ANNEX J

Exposures and effects of the Chernobyl accident

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INTRODUCTION

1. The accident of 26 April 1986 at the Chernobyl nuclear power plant, located in Ukraine about 20 km south of the border with Belarus, was the most severe ever to have occurred in the nuclear industry. The Committee considered the initial radiological consequences of that accident in the UNSCEAR 1988 Report [U4]. The short-term effects and treatment of radiation injuries of workers and firefighters who were present at 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", and the average individual and collective doses to the population of the northern hemisphere were evaluated in Annex D, "Exposures from the Chernobyl accident", of the 1988 Report [U4]. The objective of this Annex is (a) to review in greater detail the exposures of those most closely involved in the accident and the residents of the local areas most affected by the residual contamination and (b) to consider the health consequences that are or could be associated with these radiation exposures.

2. The impact of the accident on the workers and local residents has indeed been both serious and enormous. The accident caused the deaths within a few days or weeks of 30 power plant employees and firemen (including 28 deaths that were due to radiation exposure), brought about the evacuation of about 116,000 people from areas surrounding the reactor during 1986, and the relocation, after 1986, of about 220,000 people from what were at that time three constituent republics of the Soviet Union: Belorussia, the Russian Soviet Federated Socialist Republic (RSFSR) and the Ukraine [K23, R11, V2, V3] (these republics will hereinafter be called by their present-day country names: Belarus, the Russian Federation and Ukraine). Vast territories of those three republics were contaminated, and trace deposition of released radionuclides was measurable in all countries of the northern hemisphere. Stratospheric interhemispheric transfer may also have led to some environmental contamination in the southern hemisphere [D11]. In addition, about 240,000 workers ("liquidators") were called upon in 1986 and 1987 to take part in major mitigation activities at the reactor and within the 30-km zone surrounding the reactor; residual mitigation activities continued until 1990. All together, about 600,000 persons received the special status of "liquidator".

3. The radiation exposures resulting from the Chernobyl accident were due initially to ^{131}I and short-lived radionuclides and subsequently to radiocaesiums (^{134}Cs and ^{137}Cs) from both external exposure and the consumption of foods contaminated with these radionuclides. It was estimated in the UNSCEAR 1988 Report [U4] that, outside the regions of Belarus, the Russian Federation and Ukraine that were most affected by the accident, thyroid doses averaged over large portions of European countries were at most 25 mGy for one-year old infants. It was recognized, however, that the dose distribution was very heterogeneous, especially in countries close to the reactor site. For example, in Poland, although the countrywide population-weighted average thyroid dose was estimated to be approximately 8 mGy, the mean thyroid doses for the populations of particular districts were in the range from 0.2 to 64 mGy, and individual values for about 5% of the children were about 200 mGy [K32, K33]. It was also estimated in the UNSCEAR 1988 Report [U4] that effective doses averaged over large portions of European countries were 1 mSv or less in the first year after the accident and approximately two to five times the first-year dose over a lifetime.

4. The doses to population groups in Belarus, the Russian Federation and Ukraine living nearest the accident site and to the workers involved in mitigating the accident are, however, of particular interest, because these people have had the highest exposures and have been monitored for health effects that might be related to the radiation exposures. Research on possible health effects is focussed on, but not limited to, the investigation of leukaemia among workers involved in the accident and of thyroid cancer among children. Other health effects that are considered are non-cancer somatic disorders (e.g. thyroid abnormalities and immunological effects), reproductive effects and psychological effects. Epidemiological studies have been undertaken among the populations of Belarus, the Russian Federation and Ukraine that were most affected by the accident to investigate whether dose-effect relationships can be obtained, notably with respect to the induction of thyroid cancer resulting from internal irradiation by ^{131}I and other radioiodines in young children and to the induction of leukaemia among workers resulting from external irradiation at low dose rates. The dose estimates that are currently available are of a preliminary nature and must be refined by means of difficult and time-consuming dose reconstruction efforts. The accumulation of health statistics will also require some years of effort.

5. Because of the questions that have arisen about the local exposures and effects of the Chernobyl accident, the Committee feels that a review of information at this stage, almost 15 years after the accident, is warranted. Of course, even longer-term studies will be needed to determine the full consequences of the accident. It is the intention to evaluate in this Annex the data thus far collected on the local doses and effects in relation to and as a contribution to the broader knowledge of radiation effects in humans. Within the last few years, several international conferences were held to review the aftermath of the accident, and extensive use can be made of the proceedings of these conferences [E3, I15, T22, W7]; also, use was made of books, e.g. [I5, K19, M14, M15], and of special issues of scientific journals, e.g. [K42], devoted to the Chernobyl accident.

6. The populations considered in this Annex are (a) the workers involved in the mitigation of the accident, either during the accident itself (including firemen and power plant personnel who received doses leading to deterministic effects) or after the accident (recovery operation workers); (b) members of the general public who were evacuated to avert excessive radiation exposures; and (c) inhabitants of contaminated areas who were not evacuated. The contaminated areas, which are defined in this Annex as being those where the average ^{137}Cs ground deposition density exceeded 37 kBq m^{-2} (1 Ci km^{-2}), are found mainly in Belarus, in the Russian Federation and in Ukraine. Information on the contamination levels and radiation doses in other countries will be presented only if it is related to epidemiological studies conducted in those countries.

I. PHYSICAL CONSEQUENCES OF THE ACCIDENT

7. The accident at the Chernobyl nuclear power station 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, resulting in successive steam explosions that severely damaged the reactor building and completely destroyed the reactor. An account of the accident and of the quantities of radionuclides released, to the extent that they could be known at the time, were presented by Soviet experts at the Post-Accident Review Meeting at Vienna in August 1986 [I2]. The information that has become available since 1986 will be summarized in this Chapter.

8. The radionuclide releases from the damaged 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 five-day period of declining releases associated with the hot air and fumes from the burning graphite core material. In 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 deposited with greatest density in the regions surrounding the reactor in the European part of the former Soviet Union.

A. THE ACCIDENT

9. The Chernobyl reactor is of the type RBMK, which is an abbreviation of Russian terms meaning reactor of high output, multichannel type. It is a pressurized water reactor using light water as a coolant and graphite as a moderator. Detailed information about what is currently known about the accident and the accident sequence has been reported, notably in 1992 by the International Atomic Energy Agency (IAEA) [I7], in 1994 in a report of the Massachusetts Institute of Technology [S1], in 1995 by the Ukrainian Academy of Sciences [P4], and in 1991–1996 by the Kurchatov Institute [B24, C5, K20, K21, S22, V4]. A simplified description of the events leading to the accident and of the measures taken to control its consequences is provided in the following paragraphs. As is the case in an accident with unexpected and unknown events and outcomes, many questions remain to be satisfactorily resolved.

10. The events leading to the accident at the Chernobyl Unit 4 reactor at about 1.24 a.m. on 26 April 1986 resulted from efforts to conduct a test on an electric control system, which allows power to be provided in the event of a station blackout [I2]. Actions taken during this exercise resulted in a significant variation in the temperature and flow rate of the inlet water to the reactor core (beginning at about 1.03 a.m.). The unstable state of the reactor before the accident is due both to basic engineering deficiencies (large positive coefficient of reactivity under certain conditions) and to faulty actions of the operators (e.g., switching off the emergency safety systems of the reactor) [G26]. The relatively fast temperature changes resulting from the operators' actions weakened the lower transition joints that link the zirconium fuel channels in the core to the steel pipes that carry the inlet cooling water [P4]. Other actions resulted in a rapid increase in the power level of the reactor [I7], which caused fuel fragmentation and the rapid transfer of heat from these fuel fragments to the coolant (between 1.23:43 and 1.23:49 a.m.). This generated a shock wave in the cooling water, which led to the failure of most of the lower transition joints. As a result of the failure of these transition joints, the pressurized cooling water in the primary system was released, and it immediately flashed into steam.

11. The steam explosion occurred at 1.23:49. It is surmised that the reactor core might have been lifted up by the explosion [P4], during which time all water left the reactor core. This resulted in an extremely rapid increase in reactivity, which led to vaporization of part of the fuel at the centre of some fuel assemblies and which was terminated by a large explosion attributable to rapid expansion of the fuel vapour disassembling the core. This explosion, which occurred at about 1.24 a.m., blew the core apart and destroyed most of the building. Fuel, core components, and structural items were blown from the reactor hall onto the roof of adjacent buildings and the ground around the reactor building. A major release of radioactive materials into the environment also occurred as a result of this explosion.

12. The core debris dispersed by the explosion started multiple (more than 30) fires on the roofs of the reactor building and the machine hall, which were covered with highly flammable tar. Some of those fires spread to the machine hall and, through cable tubes, to the vicinity of the Unit 3 reactor. A first group of 14 firemen arrived on the scene of the accident at 1.28 a.m. Reinforcements were brought in until about 4 a.m., when 250 firemen were available and 69 firemen participated in fire control activities. These activities were carried out at up to 70 m above the ground under harsh conditions of high radiation levels and dense smoke. By 2.10 a.m., the largest fires on the roof of the machine hall had been put out, while by 2.30 a.m. the largest fires on the roof of the reactor hall were under control. By about 4.50 a.m., most of the fires had been extinguished. These actions caused the deaths of five firefighters.

13. It is unclear whether fires were originating from the reactor cavity during the first 20 h after the explosion. However, there was considerable steam and water because of the actions of both the firefighters and the reactor plant personnel. Approximately 20 h after the explosion, at 9.41 p.m., a large fire started as the material in the reactor became hot enough to ignite combustible gases released from the disrupted core, e.g. hydrogen from zirconium-water reactions and carbon monoxide from the reaction of hot graphite with steam. The fire made noise when it started (some witnesses called it an explosion) and burned with a large flame that initially reached at least 50 m above the top of the destroyed reactor hall [P4].

14. The first measures taken to control the fire and the radionuclide releases consisted of dumping neutron-absorbing compounds and fire-control materials into the crater formed by the destruction of the reactor. The total amount of materials dumped on the reactor was approximately 5,000 t, including about 40 t of boron compounds, 2,400 t of lead, 1,800 t of sand and clay, and 600 t of dolomite, as well as sodium phosphate and polymer liquids [B4]. About 150 t of materials were dumped on 27 April, followed by 300 t on 28 April, 750 t on 29 April, 1,500 t on 30 April, 1,900 t on 1 May, and 400 t on 2 May. About 1,800 helicopter flights were carried out to dump materials onto the reactor. During the first flights, the helicopters remained stationary over the reactor while dumping the materials. However, as the dose rates received by the helicopter pilots during this procedure were judged to be too high, it was decided that the materials should be dumped while the helicopters travelled over the reactor. This procedure, which had a poor accuracy, caused additional destruction of the standing structures and spread the contamination. In fact, much of the material delivered by the helicopters was dumped on the roof of the reactor hall, where a glowing fire was observed, because the reactor core was partially obstructed by the upper biological shield, broken piping, and other debris, and rising smoke made it difficult to see and identify the core location (see Figure I). The material dumping campaign was stopped on day 7 (2 May) through day 10 (5 May) after the accident because of fears that the building support structures could be compromised. If that happened, it would allow the core to be less restrained from possible meltdown, and steam explosions would occur if the core were to interact with the pressure suppression pool beneath the reactor. The increasing release rates on days 7 through 10 were associated with the rising temperature of the fuel in the core. Cooling of the reactor structure with liquid nitrogen using pipelines originating from Unit 3 was initiated only at late stages after the accident. The abrupt ending of the releases was said to occur upon extinguishing the fire and through transformation of the fission products into more chemically stable compounds [I2].

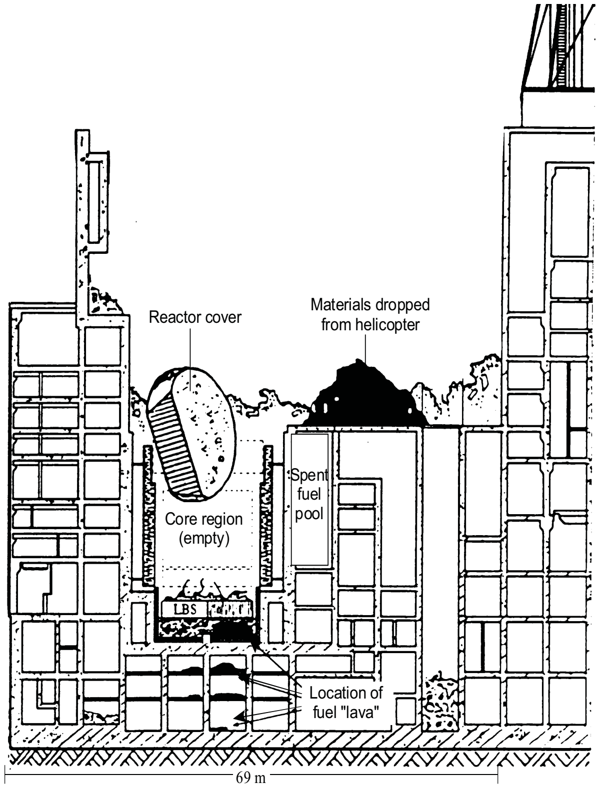


Figure I. Cross-section view of damaged Unit 4 Chernobyl reactor building.

15. The further sequence of events is still somewhat speculative, but the following description conforms with the observations of residual damage to the reactor [S1, S18]. It is suggested that the melted core materials (also called fuel-containing masses, corium, or lava) settled to the bottom of the core shaft, with the fuel forming a metallic layer below the graphite. The graphite layer had a filtering effect on the release of volatile compounds. This is evidenced by a concentration of caesium in the corium of 35% [S1], somewhat higher than would otherwise have been expected in the highly oxidizing conditions that prevailed in the presence of burning graphite. The very high temperatures in the core shaft would have suppressed plate-out of radionuclides and maintained high release rates of penetrating gases and aerosols. After about 6.5 days, the upper graphite layer would have burned off. This is evidenced by the absence of carbon or carbon-containing compounds in the corium. At this stage, without the filtering effect of an upper graphite layer, the release of volatile fission products from the fuel may have increased,

although non-volatile fission products and actinides would have been inhibited because of reduced particulate emission.

16. On day 8 after the accident, it would appear that the corium melted through the lower biological shield (LBS) and flowed onto the floor of the sub-reactor region (see Figure I). This rapid redistribution of the corium and increase in surface area as it spread horizontally would have enhanced the radionuclide releases. The corium produced steam on contact with the water remaining in the pressure suppression pool, causing an increase in aerosols. This may account for the peak releases of radionuclides seen at the last stage of the active period.

