage of live embryos in broods of the particularly radiosensitive polychaete worm, *Neanthes arenaceodentata*. This radiosensitivity is confirmed by the finding of an increased incidence of radiation-induced sister chromosome exchanges in juvenile worms exposed at total doses greater than 0.17 Gy. The explanation was that the response was due to the induction of dominant lethal mutations in gametes of irradiated adult worms [F5].

279. For fish, the existing knowledge mainly relates to acute exposures greater than 5 Gy. Acute doses below 1 Gy are unlikely to have any significant influence on their general health (morbidity). Fish embryos are much more radiosensitive than free swimming larvae, juveniles and adults. Doses less than 2 Gy are likely to have little effect on mortality. The lowest dose reported in the FRED with significant effect, is as low as 0.16 Gy delivered in the early 1-cell stage of

development and the consequent mortality is scored over long periods—150 days post fertilization. The developing fish embryo is very sensitive to the effects of acute irradiation, particularly at the very early stages just prior to, or immediately after the actual fertilization and during the process of division of the single cell. Irradiation of silver salmon embryos at this stage gave an estimated LD_{50} of 0.16 Gy when assessed at 150 days post-irradiation. Apart from this critical period in embryonic development, FASSET [F5] concluded that it appears unlikely that significant effects will follow doses below 0.5 Gy. An acute dose of this magnitude at any later stage of development will be unlikely to have any significant influence on adult male and female fertility. Mutagenic damages (specific locus mutations, dominant and recessive lethal mutations, polygenic characters, and chromosome aberrations) have been observed at all radiation doses used in the relevant studies. Where comparisons of relative radiosensitivity have been made, it has been concluded that fish show a sensitivity similar to, and most often less than, that of the mouse. There is a single example of apparently greater sensitivity—for specific locus mutations induced in medaka sperm [R9]. Although there are no data relating to radiation-induced mutagenesis in marine fish, there is no reasonable basis for expecting them to respond differently from freshwater fish.

6. Effects on populations and ecosystems

280. Ecosystems consist of various organisms that have a wide range of radiosensitivities and interact with one another in a complex fashion. As a result, indirect responses to the direct effects of radiation exposure are observed in the natural environment. Since these indirect responses cannot necessarily be deduced from the effects on individuals and populations, effects at the community level are evaluated by mathematical modelling, model ecosystem experiments and field irradiation experiments.

281. In mathematical modelling, physical, chemical and biological components of natural ecosystems and interactions among them are mathematically defined, and ecosystems are simulated in computers. Effects on the entire ecosystems are evaluated by applying single-species effect data to the mathematically constructed ecosystems. For example, Bartell et al. developed a comprehensive aquatic-systems model (CASM) [D6]. The CASM model is a bioenergetic ecosystem model that simulates the daily production dynamics of populations (including predator–prey interactions) with time, in relation to daily changes in light intensity, water temperature, and nutrient availability. This model has been adopted for estimating the ecological risks of chemicals for aquatic ecosystems in Quebec [B24], central Florida [B25] and Japan [N7]. In time, this type of model will also be useful for the evaluation of the effects of radiation exposure.

282. Model ecosystem experiments provide biotic or abiotic simplicity, controllability and replicability, which cannot be expected in field experiments. At the same time, they simulate the inter-species interactions of natural ecosystems. It is therefore expected that model ecosystem experiments can investigate the indirect effects of radiation exposure, which cannot be evaluated by conventional single-species experiments. Model ecosystem experiments can therefore be regarded as a bridge between single-species experiments and field experiments. Some model ecosystem experiments have been performed to investigate the effects of radiation exposure. For example, Williams and Murdoch [W14] made studies using two different types of marine model ecosystems. However, no effects for 23 possible effect endpoints were observed at dose rates of up to 0.79 Gy/d.

283. Ferens and Beyers [F18] acutely irradiated aquatic model ecosystems derived from a sewage oxidation pond consisting of various kinds of microorganisms. Effects on biomass, chlorophyll content and gross-community metabolism were more severe at doses of 1,000 Gy than at 10,000 Gy. This unexpected phenomenon might arise from the disappearance of inhibitory inter-species interactions after elimination of certain species at doses of 10,000 Gy.