17. Approximately nine days after the accident, the corium began to lose its ability to interact with the surrounding materials. It solidified relatively rapidly, causing little damage to metallic piping in the lower regions of the reactor building. The chemistry of the corium was altered by the large mass of the lower biological shield taken up into the molten corium (about 400 of the 1,200-t shield of stainless steel construction and serpentine filler material). The decay heat was significantly lowered, and the radionuclide releases dropped by two to three orders of magnitude. Visual evidence of the disposition of the corium supports this sequence of events.

18. On the basis of an extensive series of measurements in 1987–1990 of heat flux and radiation intensities and from an analysis of photographs, an approximate mass balance of the reactor fuel distribution was established (data reported by Borovoi and Sich [B16, S1]). The amount of fuel in the lower regions of the reactor building was estimated to be 135 ± 27 t, which is 71% of the core load at the time of the accident (190.3 t). The remainder of the fuel was accounted for as follows: fuel in the upper levels of the reactor building (38 ± 5 t); fuel released beyond the reactor building (6.7 ± 1 t); and unaccounted for fuel (10.7 t), possibly largely on the roof of the reactor hall under the pile of materials dumped by the helicopters.

19. Different estimates of the reactor fuel distribution have been proposed by others. Purvis [P4] indicated that the amount of fuel in the lava, plus fragments of the reactor core under the level of the bottom of the reactor, is between 27 and 100 t and that the total amount of the fuel in the reactor hall area is between 77 and 140 t. Kisselev et al. [K12, K15] reported that only 24 ± 4 t were identified by visual means in the lower region of the reactor. It may be that most of the fuel is on the roof of the reactor hall and is covered by the material that was dropped on it from helicopters. Only the removal of this layer of material will allow making a better determination of the reactor fuel distribution.

B. RELEASE OF RADIONUCLIDES

20. Two basic methods were used to estimate the release of radionuclides in the accident. The first method consists 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 consists in measuring the radionuclide deposition density on the ground all around the reactor; if it is assumed that all of the released amounts deposited within the area where the measurements were made, the amounts deposited are equal to the amounts released. In both methods, air samples taken over 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 fallout also led to information on the physical and chemical properties of the radioactive materials that were released into the atmosphere. It is worth noting, however, that the doses were estimated on the basis of environmental and human measurements and that the knowledge of the quantities released was not needed for that purpose.

1. Estimation of radionuclide amounts released

21. From the radiological point of view, ^{131}I and ^{137}Cs are the most important radionuclides to consider, because they are responsible for most of the radiation exposure received by the general population.

22. Several estimates have been made of the radionuclide core inventory at the time of the accident. Some of these estimates are based on the burn-up of individual fuel assemblies that has been made available [B1, S1]. The average burn-up of 10.9 GW d t^{-1} [B1], published in 1989, is similar to the originally reported value of 10.3 GW d t^{-1} [I2], but with non-linear accumulation of actinides, more detailed values of burn-up allow more precise estimation of the core inventories. In the case of ^{132}Te and of the short-lived radioiodines, Khrouch et al. [K16] took into account the variations in the power level of the reactor during the 24 hours before the accident, as described in [S20]. An extended list of radionuclides present in the core at the time of the accident is presented in Table 1. The values used by the Committee in this Annex are those presented in the last column on the right. For comparison purposes, the initial estimates of the core inventory as presented in 1986 [I2], which were used by the Committee in the UNSCEAR 1988 Report [U4], are also presented in Table 1; these 1986 estimates, however, have been decay-corrected to 6 May 1986, that is, 10 days after the beginning of the accident. The large differences observed between initial and recent estimates for short-lived radionuclides (radioactive half-lives of less than 10 days) are mainly due to radioactive decay between the actual day of release and 6 May, while minor differences may have been caused by the use of different computer codes to calculate the build-up of activity in the reactor core. For ^{137}Cs, the 1986 and current estimates of core inventory at the time of the accident are 290 and 260 PBq, respectively. For ^{131}I, the corresponding values are 1,300 and 3,200 PBq, respectively.

23. There are several estimates of radionuclides released in the accident based on recent evaluations. Three such listings, including two taken from the IAEA international conference that took place at Vienna in 1996 [D8], are given in Table 2 and compared to the original estimates of 1986 [I2]. The estimates of Buzulukov and Dobrynin [B4], as well as those of Kruger et al. [K37], are based on analyses of core inventories [B1, B3]. There is general agreement on the releases of most radionuclides, and in particular those of ^{137}Cs and ^{131}I, presented in the 1996 evaluations. The values used by the Committee in this Annex are those presented in the last column on the right. The release of ^{137}Cs is estimated to be 85 PBq, about 30% of the core inventory and that of ^{131}I is estimated to be 1,760 PBq, about 50% of the core inventory.

24. In the UNSCEAR 1988 Report [U4], estimates were made of the release of ^{137}Cs and ^{131}I in the accident. From average deposition densities of ^{137}Cs and the areas of land and ocean regions, the total ^{137}Cs deposit in the northern hemisphere was estimated to be 70 PBq, which is in fairly good agreement with the current estimate.

25. The release of ^{131}I was estimated in the UNSCEAR 1988 Report to be 330 PBq on the basis of the reported ^{131}I inventory of 1,300 PBq [I2] and of a release fraction of 25% [U4]. This, however, was the inventory of ^{131}I at the end of the release period (6 May 1986). It would have been higher at the beginning of the accident. The ^{131}I inventory is now estimated to be 3,200 PBq, as shown in Table 1, and because the fractional release of ^{131}I is likely to have been about 50%, the ^{131}I release given in the UNSCEAR 1988 Report is lower than the current estimate by a factor of about 5.

26. The results presented in Table 2 are incomplete with respect to the releases of ^{132}Te and of the short-lived radioiodines (^{132}I to ^{135}I). In this Annex, the releases of those radionuclides have been scaled to the releases of ^{131}I, using the radionuclide inventories presented in Table 1 and taking into account the radioactive half-lives of the radionuclides. The following procedure was used: (a) the release rates at the time of the steam explosion were estimated from the radionuclide inventories presented in Table 1, assuming no fractionation for the short-lived radioiodines (^{133}I, ^{134}I and ^{135}I) with respect to ^{131}I, a value of 0.85 for the ratio of the release rates of ^{132}Te and of ^{131}I, and radioactive equilibrium between ^{132}I and ^{132}Te in the materials released. The activity ratios to ^{131}I in the initial release rates are therefore estimated to have been 1.5 for ^{133}I, 0.64 for ^{134}I, 0.9 for ^{135}I, and 0.85 for ^{132}Te and ^{132}I; (b) the variation with time of the release rate of ^{131}I over the first 10 days following the steam explosion was assessed using published data [A4, I6]. The estimated daily releases of ^{131}I are presented in Table 3; and (c) the variation with time of the release rates of the short-lived radioiodines and of ^{132}Te has been assumed to be the same as that of ^{131}I, but a correction was made to take into account the differences in radioactive half-lives. The variation with time of the daily releases of ^{131}I, ^{133}I and ^{132}Te, which are adopted in this Annex, are illustrated in Figure II; for comparison purposes, the estimated daily releases of ^{137}Cs are also shown in Figure II.

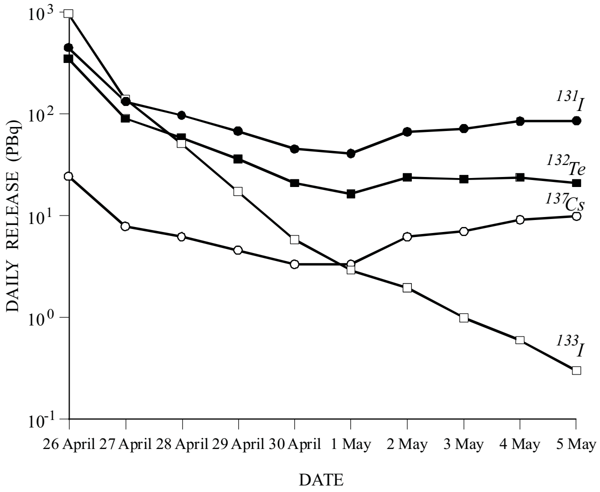


Figure II. Daily release of iodine-131, iodine-133, tellurium-132 and caesium-137 from the Chernobyl reactor.

27. The overall releases of short-lived radioiodines and of ^{132}Te are presented in Table 4; they are found to be substantially lower than those of ^{131}I. This is due to the fact that most of the short-lived radioiodines decayed in the reactor instead of being released.

28. Additional, qualitative information on the pattern of release of radionuclides from the reactor is given in Figure III. The concentrations of radionuclides in air were determined in air samples collected by helicopter above the damaged reactor [B4]. Although the releases were considerably reduced on 5 and 6 May (days 9 and 10 after the accident), continuing low-level releases occurred in the following week and for up to 40 days after the accident. Particularly on 15 and 16 May, higher concentrations were observed, attributable to continuing outbreaks of fires or to hot areas of the reactor [I6]. These later releases can be correlated with increased concentrations of radionuclides in air measured at Kiev and Vilnius [I6, I35, U16].

2. Physical and chemical properties of the radioactive materials released

29. There were only a few measurements of the aerodynamic size of the radioactive particles released during the first days of the accident. A crude analysis of air samples, taken at 400-600 m above the ground in the vicinity of the Chernobyl power plant on 27 April 1986, indicated that large radioactive particles, varying in size from several to tens of micrometers, were found, together with an abundance of smaller particles [I6]. In a carefully designed experiment, aerosol samples taken on 14 and 16 May 1986 with a device installed on an aircraft that flew above the damaged reactor were analysed by spectrometry [B6, G14]. The activity distribution of the particle sizes was found to be well represented as the superposition of two log-normal functions:

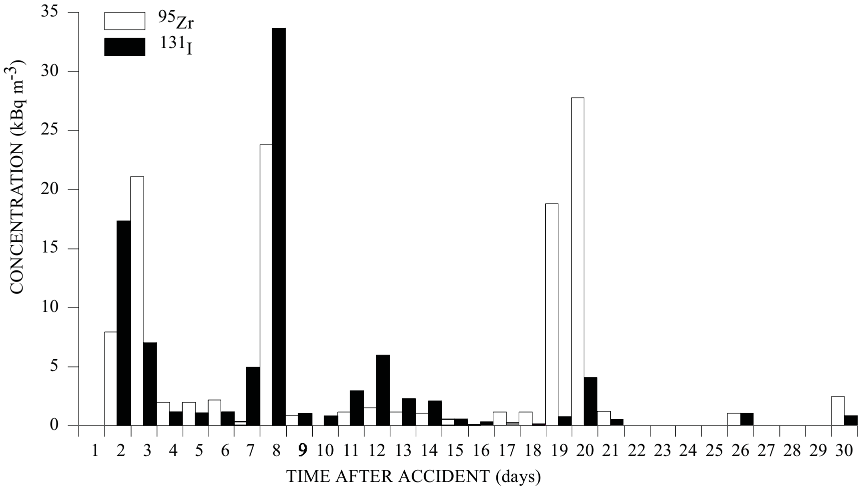


Figure III. Concentration of radionuclides in air measured above the damaged Chernobyl reactor [B6].

one with an activity median aerodynamic diameter (AMAD) ranging from 0.3 to 1.5 µm and a geometric standard deviation (GSD) of 1.6–1.8, and another with an AMAD of more than 10 µm. The larger particles contained about 80%–90% of the activity of non-volatile radionuclides such as ^{95}Zr, ^{95}Nb, ^{140}La, ^{141}Ce, ^{144}Ce and transuranium radionuclides embedded in the uranium matrix of the fuel [K35]. The geometric sizes of the fuel particles collected in Hungary, Finland and Bulgaria ranged from 0.5 to 10 µm, with an average of 5 µm [B35, L40, V9]. Taking the density of fuel particles to be 9 g cm^{-3}, their aerodynamic diameter therefore ranged from 1.5 to 30 µm, with an average value of 15 µm. Similar average values were obtained for fuel particles collected in May 1986 in southern Germany [R20] and for those collected in the 30-km zone in September 1986 [G27].

30. It was observed that Chernobyl fallout consisted of hot particles in addition to more homogeneously distributed radioactive material [D6, D7, K34, S26, S27, S28]. These hot particles can be classified into two broad categories: (a) fuel fragments with a mixture of fission products bound to a matrix of uranium oxide, similar to the composition of the fuel in the core, but sometimes strongly depleted in caesium, iodine and ruthenium, and (b) particles consisting of one dominant element (ruthenium or barium) but sometimes having traces of other elements [D6, J3, J4, K35, K36, S27]. These monoelemental particles may have originated from embedments of these elements produced in the fuel during reactor operation and released during the fragmentation of the fuel [D7]. Typical activities per hot particle are 0.1–1 kBq for fuel fragments and 0.5–10 kBq for ruthenium particles [D6]; a typical effective diameter is about 10 µm, to be compared with sizes of 0.4–0.7 µm for the particles associated with the activities of ^{131}I and ^{137}Cs [D6, D7]. Hot particles deposited in the pulmonary region will have a long retention time, leading to considerable local doses [B33, L23]. In the immediate vicinity of a 1 kBq ruthenium particle, the dose rate is about 1,000 Gy h^{-1}, which causes cell killing; however, sublethal doses are received by cells within a few millimetres of the hot particle. Although it was demonstrated in the 1970s that radiation doses from alpha-emitting hot particles are not more radiotoxic than the same activity uniformly distributed in the whole lung [B28, L33, L34, L35, R15], it is not clear whether the same conclusion can be reached for beta-emitting hot particles [B33, S27].

C. GROUND CONTAMINATION

1. Areas of the former Soviet Union

31. Radioactive contamination of the ground was found to some extent in practically every country of the northern hemisphere [U4]. In this Annex, contaminated areas are defined as areas where the average ^{137}Cs deposition densities 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. As shown in Table 5, the contaminated areas were found mainly in Belarus, in the Russian Federation and in Ukraine [I24].

32. The radionuclides released in the accident deposited over most of the European territory of the former Soviet Union. A map of this territory is presented in Figure IV. The main city gives its name to each region. The regions (*oblasts*) are subdivided into districts (*raions*).

33. The characteristics of the basic plume developments were illustrated in the UNSCEAR 1988 Report [U4]. Further details have been presented by Borzilov and Klepikova [B7] and are illustrated in Figure V. The important releases lasted 10 days; during that time, the wind changed direction often, so that all areas surrounding the reactor site received some fallout at one time or another.

34. The initial plumes of materials released from the Chernobyl reactor 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

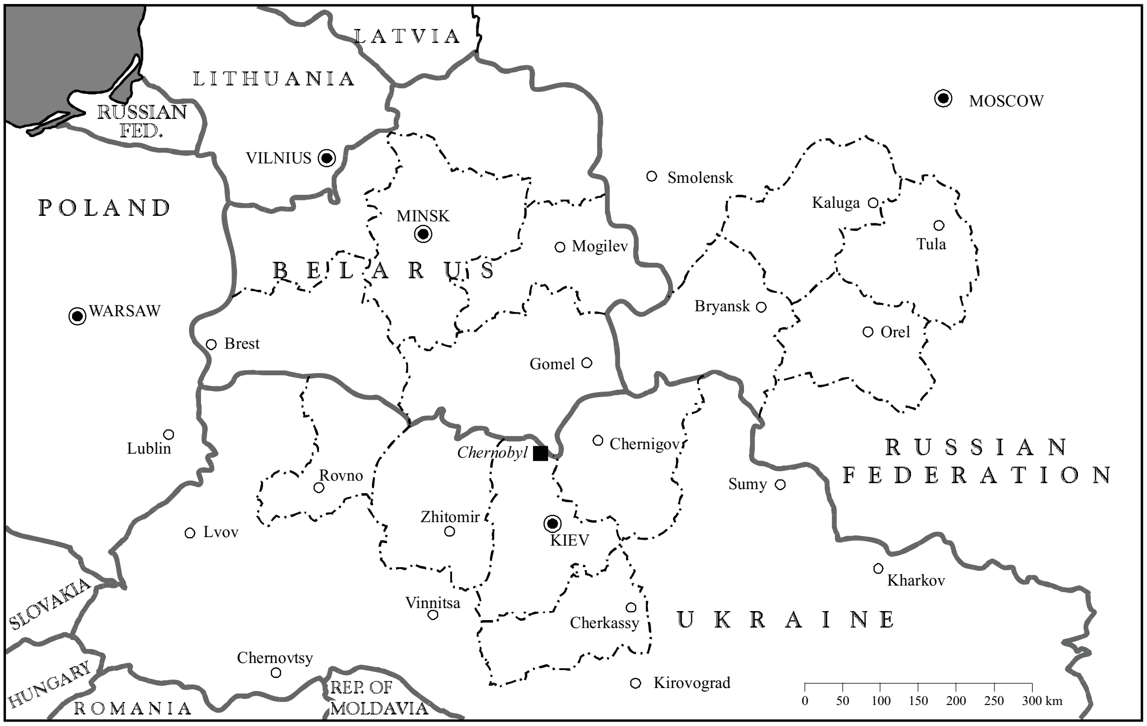


Figure IV. Administrative regions surrounding the Chernobyl reactor.

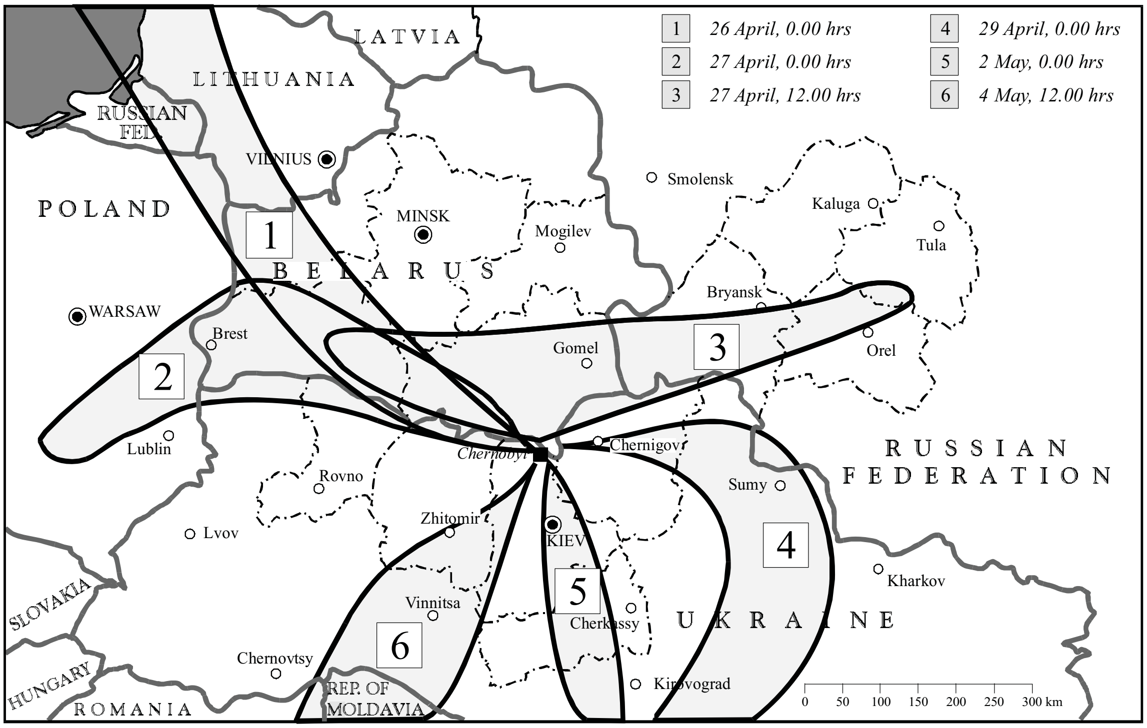


Figure V. Plume formation by meteorological conditions for instantaneous releases on dates and times (GMT) indicated [B7].

deposition of radioactive materials from the plume that passed over at that time (Figure V, trace 3). The contamination of Ukrainian territory south of Chernobyl occurred after 28 April (Figure V, traces 4, 5 and 6). Rainfall occurred in an inhomogeneous pattern, causing uneven contamination areas. The general pattern of ^{137}Cs deposition based on calculations from meteorological conditions has been shown to match the measured contamination pattern rather well [B7].

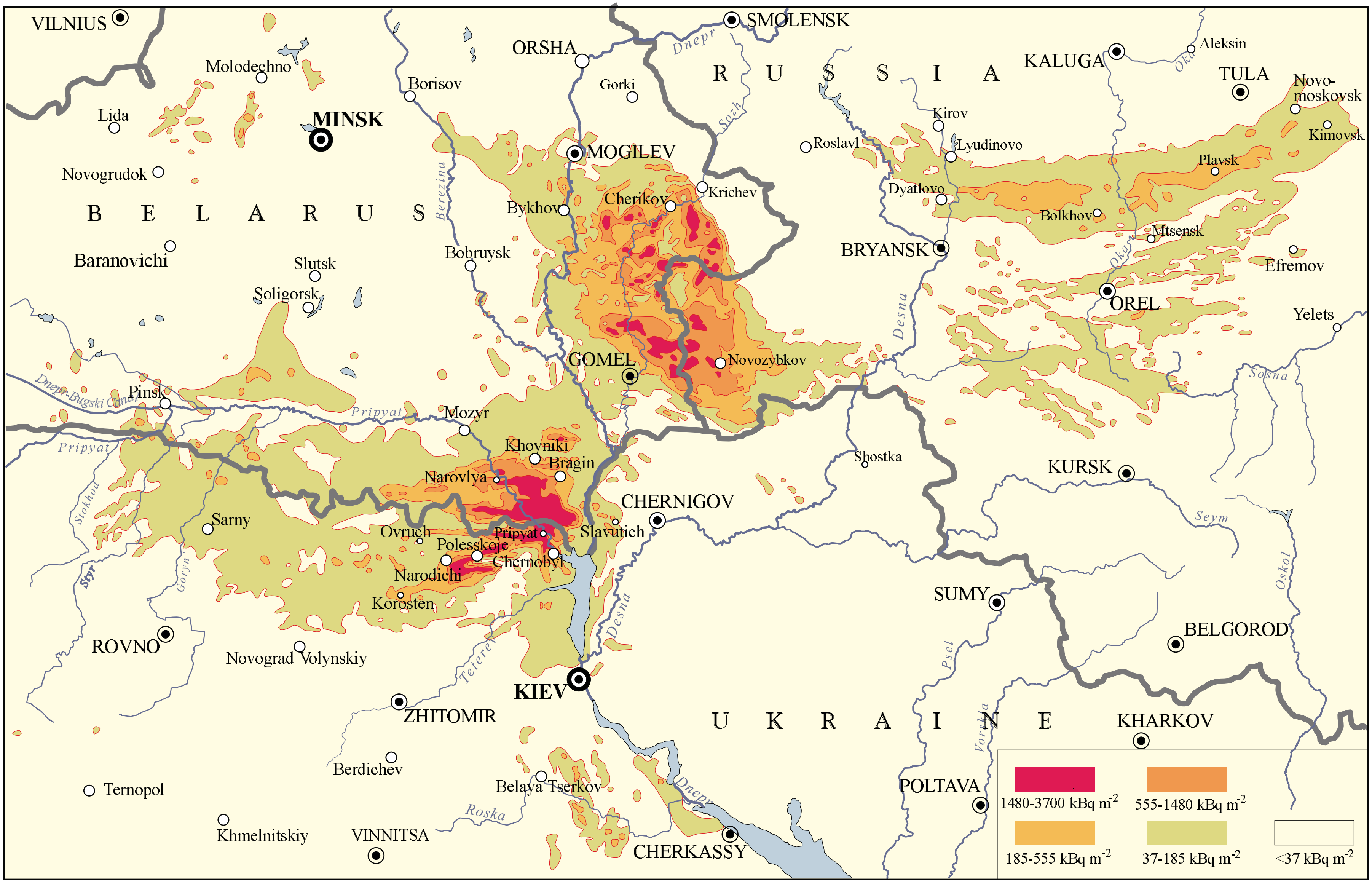


Figure VI. Surface ground deposition of caesium-137 released in the Chernobyl accident [I1, I3].

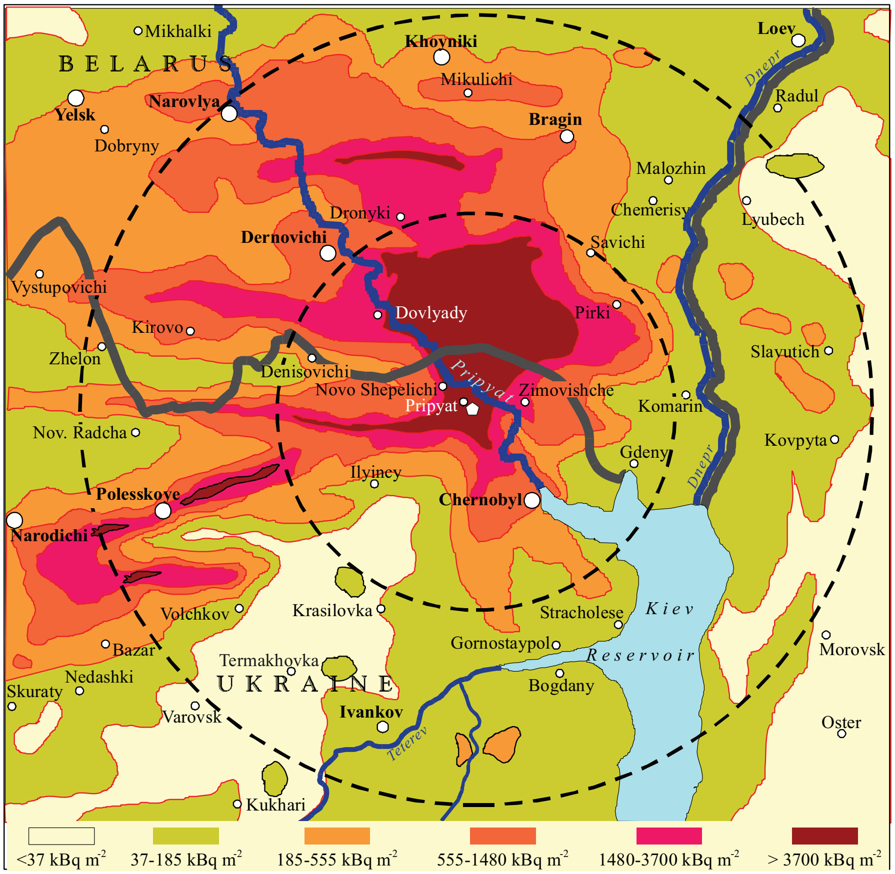


Figure VII. Surface ground deposition of caesium-137 in the immediate vicinity of the Chernobyl reactor [I1, I24].
The distances of 30 km and 60 km from the nuclear power plant are indicated.

35. The detailed contamination patterns have been established from extensive monitoring of the affected territory. The contamination of soil with ^{137}Cs in the most affected areas of Belarus, the Russian Federation and Ukraine is shown in Figure VI, and the ^{137}Cs contamination of soil in the immediate area surrounding the reactor is shown in Figure VII. The deposition of ^{90}Sr and of nuclear fuel particles, usually represented as the deposition of their marker, ^{95}Zr or ^{144}Ce, were relatively localized. The contamination maps for these radionuclides are illustrated in Figures VIII and IX. An important deposition map to be established is that of ^{131}I. Estimated ^{131}I deposition in Belarus and the western part of the Russian Federation is shown in Figure X. Because there were not enough measurements at the time of deposition, the ^{131}I deposition pattern can be only approximated from limited data and relationships inferred from ^{137}Cs deposition. Because the ^{131}I to ^{137}Cs ratio was observed to vary from 5 to 60, the ^{131}I deposition densities estimated for areas without ^{131}I measurements are not very reliable. Measurements of the current concentrations of ^{129}I in soil could provide valuable information on the ^{131}I deposition pattern [S45].

36. The principal physico-chemical form of the deposited radionuclides are: (a) dispersed fuel particles, (b) condensation-generated particles, and (c) mixed-type particles, including the adsorption-generated ones [I22]. The radionuclide distribution in the nearby contaminated zone (<100 km), also called the near zone, differs 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 (Zr, Mo, Ce and Np) were to a large extent deposited in the near zone. Intermediate elements (Ru, Ba, Sr) and fuel elements (Pu, U) were also deposited largely in the near zone. The volatile elements (I, Te and Cs) in the form of condensation-generated particles, were more widely dispersed into the far zone [I6]. Of course, this characterization oversimplifies the actual dispersion pattern.