284. Fuma et al. [F19] studied effects of acute gamma irradiation on the aquatic model ecosystem consisting of the flagellate alga, *Euglena gracilis*, as a producer, the ciliate protozoan, *Tetrahymena thermophila*, as a consumer and the bacterium, *Escherichia coli*, as a decomposer. After a dose of 1,000 Gy, the cell density of *T. thermophila* was increased temporarily, and then decreased compared with controls. This complicated change in *T. thermophila* might be an indirect response to direct effects on the other species, i.e. extinction of *E. coli* and decrease in *Eu. gracilis*. Doi et al. [D7] mathematically simulated a dose–effect relationship for this experimental model ecosystem with a particle-based model, in which inter-species interactions were taken into consideration. This suggests that experimental model ecosystems are useful for validation of mathematical models.

285. Hinton et al. [H12] constructed a Low Dose-Rate Irradiation Facility (LoDIF) in the Savannah River Ecology Laboratory (Aiken, South Carolina, USA). This facility consists of outdoor open-air tanks and is designed to house a variety of aquatic organisms. Gamma irradiation is conducted with an irradiator placed over each tank. Each irradiator contains a 0.74, 7.4 or 74.0 MBq sealed ^{137}Cs source. The 7.4 MBq source delivers a mean dose rate of approximately 10 mGy/d. The LoDIF is now used only for studies of the effects of chronic irradiation on the reproduction of small fish (Japanese medaka; *Oryzias latipes*), but can be used as an experimental model ecosystem.

286. Some field irradiation experiments have been performed, though these have already been terminated. The Brookhaven Irradiated Forest Experiment is a typical example. This experiment was designed to study the effects of radiation exposure on plant and animal communities [W15]. In 1961, a 350 TBq ^{137}Cs source was placed in an oak–pine forest at the Brookhaven National Laboratory (Upton, New York, USA). The dose rate within a few metres from the

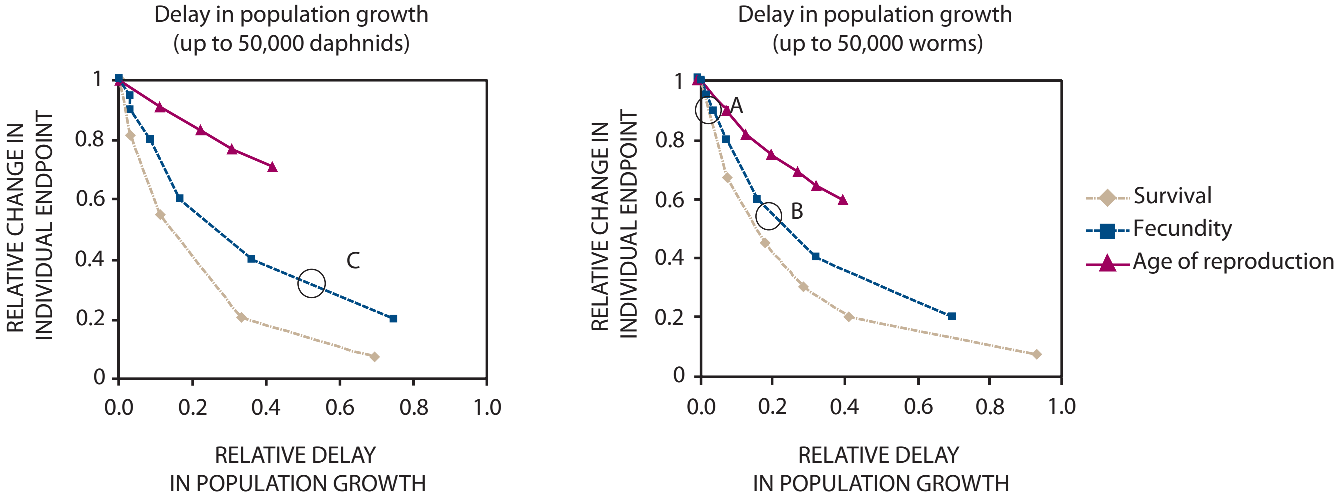
source was in the order of 10 Gy/d; it decreased to background levels beyond 300 m. After commencement of irradiation, biomass, species composition, densities and other ecological parameters were measured for plants, insects, fungi, lichens and soil algae. Many examples of the indirect effects described in the UNSCEAR 1996 Report [U4] were observed in a series of experiments conducted with this source.

287. Two field-irradiation experiments were conducted at the Whiteshell Laboratories in Manitoba, Canada. One is the Field-Irradiated Gamma (FIG) experiment in which a boreal forest was chronically irradiated from 1973–1986 to study the effects on plant communities [G13]. The radiation source was 370 TBq ^{137}Cs, and the dose rates ranged from 0.12–1,560 mGy/d. The effects of radiation exposure were investigated for tree canopy, naturally growing shrubs, ground cover species, germination of seeds, morphological change and tree-ring growth. One experimental observation was that the seed germination of Jack Pine showed deleterious effects at a dose rate of 1.1 mGy/h [S38]. In contrast, reference [S38] reported hormetic effects (increased germination) at dose rates up to 0.6 mGy/h. The other experiment was the Zoological Environment Under Stress (ZEUS) that was performed from 1981–1985 to study the effects on the individual or population characteristics of meadow voles [M11]. Vole populations were irradiated at nominal dose rates of 200, 9,000 and 40,000 times that from natural background radiation. No effects on individual or population-level characteristics were observed at a dose rate up to 81 mGy/d, the highest dose rate used. Mihok noted that experiments with radiation had not shown any individual or population effect from chronic exposure to low-LET external radiation in the range of 10–100 mGy/d and that the current guidelines in the range of 1–10 mGy/d appeared suitable as benchmarks for general environmental protection purposes [M11].

288. Simulation can be used to illustrate population-level effects arising from individual effects with different endpoints. By modelling the delay in population growth on the basis of the observed effects on individual traits (figure XV), simulation of the effects of chronic exposure to radionuclides at the population level appeared to be mediated through individual-effect endpoints as follows: *(a)* effects on the hatchability of cocoons and the number of hatchlings per hatched cocoon for earthworms; and *(b)* effects on larval resistance to starvation for daphnids. Ultimately, effects increase the early mortality of larvae in both species (offspring are produced but they never reach reproduction age) which are, with regard to population dynamics, equivalent to not producing those offspring. Observed effects can be assimilated to a reduction in fecundity in every case: 10% reduction in fecundity in earthworms at a dose rate of 4 mGy/h (point A on figure XV), 55% reduction in fecundity in earthworms at a dose rate of 11 mGy/h (point B on figure XV), 70% reduction in starved control daphnids and up to 100% reduction (i.e. extinction) in starved contaminated daphnids independent of the dose rate (point C on figure XV). The last result indicates that this species becomes more vulnerable to food depletion for the radionuclide-contaminated environment than for non-contaminated habitats [G3].

Figure XV. Relationship between effects at the individual level and their relative consequence at the population level (from reference [G3])

Earthworms chronically exposed to external gamma radiation: A: 10% reduction in fecundity at 3.3–3.6 mGy/h; B: 55% reduction in fecundity at the dose rate of 9–9.5 mGy/h. Daphnids chronically exposed to internal alpha radiation (^{241}Am); C: 70% reduction in starved control and up to 100% reduction (i.e. extinction) independent of the dose rate



289. The consequences of radiation exposure at the population level depend on the particular stage in the life history of the organism. Small effects on individual endpoints critical for population dynamics may impair population growth rate to a greater extent than large effects on neutral individual endpoints. The impact of chronic exposure to radionuclides at the population level depends on which stage in the life history is impaired. Individual endpoints do not show the same importance at the population level, population growth being by far more sensitive to changes in age of reproduction than changes in fecundity or survival [A26, G3] (figure XV).

290. Specific studies have provided evidence linking genotoxic syndrome to population-level changes [T20, T21, T22, T23]. Trabalka and Allen [T19] raised 2 generations of mosquitofish collected from a radionuclide-contaminated site. They showed that fish from the F_2 generation were less tolerant to thermal stress than fish from the control site.

291. Mutations occur at the molecular level, but heritable mutations in germ cells are capable of affecting the genetic diversity of populations, and can lead to increased or decreased genetic diversity, as well as to changes in phenotype that can affect Darwinian fitness. Increases in mutation rate can increase genetic diversity of the population by producing new alleles or genotypes, but they can also result in decreased genetic diversity, since the mutations could reduce the viability or fertility of the individuals [T14]. Consequently, increases in mutation rate can affect the genetic structure of the population, and thereby have ecologically relevant effects.

292. Exposure to contaminants can lead to alterations in the genetic makeup of populations, a process termed evolutionary toxicology. It is generally hypothesized that there is an alteration of genotype frequencies and a reduction in genetic variation in genotoxicant-contaminated environments. These changes may occur as a result of selection on specific alleles, selection for multi-locus genotypes, mortality in specific life stages, and changes in breeding period. They may induce reduction in population size, alterations in the degree of inbreeding, alteration of the level of gene flow and changes in age or class structure. Potentially, these shifts may alter population viability and fitness. Theodorakis and Shugart [T21] observed a higher percentage of polymorphism and heterozygosity in mosquitofish from the radionuclide-contaminated site, correlated with a higher fitness and lower level of DNA strand breaks. These findings suggest that there is a selective advantage in radionuclide-contaminated areas. More surprisingly, they found a higher genetic diversity in the radionuclide-contaminated populations, for which no definite explanation was given. The authors hypothesized that the higher diversity was linked to genomic rearrangements or different life-history processes.