37. Areas of high contamination from ^{137}Cs occurred throughout the far zone, depending primarily on rainfall at the time the plume passed over. The composition of the deposited radionuclides in these highly contaminated areas was relatively similar. Some ratios of radionuclides in different districts of the near and far zones are given in Table 6.

38. The three main areas of contamination have been 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 the

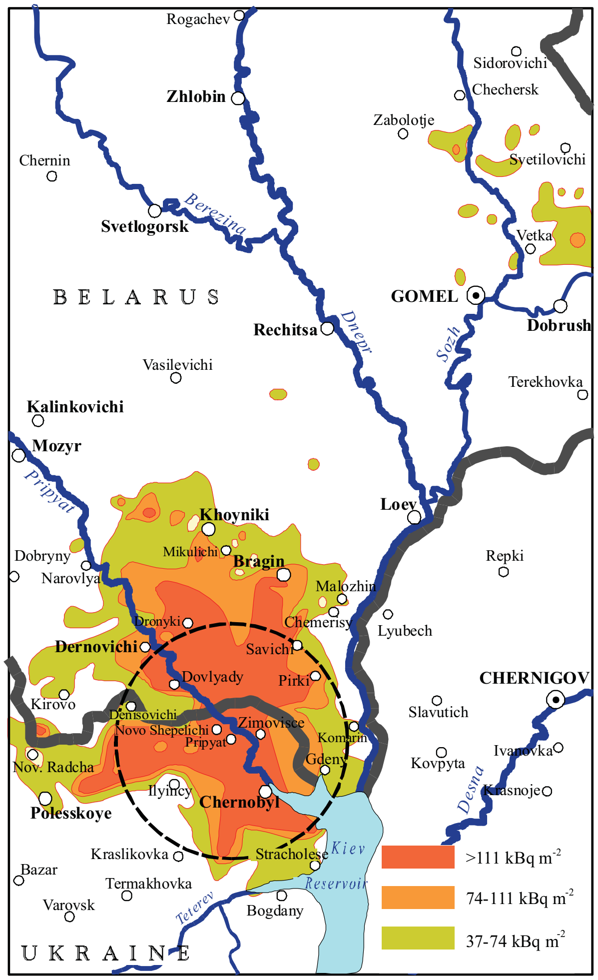


Figure VIII. Surface ground deposition of strontium-90 released in the Chernobyl accident [I1].

Kiev, Zhitomir, Chernigov, Rovno and Lutsk regions of Ukraine and in the southern parts of the Gomel and Brest regions 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 regions (Figure VII).

39. The Gomel-Mogilev-Bryansk contamination area is centred 200 km to the north-northeast of the reactor at the boundary of the Gomel and Mogilev regions of Belarus and of the Bryansk region of the Russian Federation. In some areas contamination was comparable to that in the Central area; deposition densities even reached 5 MBq m^{-2} in some villages of the Mogilev and Bryansk regions.

40. The Kaluga-Tula-Orel area is located 500 km to the northeast of the reactor. Contamination there came from the same radioactive cloud that caused contamination in the Gomel-Mogilev-Bryansk area as a result of rainfall on 28–29 April. The ^{137}Cs deposition density was, however, lower in this area, generally less than 500 kBq m^{-2}.

41. Outside these three main contaminated areas there were many areas where the ^{137}Cs deposition density was in the range 37–200 kBq m^{-2}. Rather detailed surveys of the contamination of the entire European part of the former Soviet Union have been completed [I3, I6, I24]. A map of measured ^{137}Cs deposition is presented in Figure VI. The areas affected by ^{137}Cs contamination are listed in Table 7. As can be seen, 146,100 km^2 experienced a ^{137}Cs deposition density greater than 37 kBq m^{-2} (1 Ci km^{-2}). The total quantity of ^{137}Cs deposited as a result of the accident in the contaminated areas of the former Soviet Union, including in areas of lesser deposition, is estimated in Table 8 to be 43 PBq. A ^{137}Cs background of 2–4 kBq m^{-2} attributable to residual levels from atmospheric nuclear weapons testing from earlier years must be subtracted to obtain the total deposit attributable to the Chernobyl accident. When this is done, the total ^{137}Cs deposit from the accident is found to be approximately 40 PBq (Table 8). The total may be 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 is estimated to be 29 PBq, and the residual activity there from atmospheric nuclear weapons testing is about 0.5 PBq.

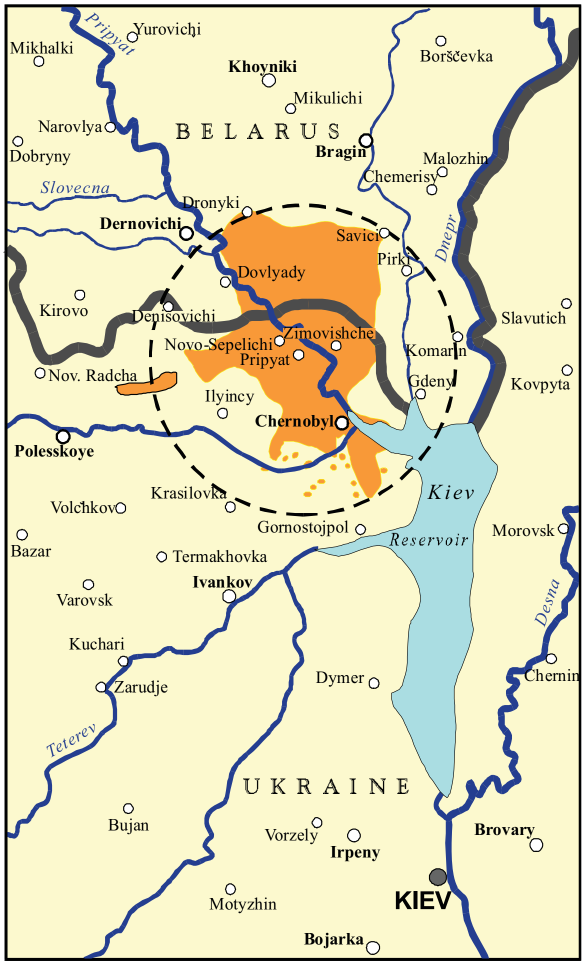


Figure IX. Surface ground deposition of plutonium-239 and plutonium-240 released in the Chernobyl accident at levels exceeding 3.7 kBq m^{-2} [I1].

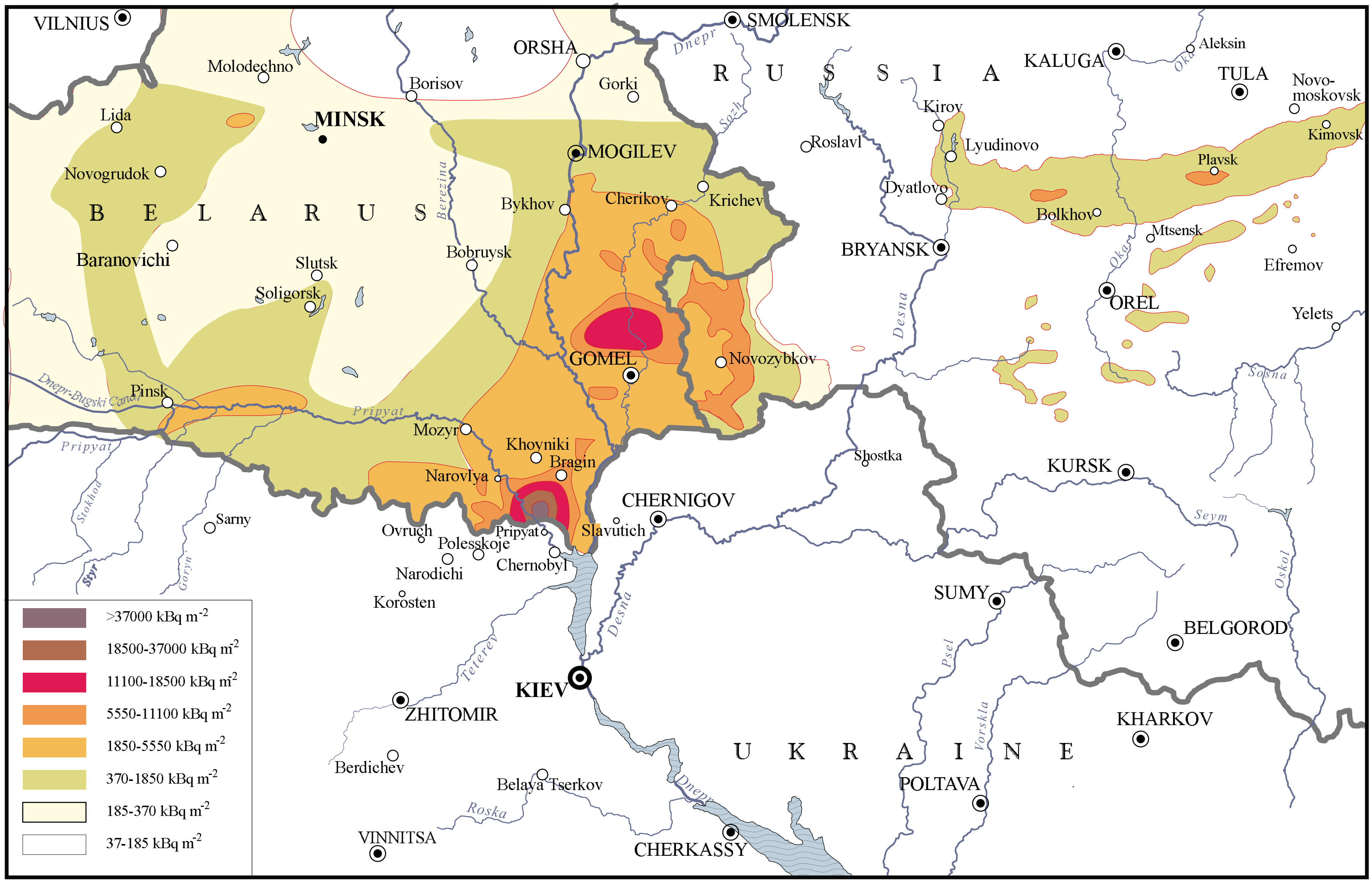
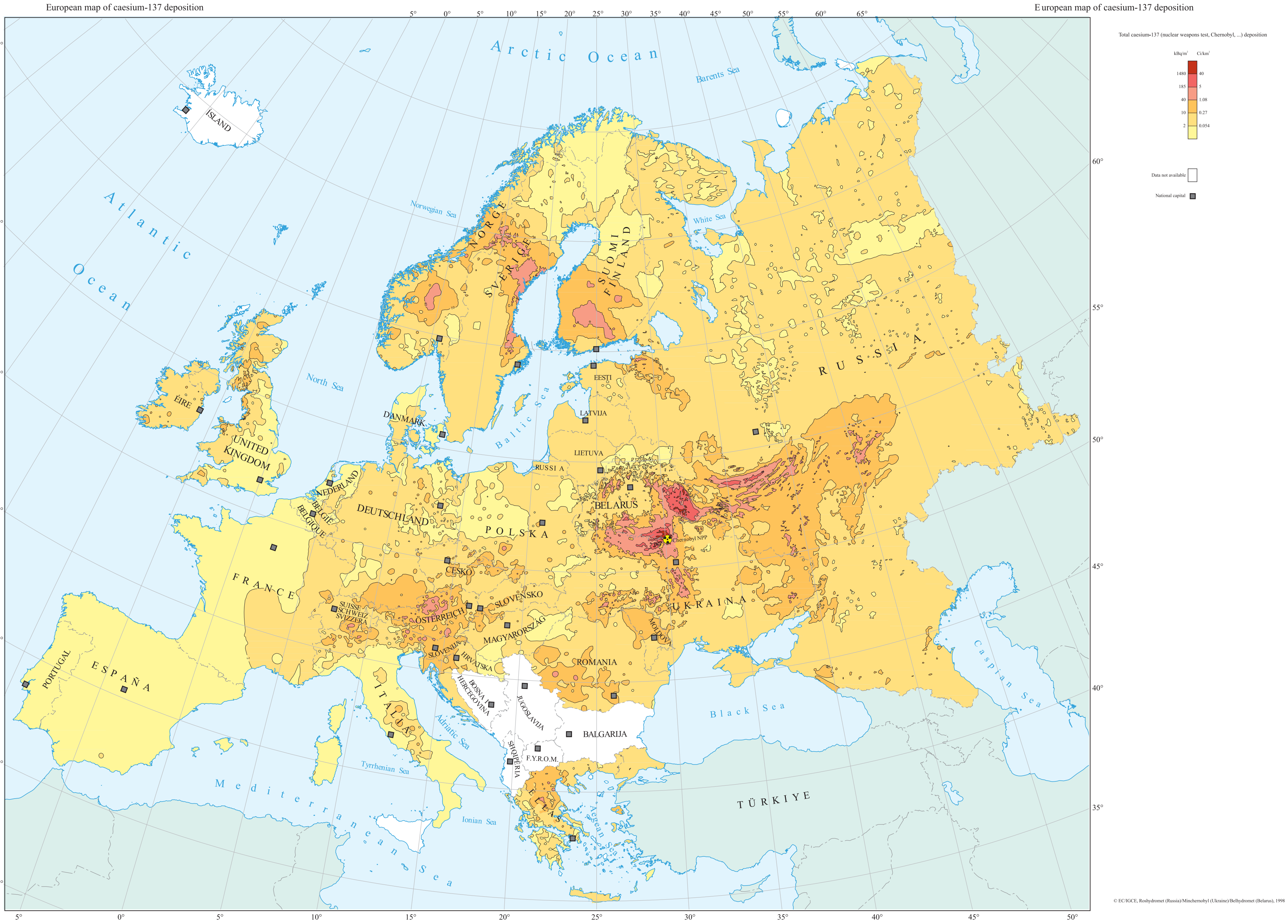


Figure X. Estimated surface ground deposition in Belarus and western Russia of iodine-131 released in the Chernobyl accident [B25, P19].

Figure XI. Surface ground deposition of caesium-137 released in Europe after the Chernobyl accident [D13].



42. During the first weeks after the accident, most of the activity deposited on the ground consisted of short-lived radionuclides, of which ^{131}I was the most important radiologically. Maps of ^{131}I deposition have been prepared for Belarus and part of the Russian Federation (Figure X). As indicated in paragraph 35, these maps are based on the limited number of measurements of ^{131}I deposition density available in the former Soviet Union, and they use ^{137}Cs measurements as a guide in areas where ^{131}I was not measured. These maps must be regarded with caution, as the ratio of the ^{131}I to ^{137}Cs deposition densities was found to vary in a relatively large range, at least in Belarus.