293. Even though several factors complicate extrapolations of individual-level effects to populations, current knowledge supports the conclusion that measures intended to limit radiation damage to individuals to an acceptable degree will also provide a sufficient degree of protection for populations. However, in situations where the most sensitive life stage has not been positively identified, or where there is a lack of data on the most sensitive life stage, there may be a need to introduce a margin of safety when using the available dose–effect information on individual life stages to develop measures to protect field populations. Furthermore, population-level consequences of hereditary mutations might in some cases need to be allowed for in these extrapolations. If and how this might be done requires additional research and scientific review [G16].

294. Most studies of the effects of exposure to ionizing radiation have been performed under non-limiting growth conditions (i.e. sufficient food and space were available). In contrast, wild organisms are often regulated by various types of density-dependent factors such as competition for resources. Based on current knowledge, it is hard to draw general conclusions on how density-dependent factors may influence the propagation of effects on individuals to populations [G16].

295. In its 2008 report, the ICRP [I10] suggested that, in considering the potential effect of exposure to ionizing radiation, context should be provided by comparing the estimated dose rates to multiples of the dose rates experienced by the various biota in their natural environment. In this regard, the ICRP proposed the use of the concept of “Derived Consideration Levels” (DCLs) which were intended to serve as points of reference for assessing the potential effects of exposure to ionizing radiation on non-human biota. In doing this, the ICRP compiled available information for their various biota categories and summarized the data into bands of dose rate from less than 0.1 to more than 100 mGy/d. In commenting on the available data, the ICRP emphasized that the data are both incomplete and of varied quality and that their summary tables represent “an extreme oversimplification of existing data”. The range of DCLs (dose rates) for various biota categories (e.g. mammals, birds, and trees) summarized by ICRP were:

– With regard to the mammals (“higher vertebrates”), deer and rat, the ICRP suggested that at dose rates in the region of 0.1–1 mGy/d, there was only a very low probability of certain effects occurring that could result in reduced reproductive success or morbidity. At dose rates in the band of 1–10 mGy/d, there was some potential for reduced reproductive success;

– For birds (the reference bird was the duck), the ICRP suggested that based on metabolism, longevity, and reproductive behaviour, it was reasonable to assume similar results to those for mammals;

– With regard to the “lower” poikilothermic vertebrates (frog, trout and flatfish), data are generally lacking below about 1 mGy/d. However, considering the general lack of physiological data on amphibians, the ICRP suggested a lower DCL (dose-rate) band of 0.01–0.1 mGy/d for frogs compared to the two types of fish. For dose rates in the range of 1–10 mGy/d, the ICRP suggested that some reduction in reproductive capacity might occur in frogs and possibly also in fish species;

- The ICRP indicated that there are essentially no data for the invertebrates, bee, crab and earthworm, but suggested that invertebrates are less sensitive and recommended a DCL of 10–100 mGy/d; and
- The data for trees, plants and seaweeds are highly variable across species, the best data being for pine trees. The ICRP suggested DCLs of 1–10 mGy/d for grasses and seaweeds but a 10-times lower value for pine trees, which they attribute in part to their potential for very long periods of exposure.

V. SUMMARY AND CONCLUSIONS

296. All living organisms have existed and developed in environments where they are exposed to ionizing radiation from the natural background and, recently, to radiation resulting from global fallout of radioactive material following the atmospheric nuclear weapons tests. In addition, biota are exposed, generally in areas of limited spatial extent, to radiation from man's activities, such as the controlled discharge of radionuclides to the air, ground or aquatic systems, or from accidental releases of radionuclides.

297. Prior to the development of the annex, "Effects of radiation on the environment" of the UNSCEAR 1996 Report [U4], the Committee had not specifically addressed the effects of radiation exposure on plant and animal communities. Living organisms had been considered primarily as part of the environment in which radionuclides might be dispersed and as resources that, if they took up radionuclides, might contribute to human exposures via the human food chains. Like humans, however, organisms are themselves exposed internally from radionuclides that they may have taken up from the environment, and externally due to radiation from radionuclides in the environment.

298. In the past decades, scientific and regulatory activities related to radiation protection focused on the radiation exposure of humans arising from both artificial and natural sources. The prevailing view was that, if humans were adequately protected, then "other living things are also likely to be sufficiently protected" [I8] or "other species are not put at risk" [I5]. Over time, the general validity of this view has been challenged on occasion and more attention has therefore been given to the potential effects of exposure to ionizing radiation on non-human biota. In part, this has occurred as a result of the increased worldwide concern over sustainability of the environment, including the need to maintain biodiversity and protect habitats or endangered species (e.g. [U22, U23]), and, in part, as a result of various efforts to assess the effects of exposure to ionizing radiation on plants and animals [D1, I1, I2, I3, I4, I9, N6, T1].