43. Deposition of ^{90}Sr was mostly limited to the near zone of the accident. Areas with ^{90}Sr deposition density exceeding 100 kBq m^{-2} were almost entirely within the 30-km zone, and areas exceeding 37 kBq m^{-2} were almost all within the near zone (<100 km). Only a few separate sites with ^{90}Sr deposition density in the range 37–100 kBq m^{-2} were found in the Gomel-Mogilev-Bryansk area, i.e. in the far zone (Figure VIII) [A9, B25, H13].

44. Information on the deposition of plutonium isotopes is not as extensive because of difficulties in detecting these radionuclides. The only area with plutonium levels exceeding 4 kBq m^{-2} was located within the 30-km zone (Figure IX). In the Gomel-Mogilev-Bryansk area, the ^{239,240}Pu deposition density ranged from 0.07 to 0.7 kBq m^{-2}, and in the Kaluga-Tula-Orel area, from 0.07 to 0.3 kBq m^{-2} [A9]. At Korosten, located in Ukraine about 115 km southwest of the Chernobyl power plant, where the ^{137}Cs deposition density was about 300 kBq m^{-2}, the ^{239,240}Pu deposition density due to the Chernobyl accident derived from data in [H8] is found to be only about 0.06 kBq m^{-2}, which is 4–8 times lower than the ^{239,240}Pu deposition density from global fallout.

2. Remainder of northern and southern hemisphere

45. As shown in Table 5, there are also other areas, in Europe, where the ^{137}Cs deposition density exceeded 37 kBq m^{-2}, notably, the three Scandinavian countries (Finland, Norway and Sweden), Austria and Bulgaria. In those countries, the ^{137}Cs deposition density did not exceed 185 kBq m^{-2} except in localized areas (for example, a 2–4 km^2 area in Sweden within the commune of Gävle [E6] and mountainous areas in the Austrian Province of Salzburg [L24]). The pattern of ^{137}Cs deposition density in the whole of Europe is shown in Figure XI [D13, I24].

46. Small amounts of radiocaesium and of radioiodine penetrated the lower stratosphere of the northern hemisphere during the first few days after the accident [J6, K43]. Subsequently, transfer of radiocaesium to the lower atmospheric layers of the southern hemisphere may have occurred as a result of interhemispheric air movements from the northern to the southern stratosphere, followed by subsidence in the troposphere [D11]. However, radioactive contamination was not detected in the southern hemisphere by the surveillance networks of environmental radiation. Interhemispheric transfer also occurred to a small extent through human activities, such as shipping of foods or materials to the southern hemisphere. Therefore, only very low levels of radioactive materials originating from the Chernobyl accident have been present in the biosphere of the southern hemisphere, and the resulting doses have been negligible.

D. ENVIRONMENTAL BEHAVIOUR OF DEPOSITED RADIONUCLIDES

47. The environmental behaviour of deposited radionuclides depends on the physical and chemical characteristics of the radionuclide considered, on the type of fallout (i.e. dry or wet), and on the characteristics of the environment. Special attention will be devoted to ^{131}I, ^{137}Cs and ^{90}Sr and their pathways of exposure to humans. Deposition can occur on the ground or on water surfaces. The terrestrial environment will be considered first.

1. Terrestrial environment

48. For short-lived radionuclides such as ^{131}I, the main pathway of exposure of humans is the transfer of the amounts deposited on leafy vegetables that are consumed within a few days, or on pasture grass that is grazed by cows or goats, giving rise to the contamination of milk. The amounts deposited on vegetation are retained with a half-time of about two weeks before removal to the ground surface and to the soil. Long-term transfer of ^{131}I from deposition on soil to dietary products that are consumed several weeks after the deposition has occurred need not be considered, because ^{131}I has a physical half-life of only 8 days.

49. Radionuclides deposited on soil migrate downwards and are partially absorbed by plant roots, leading in turn to upward migration into the vegetation. These processes should be considered for long-lived radionuclides, such as ^{137}Cs and ^{90}Sr. The rate and direction of the radionuclide migration into the soil-plant pathway are determined by a number of natural phenomena, including relief features, the type of plant, the structure and makeup of the soil, 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 has been rather slow, and the greater fraction of radionuclides is 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 are found in the 0–5 cm layer; in the case of peaty soils, for which radionuclide migration is faster, only 40% to 70% of ^{137}Cs and ^{90}Sr are found in that layer [I22]. The effective half-time of clearance from the root layer in meadows (0–10 cm) in mineral soils has been 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 is estimated to be 7 to 12 years [A11, A14].

50. For a given initial contamination of 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 changes. The ^{137}Cs content in plants was maximum in 1986, when the contamination was due to direct deposition on aerial surfaces. In 1987, ^{137}Cs in plants was 3–6 times lower than in 1986, as the contamination of the plants was then mainly due to root uptake. Since 1987, the transfer coefficients from deposition to plant have continued to decrease, although the rate of decrease has slowed: from 1987 to 1995, the transfer coefficients of ^{137}Cs decreased by 1.5 to 7 times, on average [I22]. Compared with ^{137}Cs from global fallout, ^{137}Cs 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 Chernobyl and fallout ^{137}Cs were about 70% and 8%, respectively [H15]. Later on, ageing processes led to similar mobility values for ^{137}Cs from the Chernobyl accident and from global fallout.

51. The variability of the transfer coefficient from deposition to pasture grass for ^{137}Cs is indicated in Table 9 for natural meadows in the Polissya area of Ukraine [S40]. The type of soil and the water content both have an influence on the transfer coefficient, the values of which were found to range from 0.6 to 190 Bq kg^{-1} (dry grass) per kBq m^{-2} (deposition on the ground) in 1988–1989 [S40]. The variability as a function of time after the accident in the Russian Federation has been studied and reported on by Shutov et al. [S41].

52. Contrary to ^{137}Cs, it seems that the exchangeability of ^{90}Sr does not keep decreasing with time after the accident and may even be increasing [B36, S41]. In the Russian Federation, no statistically significant change was found in the ^{90}Sr transfer coefficient from deposition to grass during the first 4 to 5 years following the accident [S41]. This is attributable to two competing processes: (a) ^{90}Sr conversion from a poorly soluble form, which characterized the fuel particles, to a soluble form, which is easily assimilated by plant roots, and (b) the vertical migration of ^{90}Sr into deeper layers of soil, hindering its assimilation by vegetation [S41].

53. The contamination of milk, meat and potatoes usually accounts for the bulk of the dietary intake of ^{137}Cs. However, for the residents of rural regions, mushrooms and berries from forests occupy an important place. The decrease with time of the ^{137}Cs concentrations in those foodstuffs has been extremely slow, with variations from one year to another depending on weather conditions [I22].

2. Aquatic environment

54. Deposition of radioactive materials also occurred on water surfaces. Deposition on the surfaces of seas and oceans resulted in low levels of dose because the radioactive materials were rapidly diluted into very large volumes of water.

55. In rivers and small lakes, the radioactive contamination resulted mainly from erosion of the surface layers of soil in the watershed, followed by runoff in the water bodies. In the 30-km zone, where relatively high levels of ground deposition of ^{90}Sr and ^{137}Cs occurred, the largest surface water contaminant was found to be ^{90}Sr, as ^{137}Cs was strongly adsorbed by clay minerals [A15, M19]. Much of the ^{90}Sr in water was found in dissolved form; low levels of plutonium isotopes and of ^{241}Am were also measured in the rivers of the 30-km zone [A15, M19].

56. The contribution of aquatic pathways to the dietary intake of ^{137}Cs and ^{90}Sr is usually quite small. However, the ^{137}Cs concentration in the muscle of predator fish, like perch or pike, may be quite high in lakes with long water retention times, as found in Scandinavia and in Russia [H16, K47, R21, T23]. For example, concentration of ^{137}Cs in the water of lakes Kozhany and Svyatoe located in severely contaminated part of the Bryansk region of Russia was still high in 1996 because of special hydrological conditions: 10–20 Bq l^{-1} of ^{137}Cs and 0.6–1.5 Bq l^{-1} of ^{90}Sr [K47]. Concentration of ^{137}Cs in the muscles of crucian (Carassius auratus gibeio) sampled in the lake Kozhany was in the range of 5–15 kBq kg^{-1} and in pike (Esox lucius) in the range 20–90 kBq kg^{-1} [K47, T23]. Activity of ^{137}Cs in inhabitants of the village Kozhany located along the coast of lake Kozhany measured by whole-body counters in summer 1996 was 7.4 ± 1.2 kBq in 38 adults who did not consume lake fish (according to interviews performed before the measurements) but was 49 ± 8 kBq in 30 people who often consumed lake fish. Taking into account seasonal changes in the ^{137}Cs whole-body activity, the average annual internal doses were estimated to be 0.3 mSv and 1.8 mSv in these two groups, respectively. Also, the relative importance of the aquatic pathways, in comparison to terrestrial pathways, may be high in areas downstream of the reactor site where ground deposition was small.

E. SUMMARY

57. The accident at the Chernobyl nuclear power station 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.

58. The radionuclide releases from the damaged reactor occurred mainly over a 10-day period, but with varying release rates. From the radiological point of view, ^{131}I and ^{137}Cs are the most important radionuclides to consider, because they are responsible for most of the radiation exposure received by the general population. The releases of ^{131}I and ^{137}Cs are estimated to have been 1,760 and 85 PBq, respectively (1 PBq = 10^{15} Bq). It is worth noting, however, that the doses were estimated on the basis of environmental and thyroid or body measurements and that knowledge of the quantities released was not needed for that purpose.

59. The three main areas of contamination, defined as those with ^{137}Cs deposition density 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. The Central area is within about 100 km of the reactor, predominantly to the west and northwest. The Gomel-Mogilev-Bryansk contamination area is centred 200 km to the north-northeast of the reactor at the boundary of the Gomel and Mogilev regions of Belarus and of the Bryansk region of the Russian Federation. The Kaluga-Tula-Orel area is located in the Russian Federation, about 500 km to the northeast of the reactor. All together, as shown in Table 7 and in Figure XI, territories with an area of approximately 150,000 km^2 were contaminated in the former Soviet Union.

60. Outside the former Soviet Union, there were many areas in northern and eastern Europe with ^{137}Cs deposition density in the range 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.

61. The environmental behaviour of deposited radionuclides depends on the physical and chemical characteristics of the radionuclide considered, on the type of fallout (i.e. 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 is the transfer of amounts deposited on leafy vegetables that are consumed by humans within a few days, or on pasture grass that is grazed by cows or goats, giving rise to the contamination of milk. The amounts deposited on vegetation are retained with a 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 need to be considered.

II. RADIATION DOSES TO EXPOSED POPULATION GROUPS

62. It is convenient to classify into three categories the populations who were exposed to radiation following the Chernobyl accident: (a) the workers involved in the accident, either during the emergency period or during the clean-up phase; (b) inhabitants of evacuated areas; and (c) inhabitants of contaminated areas who were not evacuated. The available information on the doses received by the three categories of exposed populations will be presented and discussed in turn. Doses from external irradiation and from internal irradiation will be presented separately. The external exposures due to gamma radiation were relatively uniform over all organs and tissues of the body, as their main contributors were ^{132}Te-^{132}I, ^{131}I and ^{140}Ba-^{140}La for evacuees, ^{134}Cs and ^{137}Cs for inhabitants of contaminated areas who were not evacuated, and radionuclides emitting photons of moderately high energy for workers. These external doses from gamma radiation have been expressed in terms of effective dose. With regard to internal irradiation, absorbed doses in the thyroid have been estimated for exposures to radioiodines and effective doses have been estimated for exposures to radiocaesiums.

63. Doses have in almost all cases been estimated by means of physical dosimetry techniques. Biological indicators of dose has been mainly used, within days or weeks after the accident, to estimate doses received by the emergency workers, who received high doses from external irradiation and for whom dosemeters were either not operational nor available. Unlike physical dosimetry, biological dosimetric methods are generally not applicable to doses below 0.1 Gy and reflect inter-individual variations in radiation sensitivity. Soon after the accident, biological dosimetry is usually based on the measurement of the frequency of unstable chromosome aberrations (dicentric and centric rings). By comparing the rate of dicentric chromosomes and centric rings with a standard dose-effect curve obtained in an experiment *in vitro*, it is possible to determine a radiation dose. This method has been recommended for practical use in documents of WHO and IAEA. However, the use of dicentric as well as other aberrations of the unstable type for the purposes of biological dosimetry is not always possible, since the frequency of cells containing such aberrations declines in time after exposure.

64. For retrospective dosimetry long after the exposure, biological dosimetry can be a complement to physical dosimetry, but only techniques where radiation damage to the biological indicator is stable and persistent and not subject to biochemical, physiological or immunological turnover, repair or depletion are useful. In that respect, the analysis of stable aberrations (translocations), the frequency of which remains constant for a long time after exposure to radiation, is promising. The probability of occurrence of stable (translocations) and unstable (dicentrics) aberrations after exposure is the same. However, translocations are not subjected to selection during cell proliferation, in contrast to dicentrics. Fluorescence *in situ* hybridization (FISH) or Fast-FISH in conjunction with chromosome painting may be useful in retrospective dosimetry for several decades after exposure.

65. Other biological (or biophysical) techniques for measuring doses are electron spin resonance (ESR) or optically stimulated luminescence (OSL). These techniques are used in retrospective dosimetry to measure the radiation damage accumulated in biological tissue such as bone, teeth, fingernails and hair. Also, the gene mutation glycophorin A that is associated with blood cells may be used. Currently, the detection limits for FISH, ESR and OSL are about 0.1 Gy [P28]. At low dose levels, however, the estimation of the dose due to the radiation accident is

highly unreliable because of the uncertainty in the background dose resulting from other radiation exposures (medical irradiation, natural background, etc.) or, in the case of FISH, from other factors such as smoking.

A. WORKERS INVOLVED IN THE ACCIDENT

66. The workers involved in various ways in the accident can be divided into two groups: (a) those involved in emergency measures during the first day of the accident (26 April 1986), who will be referred to as emergency workers in this Annex, and (b) those active in 1986–1990 at the power station or in the zone surrounding it for the decontamination work, sarcophagus construction and other clean-up operations. This second group of workers is referred to as recovery operation workers in this Annex, although the term liquidator gained common usage in the former Soviet Union.

1. Emergency workers

67. The emergency workers are the people who dealt with the consequences of the accident on the very first day (26 April 1986), i.e. the staff of the plant, the firemen involved with the initial emergency, the guards and the staff of the local medical facility. Most of them were at the reactor site at the time of the accident or arrived at the plant during the few first hours. In the Russian literature, two other categories of people are referred to: (a) the "accident witnesses", who were present at the plant at the time of the accident and who may or may not have been involved in emergency operations (so that part of them are also classified as "emergency workers") and (b) the "accident victims", who were sent to the local medical facility and then transferred to special hospitals in Moscow and Kiev. All accident victims were emergency workers and/or accident witnesses. The numbers of accident witnesses and emergency workers are listed in Table 10. According to Table 10, on the morning of 26 April, about 600 emergency workers were on the site of the Chernobyl power plant.

68. The power plant personnel wore only film badges that could not register doses in excess of 20 mSv. All of these badges were overexposed. The firemen had no dosimeters and no dosimetric control. Dose rates on the roof and in the rooms of the reactor block reached hundreds of gray per hour. Measured exposure rates in the vicinity of the reactor at the time of the accident are shown in Figure XII.

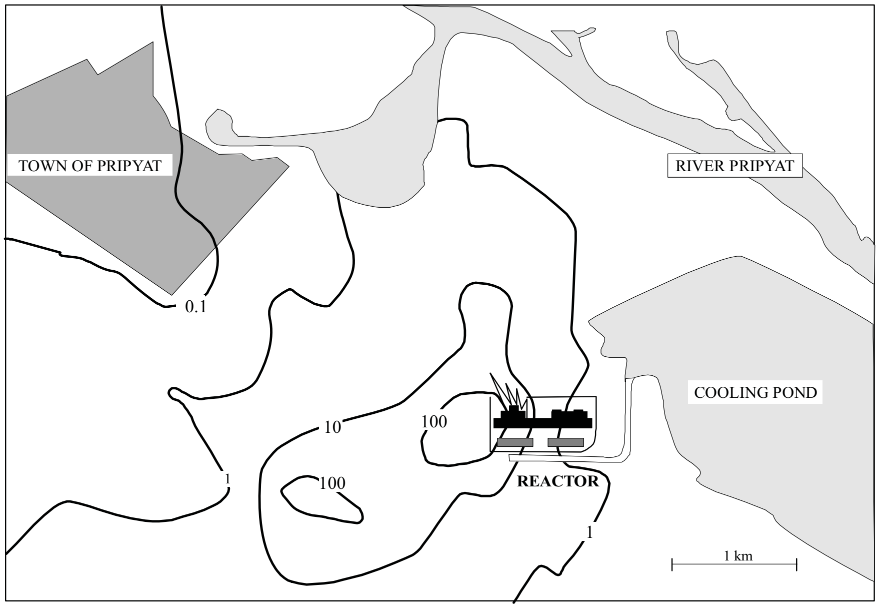


Figure XII. Measured exposure rates in air on 26 April 1986 in the local area of the Chernobyl reactor.
Units of isolines are R h^{-1}.

69. The highest doses were received by the firemen and the personnel of the power station on the night of the accident. Some symptoms of acute radiation sickness were observed in 237 workers. Following clinical tests, an initial diagnosis of acute radiation sickness was made in 145 of these persons. On further analysis of the clinical data, acute radiation sickness was confirmed later (in 1992) in 134 individuals. The health effects that were observed among the emergency workers are discussed in Chapters III and IV.

70. The most important exposures were due to external irradiation (relatively uniform whole-body gamma irradiation and beta irradiation of extensive body surfaces), as the intake of radionuclides through inhalation was relatively small (except in two cases) [U4]. Because all of the dosimeters worn by the workers were overexposed, they could not be used to estimate the gamma doses received via external irradiation. However, relevant information was obtained by means of biological dosimetry for the treated

persons. The estimated ranges of doses for the 134 emergency workers with confirmed acute radiation sickness are given in Table 11. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy. Ninety-three patients received higher doses and had more severe acute radiation sickness: 50 persons with doses between 2.2 and 4.1 Gy, 22 between 4.2 and 6.4 Gy, and 21 between 6.5 and 16 Gy [I5]. As shown in Table 12, the relative errors were 10%–20% for doses greater than 6 Gy; they increased as the dose level decreased, to about 100% for whole-body doses of about 1 Gy, and were even greater for doses of less than 0.5 Gy. The skin doses from beta exposures evaluated for eight patients with acute radiation sickness ranged from 10 to 30 times the dose from whole-body gamma radiation [B10].

71. Internal doses were determined from thyroid and whole-body measurements performed on the persons under treatment, as well as from urine analysis and from post-mortem analysis of organs and tissues. For most of the patients, more than 20 radionuclides were detectable in the whole-body gamma measurements; however, apart from the radioiodines and radiocaesiums, the contribution to the internal doses from the other radionuclides was negligible [U4]. Internal doses evaluated for 23 persons who died of acute radiation sickness are shown in Table 13. The lung and thyroid doses, calculated to the time of death, are estimated to have ranged from 0.00026 to 0.04 Gy and from 0.021 to 4.1 Gy, respectively. Some of the low thyroid doses may be due to the fact that stable iodine pills were distributed among the reactor staff less than half an hour after the beginning of the accident. It is also speculated that the internal doses received by the emergency workers who were outdoors were much lower than those received by the emergency workers who stayed indoors. For comparison purposes, the estimated external doses are also presented in Table 13. The external doses, which range from 2.9 to 11.1 Gy, are, in general, much greater than the internal doses.

72. Internal dose reconstruction was also carried out for 375 surviving emergency workers who were examined in Moscow; the results are presented in Table 14. The average doses were estimated to vary from 36 mGy to bone marrow to 280 mGy to bone surfaces, the maximum doses being about 10 times greater than the average doses. Also, thyroid doses were estimated for the 208 emergency workers admitted to Hospital 6 in Moscow within 3–4 weeks after the accident (Table 15); most of the thyroid doses were less than 1 Gy, but three exceeded 20 Gy. It is interesting to note that the measurements of ^{131}I and ^{133}I among the five emergency workers with the highest thyroid doses showed that ^{133}I contributed less than 20% to the thyroid dose. The specific values of the contributions from ^{133}I were 18% (with 74% from ^{131}I), 11% (81% from ^{131}I), 6% (86% from ^{131}I), 10% (82% from ^{131}I) and 14% (78% from ^{131}I) for the five workers [G12]. The thyroid doses due to internal exposures are estimated to be in the range from several percent to several hundred percent of the external whole-body doses. The median value of the ratio of the thyroid to the whole-body dose was estimated to be 0.3 [K19]. Finally, information is available for the relative intakes of 16 radionuclides of 116 patients, determined from measurements in urine and in autopsy materials [D12]; according to these measurements, the average intake of ^{132}Te was found to be about 10% that of ^{131}I [D12].

2. Recovery operation workers

73. About 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators, according to laws promulgated in Belarus, the Russian Federation and Ukraine. Of those, about 240,000 were military servicemen [C7]. The principal tasks carried out by the recovery operation workers (liquidators) included decontamination of the reactor block, reactor site, and roads (1986–1990) and construction of the sarcophagus (May-November 1986), a settlement for reactor personnel (May-October 1986), the town of Slavutich (1986–1988, 1990), waste repositories (1986–1988), and dams and water filtration systems (July-September 1986, 1987) [K19]. During the entire period, radiation monitoring and security operations were also carried out.

74. Of particular interest are the 226,000 recovery operation workers who were employed in the 30-km zone in 1986–1987, as it is in this period that the highest doses were received; information concerning these workers is provided in Table 16. About half of these persons were civilian and half were military servicemen brought in for the special and short-term work. The workers were all adults, mostly males aged 20–45 years. The construction workers were those participating in building the sarcophagus around the damaged reactor. Other workers included those involved in transport and security, scientists and medical staff. The distributions of the external doses for the categories of workers listed in Table 16, as well as for the emergency workers and accident witnesses, are shown in Table 17.

75. The remainder of the recovery operation workers (about 400,000), who generally received lower doses, includes those who worked inside the 30-km zone in 1988–1990 (a small number of workers are still involved), those who decontaminated areas outside the 30-km zone, and other categories of people.

76. In 1986 a state registry of persons exposed to radiation was established at Obninsk. This included not only recovery operation workers but evacuees and residents of contaminated areas as well. The registry existed until the end of 1991. Starting in 1992, national registries of Belarus, the Russian Federation and Ukraine replaced the all-union registry. The number of recovery operation workers in the national registries of Belarus, the Russian Federation and Ukraine is listed in Table 18. Some 381,000 workers from these countries were involved in the years 1986–1989. To this must be added the 17,705 recovery operation workers recorded in the registries of the Baltic countries, including 7,152 from Lithuania, 5,709 from Latvia and 4,844 from Estonia [K13]. More detailed information on the registries is provided in Chapter IV. The total number of recovery operation workers

recorded in the registries appears to be about 400,000. This number is likely to increase in the future, as some organizations may not have provided all their information to the central registries; in addition, individuals may on their own initiative ask to be registered in order to benefit from certain privileges. However, the number of recovery operation workers recorded in the national registries is well below the figure of about 600,000, which corresponds to the number of people who have received special certificates confirming their status as liquidators.

(a) External effective doses from gamma radiation

77. The doses to the recovery operation workers who participated in mitigation activities within two months after the accident are not known with much certainty. Attempts to establish a dosimetric service were inadequate until the middle of June. TLDs and condenser-type dosimeters that had been secured by 28 April were insufficient in number and, in the case of the latter type, largely non-functioning, and records were lost when the dosimetric service was transferred from temporary to more permanent quarters. In June, TLD dosimeters were available in large numbers, and a databank of recorded values could be established. From July 1986 onwards, individual dose monitoring was performed for all non-military workers, using either TLDs or film dosimeters.

78. The dose limits for external irradiation varied with time and with the category of personnel. According to national regulations established before the accident [M1], for civilian workers, during 1986, the dose limit, 0.05 Sv, could be exceeded by a factor of up to 2 for a single intervention and by a factor of 5 for multiple interventions on condition of agreement by the personnel. The maximum dose allowed during the year 1986 was, therefore, 0.25 Sv. In 1987, the annual dose limits for civilian personnel were lowered to 0.05 or to 0.1 Sv, according to the type of work performed on the site. However, a dose of up to 0.25 Sv could be allowed by the Ministry of Health for a limited number of workers for the implementation of extremely important interventions. In 1988, the annual dose limit was set at 0.05 Sv for all civilian workers, except those involved in the decontamination of the engine hall inside the sarcophagus; for them, the annual dose limit was set at 0.1 Sv. From 1989 onwards, the annual dose limit was set at 0.05 Sv for all civilian workers, without exception [M1, M12]. For military workers, a dose limit of 0.5 Sv, corresponding to radiation exposures during wartime, was applied until 21 May 1986, when the Ministry of Defence lowered the dose limit to 0.25 Sv [C7]. From 1987 onwards, the dose limits were the same for military and civilian personnel.

79. Estimates of effective doses from external gamma irradiation were generally obtained in one of three ways: (a) individual dosimetry for all civilian workers and a small part of the military personnel after June 1986; (in 1987, they were identified as those working in locations where the exposure rate was greater than 1 mR h^{-1}); (b) group dosimetry (an individual dosimeter was assigned to one member of a group of recovery operation workers assigned to perform a particular task, and all members of the group were assumed to receive the same dose; in some cases, no member of the group wore an individual dosimeter and the dose was assigned on the basis of previous experience); or (c) time-and-motion studies (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). Methods (b) and (c) were used for the civilian workers before June 1986, when the number of individual dosimeters was insufficient, and for the majority of the military personnel at any time. For example, effective doses from external irradiation have been reconstructed by physical means for the staff of the reactor, as well as for the workers who had been detailed to assist them, exposed from 26 April to 5 May 1986 [K19]. Personnel location record cards filled in by workers were analysed by experts who had reliable information on the radiation conditions and who had personally participated in ensuring the radiation safety of all operations following the accident. Using this method, two values were determined: the maximum possible dose and the expected dose. The maximum possible effective doses ranged from less than 0.1 Sv to a few sievert and were estimated to be about twice the expected doses. It seems that in most cases the maximum possible effective doses are those that were officially recorded.

80. The main sources of uncertainty associated with the different methods of dose estimation were as follows: (a) individual dosimetry: incorrect use of the dosimeters (inadvertent or deliberate actions leading to either overexposure or underexposure of the dosimeters); (b) group dosimetry: very high gradient of exposure rate at the working places at the reactor site; and (c) time-and-motion studies: deficiencies in data on itineraries and time spent at the various working places, combined with uncertainties in the exposure rates. Uncertainties associated with the different methods of dose estimation are 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 method (c) [P15].

81. The registry data show that the annual averages of the officially recorded doses decreased from year to year, being about 170 mSv in 1986, 130 mSv in 1987, 30 mSv in 1988, and 15 mSv in 1989 [I34, S14, T9]. It is, however, difficult to assess the validity of the results that have been reported for a variety of reasons, including (a) the fact that different dosimeters were used by different organizations without any intercalibration; (b) the high number of recorded doses very close to the dose limit; and (c) the high number of rounded values such as 0.1, 0.2, or 0.5 Sv [K19]. However, the doses do not seem to have been systematically overestimated, because biological dosimetry performed on limited numbers of workers produced results that are also very uncertain but compatible nonetheless with the physical dose estimates [L18]. It seems reasonable to assume that the average effective dose from external gamma irradiation to recovery operation workers in the years 1986–1987 was about 100 mSv, with individual

effective doses ranging from less than 10 mSv to more than 500 mSv. Using the numbers presented in Table 18, the collective effective dose is estimated to be about 40,000 man Sv.

82. A particular group of workers who may have been exposed to substantial doses from external irradiation is made up of the 1,125 helicopter pilots who were involved in mitigation activities at the power plant in the first three months after the accident [U15]. The doses to pilots were estimated using either personal dosimeters or, less reliably, calculations in which the damaged reactor was treated as a collimated point source of radiation [U15]. The doses obtained by calculation were checked against the results derived from the personal dosimeters for about 200 pilots. That comparison showed a discrepancy of (a) less 0.05 Sv for about 10% of pilots, (b) from 0.05 to 0.1 Sv for about 33%, and (c) more than 0.1 Sv for about 57% [U15]. The simplification used to describe the origin of the radiation emitted from the damaged reactor is the main source of uncertainty in the assessment of the doses received by the helicopter pilots. The average dose estimates are 0.26 Sv for the pilots who took part in the mitigation activities from the end of April to the beginning of May, and 0.14 Sv for the pilots who were exposed after the beginning of May.