299. Since the Committee issued its first report in 1996 [U4] on the doses and dose rates of ionizing radiation below which effects on populations of non-human biota are unlikely, the approaches to evaluating radiation doses have been reviewed and progress has been made (e.g. by the DOE [U26], the Environment Agency [C1], FASSET [F1], ERICA [E1]). In addition, the continuing follow-up of the consequences of the Chernobyl accident has provided a great deal of new information on the radiobiological effects of ionizing radiation exposure on non-human biota (e.g. [E8, G26]). Similarly, information not previously available to the Committee on the levels of radiation exposure below which radiobiological effects on non-human biota are unlikely has been further compiled and evaluated, in part, through the work carried out in support of the development of the FASSET effects database, FRED, and the subsequent FREDERICA effects database [B26, E1, F1]. The Committee undertook a review of the new scientific information that had become available since its previous report and assessed whether it needed to modify its previous recommendations concerning the dose rates below which effects on non-human biota are considered unlikely.

A. Estimating dose to non-human biota

300. The radiation dose received by an organism (or some organ or tissue of the organism) is the sum of both the external and internal exposure. Absorbed doses are calculated as the dosimetric endpoint; however, for radionuclides taken into the organism, an appropriate factor may be applied in order to account for the different RBEs of the different kinds of radiation.

301. External exposures of biota are the result of complex and non-linear interactions of various factors, such as the levels of radionuclides in the habitat, the geometrical relationship between the radiation source and the target, the shielding properties of materials in the environment, the size of the organism and the radionuclide-specific decay properties (characterized by the radiation type, the energies emitted and their emission probabilities).

302. Internal exposures of plants and animals are determined by the activity concentration in the organism, the size of the organism, the radionuclide distribution and the specific decay properties of the radionuclide.

303. In considering the potential effects of ionizing radiation exposure on non-human biota, the Committee assumed

that natural populations of non-human biota are in a state of dynamic equilibrium within their environment. Equilibrium models assume that radionuclide concentrations reach equilibrium within various environmental compartments and that transfer between compartments is reasonably characterized by time-invariant ratios of concentration between the compartments. One of the advantages of the equilibrium model is its simplicity. Such models are widely used by national regulators for assessment purposes. However, when it is necessary to assess a time-dependent response—for example, when considering an accidental release of radionuclides—dynamic radioecological models are needed. Within the context of this annex, equilibrium models have been assumed in the exposure assessments, unless otherwise indicated. Readers interested in dynamic radioecological models are referred to the published literature [M4, M7, S1, W3].

B. Summary of dose–effects data from the UNSCEAR 1996 Report

304. Notwithstanding the limitations of the data available in 1996, the Committee considered it unlikely that radiation exposures causing only minor effects on the most exposed individual would have significant effects on the population. It also suggested that the effects of radiation exposure at the population and community levels are manifest as some combination of direct changes due to radiation damage and indirect responses to the direct changes [U4].

305. The Committee considered that the individual responses to radiation exposure likely to be significant at the population level are mortality (affecting age distribution, death rate and density), fertility and fecundity (both affecting birth rate, age distribution, number and density) and the induction of mutations (birth rate and death rate). The response of these individual functions to radiation exposure could be traced to events at the cellular level in specific tissues or organs. An extended summary discussing the processes involved had been provided in annex J, “Non-stochastic effects of irradiation”, of the UNSCEAR 1982 Report [U9]. The Committee also considered there was a substantial body of evidence indicating that the most radiosensitive sites are associated with the cell nucleus, specifically the chromosomes, and that, to a lesser extent, damage to intracellular membranes was additionally involved. The end result is that the cells lose their reproductive potential. For most cell types, at moderate doses, death occurs when the cell attempts to divide; death does not, however, always occur at the first post-exposure division: at doses of a few gray, several division cycles might be successfully completed before death eventually occurred. It was also well known that radiosensitivity varies within the cell cycle, with the greatest sensitivities being apparent at mitosis and the commencement of DNA synthesis [U9]. It followed that the greatest radiosensitivity is likely to be found in cell systems undergoing rapid cell division for either renewal (e.g. spermatogonia) or growth (e.g. plant meristems and the developing embryo); these examples clearly underlie the processes in individual organisms that are important for the maintenance of the population. Effects of radiation exposure on populations occur as the result of exposure of individual organisms. The propagation of effects from individual organisms to populations is complex and depends on a number of factors; however, the Committee considered that of the various effects on populations of non-human biota, the key effects are those that affected reproductive success.