83. Another group of workers that may have been exposed to substantial doses from external irradiation is the 672 workers from the Kurchatov Institute, a group that includes those who were assigned special tasks inside the damaged unit 4 before and after the construction of the sarcophagus [S36]. Recorded and calculated doses available for 501 workers show that more than 20% of them received doses between 0.05 and 0.25 Sv, and that about 5% of them received doses between 0.25 and 1.5 Sv [S36]. A number of nuclear research specialists worked in high-radiation areas of the sarcophagus, without formal recording of doses, on their own personal initiative, and were exposed to annual levels greater than the dose limit of 0.05 Sv applicable since 1988. Doses for this group of 29 persons have been estimated using electron spin resonance analysis of tooth enamel as well as stable and unstable chromosome aberration techniques [S42, S47]. It was found that 14 of those 29 persons received doses lower than 0.25 Sv, 5 had doses between 0.25 and 0.5 Sv, 6 between 0.5 and 1 Sv, and 4 greater than 1 Sv [S42]. Additional analyses by means of the FISH technique for three of those nuclear research specialists resulted in doses of 0.9, 2.0 and 2.7 Sv [S48].

84. ***Biological dosimetry.*** Chromosome aberration levels among Chernobyl recovery operation workers were analysed in a number of additional studies. In a pilot study of a random sample of 60 workers from the Russian Federation, stratified on the level of recorded dose (31 with doses <100 mGy, 18 with 100–200 mGy, and 13 with >200 mGy), no association was found between the percentage of the genome with stable translocations measured by fluorescent *in situ* hybridization (FISH) and individual recorded physical dose estimates [C1, L18]. A good correlation was found, however, for group (rather than individual) doses. Blood samples of 52 Chernobyl recovery operation workers were analysed by FISH [S32] and simultaneously by conventional chromosome analysis. Based on FISH measurements, individual biodosimetry estimates between 0.32 and 1.0 Gy were estimated for 18 cases. Pooled data for the total group of 52 workers provided an average estimate of 0.23 Gy. For a group of 34 workers with documented doses, the mean dose estimate of 0.25 Gy compared well with the mean documented dose of 0.26 Gy, although there was no correlation between individual translocation frequencies and documented doses. Comparison between the conventional scoring and FISH analyses showed no significant difference. In a study of Estonian workers, Littlefield et al. [L41] did not detect an increase of stable translocation frequencies with reported doses and questioned whether the reported doses could have been overestimated. In conclusion, FISH does not currently appear to be a sufficiently sensitive and specific technique to allow the estimation of individual doses in the low dose range received by the majority of recovery operation workers.

85. Lazutka and Dedonyte [L30], using standard cytogenetic methods, reported no significant overall increase in chromosome aberrations over controls in 183 recovery operation workers from Lithuania with a mean dose estimate of 140 mGy, although ~20% had elevated frequencies of dicentric and ring chromosomes, possibly related to radiation exposure. Lazutka et al. [L31] also evaluated the impact of a number of possible confounders such as age, alcohol use, smoking, recent febrile illness, and diagnostic x-ray exposures on the frequency of chromosome aberrations. When transformed data were analysed by analysis of variance, alcohol abuse made a significant contribution to total aberrations, chromatid breaks, and chromatid exchanges. Smoking was associated with frequency of chromatid exchanges, and age was significantly associated with rates of chromatid exchanges and chromosome exchanges [L31]. In another study [S37], the frequency of chromosomal aberrations was evaluated in more than 500 recovery operation workers. Blood samples were taken from several days to three months after exposure to radiation. The mean frequencies of aberrations for different groups of workers were associated with doses varying from 0.14 to 0.41 Gy, with a good correlation between the doses determined by biological and physical methods [S37].

86. Glycophorin A assay (GPA) was used as a possible biological dosimeter on 782 subjects from Estonia, Latvia and Lithuania with recorded physical dose estimates [B17]. Although a slight increase in the frequency of erythrocytes with loss of the GPA allele was seen among these subjects compared to control subjects from the same countries, this difference was not significant. The pooled results indicate that the average exposures of these workers were unlikely to greatly exceed 100–200 mGy, the approximate minimum radiation dose detectable by this assay.

(b) External skin doses from beta radiation

87. In addition to effective doses from external gamma irradiation, recovery operation workers received skin doses from external beta irradiation as well as thyroid and effective doses from internal irradiation. The dose to unprotected skin from beta exposures is estimated to have been several times greater than the gamma dose. Ratios of dose rates of total exposures (beta + gamma) to gamma exposures, measured at the level of the face, ranged from 2.5 to 11 (average, around 5) for general decontamination work and from 7 to 50 (average, 28) for decontamination of the central hall of the Unit 3 reactor [O3].

(c) Internal doses

88. Because of the abundance of ^{131}I and of shorter-lived radioiodines in the environment of the reactor during the accident, the recovery operation workers who were on the site during the first few weeks after the accident may have received substantial thyroid doses from internal irradiation. Information on the thyroid doses is very limited and imprecise. From 30 April through 7 May 1986, *in vivo* thyroid measurements were carried out on more than 600 recovery operation workers. These *in vivo* measurements, which are measurements of the radiation emitted by the thyroid using detectors held or placed against the neck, were used to derive the ^{131}I thyroidal contents at the time of measurement. The thyroid doses were derived from the measured ^{131}I thyroidal contents, using assumptions on the dynamics of intake of ^{131}I and short-lived radioiodines and on the possible influence of stable iodine prophylaxis. Preliminary thyroid dose estimates (assuming a single intake at the date of the accident and no stable iodine prophylaxis) showed the following distribution [K30]: 64% of workers were exposed to less than 0.15 Gy, 32.9% to 0.15–0.75 Gy, 2.6% to 0.75–1.5 Gy, and the remaining 0.5% to 1.5–3.0 Gy. The average thyroid dose estimate for those workers is about 0.21 Gy. The thyroid doses from internal irradiation are estimated to range from several percent to several hundred percent of the effective doses from external irradiation. The median value of the ratio of the internal thyroid dose to the external effective dose was estimated to be 0.3 Gy per Sv [K19].

89. It is important to note that information on the influence of stable iodine prophylaxis is limited, as iodine prophylaxis among the recovery operation workers was not mandatory nor was it proposed to everybody. The decision to take stable iodine for prophylactic reasons was made by the individual worker or by the supervisor. The results of interviews of 176 workers (including emergency workers and recovery operation workers who arrived at the plant at the ealy stage of the accident) concerning the time when they took stable iodine for prophylaxis is presented in Table 19. According to this sample of workers, only about 20% took stable iodine before being exposed to radioiodine, while another 10% refused to take stable iodine.

90. The internal doses resulting from intakes of radionuclides such as ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{239,240}Pu, and others have been assessed for about 300 recovery operation workers who were monitored from April 1986 to April 1987 [K2, K8, P13, S11]. The majority of them were staff of the power plant who took part in the recovery work starting on days 3 and 4 after the accident. The dose assessment was based on the analysis of whole-body measurements and of radionuclide concentrations in excreta. The average value of the effective dose committed by the radionuclide intakes was estimated on the basis of ICRP Publication 30 [I17] to be 85 mSv. The part of the effective dose received between June and September 1986 was estimated to have been about 30 mSv. Internal doses from intakes in later years are expected to be much lower: routine monitoring of the ^{134}Cs + ^{137}Cs body burdens indicated average annual doses from ^{134}Cs + ^{137}Cs of about 0.1–0.2 mSv in 1987 and 1988 [V6].

B. EVACUATED PERSONS

91. The evacuation of the nearby residents was carried out at different times after the accident on the basis of the radiation situation and of the distance of the populated areas from the damaged reactor. The initial evacuations were from the town of Pripyat, located just 3 km from the damaged reactor, then from the 10-km zone and from the 30-km zone around the reactor (located mostly in Ukraine but also in Belarus). In addition, a number of villages in Belarus, the Russian Federation and Ukraine beyond the 30-km-radius circle centred on the reactor were also evacuated in 1986. The term “exclusion zone” is used in this Annex to refer to the whole area evacuated in 1986, which includes the 30-km zone.

92. In Ukraine, the residents of Pripyat (49,360 persons) and of the nearest railway station, Yanov (254 persons), 3 km from the reactor, were the first to be evacuated. On the evening of 26 April 1986, the radiation exposures in Pripyat were not considered too alarming. Exposure-rate readings were in the range 1–10 mR h^{-1} [I1], but with the seriousness of the accident becoming evident, the decision to evacuate the residents of the town was taken at 22:00. During the night, arrangements were made for nearly 1,200 buses that would be needed to transport the residents. Around noon on 27 April the evacuation order was broadcast to the people, and the evacuation began at 14:00 and finished at 17:00. The over 40,000 evacuees were taken in by families who lived in settlements in the surrounding districts, especially Polesskoe district of Ukraine. Most people stayed with these families until August 1986. After that they were resettled to apartments in Kiev [I1].

93. Also in Ukraine, the evacuation of the residents from the southern part of the 10-km zone (10,090 persons) was carried out from 30 April through 3 May. The other Ukrainian residents (28,133) inside the 30-km zone,

including Chernobyl town, were evacuated from 3 May through 7 May. On the basis of exposure-rate criteria (5–20 mR h^{-1} on 10 May 1986), 2,858 persons who resided outside the 30-km zone in the Kiev and in Zhitomir regions were evacuated from 14 May to 16 August. The last Ukrainian settlement that was evacuated was Bober, with 711 inhabitants, in September 1986. Thus, 91,406 residents from 75 settlements were evacuated in Ukraine in 1986 [S20, U14].

94. The evacuation in Belarus was conducted in three phases. During the first phase (2–7 May), 11,358 residents of 51 villages were evacuated from the 30-km zone. In a second phase (3–10 June), 6,017 residents of 28 villages beyond the 30-km zone were evacuated. In the third phase (August and September 1986), 7,350 residents of 29 villages, also beyond the 30-km zone, were evacuated. In villages evacuated during the second and third phases, the exposure rate was from 5 to 20 mR h^{-1}, corresponding to a projected annual effective dose (26 April 1986 to 25 April 1987) of more than 100 mSv. The total number of Belarusian residents who were evacuated in 1986 was 24,725 from 108 rural settlements. In the Russian Federation, only 186 residents from four settlements in the Krasnaya Gora district of Bryansk region were evacuated, mainly to other settlements of that district. In summary, by the autumn of 1986, about 116,000 residents from 187 settlements had been evacuated (Table 20). By the same time, about 60,000 cattle and other agricultural animals had been relocated from the evacuated zone.

95. The figure of 116,000, adopted in this Annex as the number of evacuees in 1986, is somewhat lower than the figure of 135,000 that was cited by the Committee in the UNSCEAR 1988 Report [U4] and by IAEA in 1996 [I15]. It is believed that the figure of 135,000 was a rough preliminary estimate that was not substantiated.

96. The extent of the exclusion zone was based on two principles: geographical and radiological (dose criteria). A detailed study of the radiation situation carried out in the exclusion zone led to the resettlement of 279 residents of two Ukrainian villages (Cheremoshnya and Nivetskoe) in June 1986. In addition, it was recommended that the residents of 27 other villages might move back after the sarcophagus was constructed (15 settlements in Ukraine and 12 settlements in Belarus). In accordance with these recommendations, 1,612 residents of 12 villages in Belarus had been resettled by December 1986. However, the Ukrainian authorities considered that resettling the residents inside the exclusion zone was economically and socially undesirable. Nevertheless, some people, mainly elderly, resettled by themselves to 15 settlements inside the exclusion zone. The population of those 15 settlements was estimated to be about 900 by spring 1987; about 1,200 by September 1988; and about 1,000 in 1990. In 1996–1997, the number is estimated to be 600–800. The decrease with time is due to migration rather than death.

1. Doses from external exposure

97. The effective doses from external exposure for the persons evacuated from the Ukrainian part of the 30-km zone were estimated from (a) measurements of exposure rates performed every hour at about 30 sites in Pripyat and daily at about 80 sites in the 30-km zone and (b) responses to questionnaires from about 35,000 evacuees from Pripyat and about 100 settlements; the questionnaires asked for information on their locations, types of houses, and activities at the time of the accident and during a few days thereafter [L9, M2, R10]. Individual effective doses were reconstructed in this way for about 30,000 evacuees from the city of Pripyat and settlements in the 30-km zone. The average effective dose from external irradiation for this cohort was estimated to be 17 mSv, with individual values varying from 0.1 to 380 mSv [L9]. This value is concordant with the absorbed dose of 20 mGy estimated for the evacuees of Pripyat using Electron Spin Resonance (ESR) measurements of sugar and exposure rate calculations [N1]. The collective effective dose for the approximately 90,000 evacuees from the Ukrainian part of the 30-km zone was assessed to be 1,500 man Sv [R12].

98. The effective doses and skin doses from external irradiation received by the evacuees from Belarusian territory were estimated on the basis of (a) 3,300 measurements of exposure rates performed in the settlements that were evacuated; (b) 220 spectrometric measurements, carried out mainly in May and June 1986, of the gamma radiation emitted by radionuclides deposited on the ground; (c) measurements of the ^{137}Cs ground deposition density for each settlement from the Belarusian data bank [D4]; and (d) responses of about 17,000 evacuees from the territory inside the 30-km zone and from adjoining areas. It was assessed that the doses to evacuees from external irradiation were mainly due to radionuclides deposited on the ground, because external irradiation during the passage of the radioactive cloud played a minor role. The method developed to assess the doses included the reconstruction of the radionuclide composition of the deposition in each of the 108 evacuated settlements in Belarusian territory and the estimation of the contribution to the dose from each radionuclide [S29]. It was assumed that 60%–80% of the effective doses was contributed by the short-lived radionuclides ^{131}I, ^{132}Te+^{132}I and ^{140}Ba+^{140}La, while the contribution from the long-lived radionuclide ^{137}Cs was estimated to be only 3%–5%. The distribution of individual doses received by the residents of a given settlement was found to be appropriately described by a log-normal function with a geometric standard deviation of about 1.5. Overall, it is estimated that about 30% of the people were exposed to effective doses lower than 10 mSv, about 86% were exposed to doses lower than 50 mSv, and only about 4% were exposed to doses greater than 100 mSv, with the average dose estimated to be 31 mSv. The highest average effective doses, about 300 mSv, were estimated to be received by the population of two villages located inside the 30-km zone in Khoyniki district: Chamkov and Masany. The uncertainty in the average dose for a settlement is estimated to be characterized with a geometric standard deviation of about

1.3. The main source of uncertainty in the estimation of the average effective doses from external irradiation for the Belarusian evacuees is the assessment of the activity ratios of ^{132}Te and ^{131}I to ^{137}Cs in the deposition. The collective effective dose from external irradiation for the 24,725 evacuees from Belarus is assessed to be 770 man Sv.