306. The Committee noted that the responses of organisms to radiation exposure are varied and might become manifest at all levels of organization, from individual biomolecules to ecosystems. The significance of a given response depends on the criterion of damage adopted, and it was not to be concluded that a response at one level of organization would necessarily produce a consequential, detectable response at a higher level of organization.

307. In its 1996 assessment, the Committee considered that reproductive changes are a more sensitive indicator of the effects of radiation exposure than mortality, and mammals are the most sensitive animal organisms. On this basis, the Committee concluded that chronic dose rates of less than 100 µGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal populations. The Committee also concluded that maximum dose rates of 400 µGy/h to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level. These conclusions refer to the effects of low-LET radiation. Where a significant part of the incremental radiation exposure comes from high-LET radiation (especially alpha particles) that is internal to the organism, it is necessary to apply an appropriate factor to adjust for the different RBEs of the different radiations.

308. Acute lethal radiation doses to plants had been noted to range from 10–1,000 Gy. In general, larger plants are more radiosensitive than smaller plants, with radiosensitivity decreasing in the order coniferous trees, deciduous trees, shrubs, herbaceous plants, lichens [U4]. The data on radiosensitivity of terrestrial animals were dominated by data on mammals, the most sensitive class of organisms. Acute lethal doses ($LD_{50/30}$) were 6–10 Gy for small mammals and 1.5–2.5 Gy for larger animals and domestic livestock [U4]. The Committee concluded [U4] that the effects of radiation exposure on birds are similar to those in small mammals. Separately, it [U4] found that reptiles and invertebrates are less radiosensitive than birds, with studies of acute radiation exposures of adult amphibians indicating LD_{50} values of between 2–22 Gy. With respect to aquatic organisms, fish are the most sensitive to the effects of radiation exposure; the developing fish embryos are particularly so. The LD_{50} for acute irradiation of marine fish is in the range of 10–25 Gy for assessment periods of up to 60 days following exposure [U4]. Overall, a notional range of dose of 1–10 Gy from acute radiation exposure is unlikely to result in effects on populations of non-human biota.

C. The current evaluation

309. Many of the new data subsequent to the Committee’s 1996 report [U4] arose from follow-up studies of the consequences of the Chernobyl accident. Prior to the accident, much of the area around the Chernobyl nuclear power plant was covered in 30–40-year old pine stands that, from a successional standpoint, represented mature, stable ecosystems [E8]. The high dose rates during the first few weeks following the accident altered the balance in the community and opened niches for immigration of new individuals. All these components and many more, were interwoven in a complex web of action and reaction that altered populations and communities of organisms. In addition to the effects from the radiation exposure, activities such as agriculture, forestry, hunting and fishing within the 30-km zone were stopped [E8]. Moreover, after the accident, the agricultural fields remained productive for a number of years and, in the absence of active management of areas that had been evacuated, many animal species, especially rodents and wild boar, consumed the abandoned cereal crops, potatoes and grasses as an additional source of forage [E8]. This advantage, along with the special reserve regulations established in the exclusion zone (i.e. a ban on hunting) tended to mask potential adverse biological effects of radiation exposure and led to an increase in the populations of wild animals, including game mammals (wild boar, roe deer, red deer, elk, wolves, foxes, hares, beaver, etc.) and bird species (black grouse, ducks, etc.) [G8, S23]. The exclusion zone has become a breeding area of the white-tailed eagle, spotted eagle, eagle owl, crane and black stork [G9].

310. Overall, based on an evaluation of the available data arising from studies of plants and animals in the zone around the Chernobyl nuclear power plant, the Chernobyl Forum [E8] arrived at a number of general observations, including:

- Radiation from radionuclides released as a result of the Chernobyl accident caused numerous acute adverse effects on the biota located in the areas of highest exposure (i.e. up to a distance of a few tens of kilometres from the release point);
- The environmental response to the increased radiation exposure incurred as a result of the Chernobyl accident was a complex interaction among radiation dose, dose rate and its temporal and spatial variations, as well as the radiosensitivities of the different taxons. Both individual and population effects caused by radiation-induced cell death were observed in plants and animals and included increased mortality of coniferous plants, soil invertebrates and mammals; reproductive losses in plants and animals; and chronic radiation sickness in animals (mammals, birds, etc.);
- No adverse radiation-induced effects were reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy during the first month after the accident (i.e. <10 mGy/d, on average); and
- Following the natural reduction of exposure levels due to radionuclide decay and migration, populations have been recovering from acute radiation effects. By the next growing season following the accident, the population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from major radiation-induced adverse effects in plants and animals.

311. Another, and even more recent comprehensive review of the effects of radiation exposure arising from the Chernobyl accident on non-human biota compiled and examined the data on effects along with the associated dosimetric information [G26]. The authors evaluated 250 references in total, of which, some 79 papers were considered to have adequate information on environmental contamination and doses to biota as well as information on the associated effects. The effects of radiation exposure were seen in both natural and agricultural systems. Consistent with the Committee’s 1996 report [U4], the authors noted that the effects depended on the radiosensitivity of the dominant species and observed that coniferous trees are one of the most sensitive plant species and mammals are the most radiosensitive animal species. Table 27 summarizes the various effects seen in non-human biota around the Chernobyl nuclear power plant and the corresponding doses or dose rates below which such effects were not observed.

312. Alexakhin et al. [A29] reported on the environmental and agricultural impact of the Chernobyl accident. These authors described the effects of countermeasures on the doses to ecosystems and the public. High radiation doses within the 30-km exclusion zone led to numerous effects on biota ranging from subtle effects at the molecular and subcellular levels, to significant degradation of ecosystems, pine stands for example. On the other hand, evacuation of people from the 30-km zone reduced stresses arising from human use of the environment. Exclusion of people, along with the special reserve regulations established in the exclusion zone (i.e. a ban on hunting) overcame potential adverse biological effects of radiation exposure and led to an increase in the populations of wild animals and birds. Based on an evaluation of the FRED database, FASSET concluded that the information available on the effects of radiation exposure on non-human biota from low dose rates (less than about 100 µGy/h or 2.4 mGy/d) for continuous irradiation is reasonable for both plants and animals and that, for chronic exposure conditions, “the reviewed effects data give few indications for readily observable effects at chronic dose rates below 100 µGy/h”. However, it advised that “using this information for establishing environmentally ‘safe levels’ of radiation should be done with caution, considering that the database contains large information gaps for environmentally relevant dose rates and ecologically important wildlife groups” [F5, R9].

313. For chronic exposures, the ERICA project used statistical methods to estimate the dose rates below which 95% of species in the aquatic/terrestrial ecosystems should be protected. Their analysis of the data on effects from external gamma irradiation of species of different ecosystems concluded that there was no statistical justification to attempt to derive ecosystem specific screening dose rates and hence all data were analysed together as a "generic" ecosystem. The resultant dose rate that would protect 95% of the species in the generic ecosystem was estimated at 82 µGy/h (with 95th percentile confidence intervals of 23.8 and 336 µGy/h). This is generally consistent with the Committee's 1996 assessment [E11, G27]. It should be noted that these authors implicitly adopted a further safety factor of 5 in an attempt to account for data limitations.

314. ERICA also applied the same statistical methods to the data on effects for acute exposure conditions but in this case, a statistically significant difference was seen between marine ecosystems compared to terrestrial and freshwater ecosystems. The values derived from a statistical analysis of the set of doses giving a 50% change in the observed effect for limiting the potentially affected fraction to 5% of the species under acute external gamma irradiation varied from about 1–5.5 Gy, according to the ecosystems type, with the associated 95% confidence intervals covering less than one order of magnitude. For screening purposes, ERICA applied a further *SF* of 5 and reported Predicted No-Effect Doses (PNED) of 900 mGy for marine ecosystems and 300 mGy for terrestrial and freshwater ecosystems [G3, G15, G27]. The application of such additional safety factors is of great interest in developing regulatory approaches for the protection of non-human biota; however, such judgements are beyond those of the Committee and properly lie in the domain of the ICRP and national authorities.

315. Information on the effects of acute doses of radiation has also been reviewed. For example, soil fauna are unlikely to be affected at doses below about 1 Gy [G3]. The same authors reported data that suggested that the reproductive capacity of Scots pine is inhibited at doses in the range of 0.5–5 Gy. The radiosensitivity of spruce is greater than that of pines with malformed needles, buds, and shoot growth at absorbed doses as low as 0.7–1 Gy [K1]. Information has been reported [G3] that shows a decrease in population density and species composition of forest litter mesofauna at doses in the range of 1–9 Gy. Based on a review of the FRED, FASSET concluded that acute doses of up to 1 Gy have no significant effect on annelids, molluscs and crustaceans, that acute doses below about 1 Gy are unlikely to have a significant effect on general health (morbidity), and that doses below about 0.5 Gy are unlikely to have any significant effect on adult male and female fertility [F5]. When the SSD method was applied to data on the effects of acute exposures, HDR_5 values in the range of about 1–5.5 Gy were estimated. Thus, on the basis of the available data, the Committee continues to recommend a nominal reference dose of about 1 Gy, within a factor of 2 or so, as a reference value below which population-level effects on non-human biota are unlikely in the event of an acute exposure.

D. Conclusions

316. As discussed in the UNSCEAR 1996 Report, the Committee considered it unlikely that radiation exposures causing only minor effects on the most exposed individual would have significant effects on the population. It also considered that reproductive changes are a more sensitive indicator of the effects of radiation exposure than mortality, and that mammals are the most sensitive animal organisms. Since 1996, new data on the effects of exposure to ionizing radiation have been developed from follow-up observations of non-human biota in the zone around the Chernobyl nuclear power plant (section III) and various organizations have carried out comprehensive reviews of the scientific literature on the data on effects and, in some cases, developed new approaches to the assessment of the potential risks to non-human biota (section IV). There is a considerable range of endpoints and corresponding effects levels (dose or dose rate) presented in the literature and also considerable variation in how different researchers have evaluated these data. Table 39 provides a summary of the data on the effects of radiation exposure for aggregated categories of biota. Details of endpoint effects are described in the corresponding references.

Table 39. Overall summary of data on chronic effects of radiation exposure for plants, fish and mammals

Category	*Dose rate (µGy/h)*	*Effects*	*Endpoint*	*Reference*
Plant	100–1 000	Reduced trunk growth of pine trees	Morbidity	[W4]
	400–700	Reduced numbers of herbaceous plants	Morbidity	[G26]
Fish	100–1 000	Reduction in testis mass and sperm production, lower fecundity, delayed spawning	Reproduction	[H11, K16, N1]
	200–499	Reduced spermatogonia and sperm in tissues	Reproduction	[C11]

Category	*Dose rate (µGy/h)*	*Effects*	*Endpoint*	*Reference*
Mammals	<100	No detrimental endpoints have been described	Morbidity, mortality, reproduction	[C17, L2, P8, R9, U21, Y2]
Generic ecosystems (terrestrial and aquatic)	about 80	A new statistical approach (species sensitivity distribution, SSD) was applied to the data on radiation effects to estimate HDR_5 , the dose rate at which 95% of the species in the ecosystem are protected	Morbidity, mortality, reproduction	[G3, G11, G15]

317. Overall, the Committee concluded that chronic dose rates of less than 100 µGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities and that maximum dose rates of 400 µGy/h to any individual in aquatic populations of organisms would be unlikely to have any detrimental effect at the population level. For acute exposures, significant effects on populations of non-human biota are unlikely at doses below (about) 1 Gy. These conclusions refer to the effects of exposure to low-LET radiation. Where a significant part of the incremental radiation exposure comes from high-LET radiation (alpha particles), the Committee concluded that it is necessary to take account of the different RBEs of the radiations.

318. In addition to new data on the levels at which the effects of radiation exposure have been observed, notably from follow-up studies of the consequences of the Chernobyl accident, various authors have investigated new analytical methods, notably that of species sensitivity distribution [G3, G11], which involves meta-analysis of the variations in radiosensitivity among species. However, at this time, insufficient data are available for the application of such methods. It is anticipated that as new information is developed in the future, the application of these new methods of analysis will facilitate future re-evaluations of the effects of ionizing radiation exposure on non-human biota.

319. A great deal of work has been done since 1996 to improve the data and methods for evaluating pathways through which biota are exposed to radiation from radioactive material in the host environment and many improvements in biota dosimetry have been made. However, many opportunities still remain to improve our understanding of the relation between the levels of radioactive material in the environment and the potential effects on biota residing in that environment.

320. Based on the new information described in this annex, and considering the overall limitations of the available data, the Committee considered that there is no need to change its previous conclusions of the values of nominal chronic dose rates below which direct effects on non-human species are unlikely at the population level. Nonetheless, where data of suitable scientific quality are available for a specific species endpoint and/or other level of biological organization, the Committee would encourage their use in assessments of the potential effects of radiation exposure. However, there are very limited data for many taxa and therefore many assumptions are needed to extrapolate between species. There is a need to better understand the chronic effects at a multigenerational time scale, chronic effects for multiple stressors, and the propagation of effects at the molecular and cellular levels to higher levels of ecological organization. In this respect, the application of so-called “-omic” techniques (transcriptomic, proteomic and so on) will help in future assessments.

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