99. The average skin doses from beta and gamma radiation are estimated to be 3–4 times greater than the effective doses and to range up to 1,560 mGy. The uncertainty of the average skin doses in a given settlement is estimated to be characterized by a geometric standard deviation of about 1.6.

2. Doses from internal exposure

100. The thyroid doses received from intake of ^{131}I by the evacuees from Pripyat were derived from (a) 4,969 measurements of radioiodine content of their thyroid glands made, on average, 23 days after the accident and (b) responses to questionnaires by 10,073 evacuees on their locations and consumption of stable iodine [G8]. Average individual and collective thyroid doses to the evacuees from Pripyat are shown in Table 21. The thyroid doses from ^{131}I, which were for the most part due to inhalation, were highest for 0–3-year-old children (about 1.4 Gy) and averaged about 0.2 Gy. The main factor influencing the individual dose was found to be the distance of the residence from the reactor [G8].

101. Thyroid doses from intake of ^{131}I to other evacuees from the 30-km zone were also estimated on the basis of measurements of thyroid contents in 10,676 persons [L12, R10]. When dose estimates obtained for the evacuees from Pripyat are compared with those for the evacuees from other settlements of the 30-km zone (Table 21), the doses to the latter are seen to be somewhat higher than those to the evacuees from Pripyat, especially for adults. This may be because Pripyat was evacuated before the rest of the 30-km zone, giving the population of the 30-km zone more time to consume foodstuffs contaminated with ^{131}I. Using for the settlements of the 30-km zone the same age structure as that for Pripyat in Table 21, the collective thyroid dose from ^{131}I intake for the entire population of evacuees from Ukraine is tentatively estimated to be about 30,000 man Gy. Evaluation of thyroid doses to the evacuated population of Belarus is presented in Table 22. The collective thyroid dose estimate for this population is 25,000 man Gy.

102. Inhalation of short-lived radioiodines and of ^{132}Te contributed somewhat to the thyroid dose received by evacuees. According to Goulko et al. [G5], the most important of these short-lived radionuclides is ^{133}I, amounting to about 30% of the contribution of ^{131}I to the thyroid doses. This maximal value was obtained by taking into account an inhalation for one hour occurring one hour after the accident. Khrouch et al. [K16] estimated that the contribution of all the short-lived radioiodines and of ^{132}Te could have represented about 50% of the dose from ^{131}I if the intake occurred by inhalation during the first day after the accident and about 10% if the intake occurred by both inhalation and the ingestion of contaminated foodstuffs.

103. Internal effective doses from ^{137}Cs were estimated for the Belarusian evacuees on the basis of 770 measurements of gamma-emitting radionuclides in foodstuffs and of 600 whole-body measurements of ^{137}Cs content, in addition to the environmental measurements already mentioned in Section II.B.1 [S29]. The main contribution to dose was from inhalation (about 75% of total internal dose) and radiocaesium intake in milk. The average internal exposure from radiocaesium in milk for the evacuated population is estimated to be 1.4 mSv. The main sources of uncertainty in the assessment of the internal doses from ^{137}Cs are considered to be the dates when the cows were first put on pasture in each settlement and the actual countermeasures that were applied in the settlement. The collective effective dose for the 24,725 Belarusian evacuees from internal exposure was assessed to be 150 man Sv [S29].

3. Residual and averted collective doses

104. Estimates of collective doses for the populations that were evacuated in 1986 from the contaminated areas of Belarus, the Russian Federation and Ukraine are summarized in Table 23. The collective effective and thyroid doses are estimated to be about 3,800 man Sv and 55,000 man Gy, respectively. Most of the collective doses were received by the populations of Belarus and Ukraine.

105. The evacuation of the residents of Pripyat (28 April) and of the rural settlements inside the 30-km zone (beginning of May) prevented the potential occurrence of deterministic effects and resulted in collective doses substantially lower than would have been experienced if there had been no evacuation. A comparison of the external effective doses for the Belarusians, calculated with and without evacuation from the 30-km zone, is presented in Table 24 [S24]. Because of the evacuation, the number of inhabitants with doses greater than 0.4 Sv was reduced from about 1,200 to 28 persons. The collective effective dose from external exposure averted in 1986 for the approximately 25,000 evacuated Belarusian inhabitants was estimated to be 2,260 man Sv (or approximately 75% of the dose that would have been received without evacuation). A similar assessment of averted collective dose for the evacuated Ukrainian inhabitants led to a value of about 6,000 man Sv. Therefore, the averted collective dose from external exposure for the 116,000 persons evacuated in 1986 is estimated to be 8,260 man Sv.

106. The thyroid collective dose was also reduced to some extent. Iodine prophylaxis was mostly effective in Pripyat, where about 73% of the population received iodine tablets on April 26 and 27, i.e. during the very first days after the accident. It is estimated that a single intake reduced the expected thyroid dose by a factor of 1.6–1.7 and that intakes during two consecutive days reduced it by a factor of 2.3 [R10]. In the rural areas close to the nuclear power

plant, about two thirds of the children used iodine tablets for prophylactic reasons. However, they did not start taking the tablets before 30 April, and about 75% of the children who took iodine tablets began to take them on 2–4 May. Thus, because there was a one-week delay in the use of iodine tablets and because only part of the population was covered, the averted collective thyroid dose from ingestion of contaminated milk was about 30% of the expected collective thyroid dose from that pathway, while the thyroid doses from inhalation remained unchanged. An upper estimate of the averted collective thyroid dose for the 116,000 evacuees is about 15,000 man Gy [A10].

C INHABITANTS OF CONTAMINATED AREAS OF THE FORMER SOVIET UNION

107. Areas contaminated by the Chernobyl accident have been defined with reference to the background level of ^{137}Cs deposition caused by atmospheric weapons tests, which when corrected for radioactive decay to 1986, is about 2–4 kBq m^{-2} (0.05–0.1 Ci km^{-2}). Considering variations about this level, it is usual to specify the level of 37 kBq m^{-2} (1 Ci km^{-2}) as the area affected by the Chernobyl accident. Approximately 3% of the European part of the former USSR was contaminated with ^{137}Cs deposition densities greater than 37 kBq m^{-2} [I3].

108. Many people continued to live in the contaminated territories surrounding the Chernobyl reactor, although efforts were made to limit their doses. Areas of ^{137}Cs deposition density greater than 555 kBq m^{-2} (15 Ci km^{-2}) were designated as areas of strict control. Within these areas, radiation monitoring and preventive measures were taken that have been generally successful in maintaining annual effective doses within 5 mSv. Initially, the areas of strict control included 786 settlements and a population of 273,000 in an area of 10,300 km^2 [I3, I4]. The sizes and populations of the areas of strict control within Belarus, the Russian Federation and Ukraine are given in Table 25. Those population numbers applied to the first few years following the accident. Because of extensive migration out of the most contaminated areas and into less contaminated areas, the current population in the areas of strict control is much lower in Belarus and Ukraine and somewhat lower in the Russian Federation. In 1995, the number of people living in the areas of strict control was about 150,000 [K23, R11]. The distribution of the population residing in contaminated areas in 1995 according to ^{137}Cs deposition density interval is provided in Table 26. The total population is about 5 million and is distributed almost equally among the three countries.

109. In the UNSCEAR 1988 Report [U4], the Committee evaluated separately the doses received during the first year after the accident and the doses received later on. The most important pathways of exposure of humans were found to be the ingestion of milk and other foodstuffs contaminated with ^{131}I, ^{134}Cs and ^{137}Cs and external exposure from radioactive deposits of short-lived radionuclides (^{132}Te, ^{131}I, ^{140}Ba, ^{103}Ru, ^{144}Ce, etc.) and long-lived radionuclides (essentially, ^{134}Cs and ^{137}Cs).

110. In the first few months, because of the significant release of the short-lived ^{131}I, the thyroid was the most exposed organ. The main route of exposure for thyroid dose was the pasture-cow-milk pathway, with a secondary component from inhalation. Hundreds of thousands of measurements of radioiodine contents in the thyroids of people were conducted in Belarus, the Russian Federation and Ukraine to assess the importance of the thyroid doses.

111. During the first year after the accident, doses from external irradiation in areas close to the reactor arose primarily from the ground deposition of radionuclides with half-lives of one year or less. In more distant areas, the radiocaesiums became the greatest contributors to the dose from external irradiation only one month after the accident.

112. Over the following years, the doses received by the populations from the contaminated areas have come essentially from external exposure due to ^{134}Cs and ^{137}Cs deposited on the ground and internal exposure due to contamination of foodstuffs by ^{134}Cs and ^{137}Cs. Other, usually minor, contributions to the long-term radiation exposures include the consumption of foodstuffs contaminated with ^{90}Sr and the inhalation of aerosols containing ^{239}Pu, ^{240}Pu and ^{241}Am. The internal exposures to ^{134}Cs and ^{137}Cs result in relatively uniform doses over all organs and tissues of the body. A very large number of measurements of exposure rates, as well as of radiocaesium in soil and in foodstuffs, have been made in Belarus, the Russian Federation and Ukraine to assess the effective doses and have been used to prepare compilations of annual effective doses received by the most exposed residents in the contaminated settlements. These compilations, which were prepared for regulatory purposes, tend to overestimate the average doses that were received during the years 1986–1990.

113. Since 1991, methods for average dose estimation have been introduced to account for observed changes in radiation levels, as evidenced by experimental dose determinations with TLD measurements and ^{134}Cs/^{137}Cs whole-body counting. These methods were introduced in order to make reasonable decisions regarding the radiation protection of the population, and also to obtain dose estimates for use in epidemiological studies, where accurate individual dose estimates are needed, or in risk assessment studies, where collective doses over limited areas are necessary, and they were an improvement in the general state of knowledge in the field of dose reconstruction. These methods are based on as many measurements as possible, either in the area under consideration or for the individual of interest.

114. The experience thus far acquired and the data accumulated are allowing more realistic dose assessment procedures to be formulated. For example, the external

dose estimates may be related to the contributions from each radionuclide present at the time of deposition, the reduction with time due to radioactive decay and penetration of radionuclides into soil, and shielding and occupancy for various types of buildings and population groups (urban, rural, agricultural workers, schoolchildren, etc.) [G1]. Data from whole-body counting of ^{134,137}Cs have allowed a better estimation of ^{137}Cs retention times in relation to sex for adults and in relation to age, body mass and height for children [L1]. A careful analysis of the thyroid activity measurements, along with the consideration of ^{137}Cs deposition densities and of relevant environmental parameters, has improved the reliability of estimated thyroid doses, although much work remains to be done [G7].

115. When the above methods of dose estimation are used, they may yield several estimates of dose, not necessarily comparable, for example maximal projected doses, average projected doses and actual doses. In local areas there could also be wide deviations from the average settlement dose owing to particular control measures or individual behaviour. Estimates of effective doses per unit deposition density from external and internal exposure have been derived for various districts and times following the accident. These effective dose estimates, as well as the thyroid doses from intake of radioiodines, are discussed below.

1. Doses from external exposure

116. Effective doses have been estimated in Belarus, the Russian Federation and Ukraine on the basis of (a) the large number of measurements of exposure rates and of radionuclide concentrations in soil carried out in the contaminated areas and (b) population surveys on indoor and outdoor occupancy as a function of age, season, occupation and type of dwelling. The methodology that was applied [B14] has some similarities to that used by the Committee in the UNSCEAR 1988 Report [U4]. The effective dose for a representative person of age k is calculated as

$$E_k = D_a F_k \sum_i L_{i,k} B_{i,k}$$

where D_a is the absorbed dose in air over the time period of interest at a reference location at a height of 1 m above flat, undisturbed ground; F_k is the conversion factor from absorbed dose in air to effective dose for a person of age k; $L_{i,k}$ is the location factor, which is the ratio of the absorbed doses in air at location i and at the reference location for a person of age k; and $B_{i,k}$ is the occupancy factor, that is, the fraction of time spent at location i. The location i can be indoors (place of work, place of residence, etc.) or outdoors (street, forest, backyard, etc.).

117. The absorbed dose in air at the reference location, D_a, was usually inferred from the measured or assumed radionuclide distribution in deposition. The conversion factor from absorbed dose in air to effective dose, F_k, was determined using anthropomorphic phantoms simulating individuals from one year of age to adult, containing TLDs in many organs, exposed to radiocaesium outdoors and indoors [E7, G1, G19]. The values of F_k were found to be 0.7–0.8 Sv Gy^{-1} for adults, 0.8–0.9 Sv Gy^{-1} for 7–17-year-old schoolchildren, and about 0.9–1.0 Sv Gy^{-1} for 0–7-year-old pre-schoolchildren [G1].

118. The term $\Sigma L_{i,k} B_{i,k}$, called the occupancy/ shielding or reduction factor, was derived from population surveys. Values obtained for the reduction factor for rural and urban populations in the Russian Federation [B14] are presented in Table 27, along with the values used by the Committee in the UNSCEAR 1988 Report [U4]. There is good agreement between the two sets of values used for representative groups. Detailed information on the location and occupancy factors derived from surveys among the populations of Belarus, the Russian Federation and Ukraine is available [E7]; for example, values of occupancy factors in the summertime for rural populations of the three countries are presented in Table 28.

119. It is clear from Tables 27 and 28 that there are substantial differences in the reduction factor depending on the type of dwelling and occupation. The values used for the representative group are meant to reflect the age and socioprofessional composition of the population living in a typical dwelling. Estimates of external effective doses for specific groups can be obtained by multiplying the dose for the representative group by a modifying factor, as given in Table 29 [B14]. The values of the modifying factor were validated with data from individual dosimetry (TLD measurements) [E8].

120. Values of the overall coefficient used to calculate the average external effective doses, D_b, on the basis of the absorbed dose in air, D_a, are shown in Table 30. These overall coefficients have different values for urban and rural populations, but for both populations, the values are averaged over age, occupation, and type of dwelling.

(a) Doses from external irradiation received during the first year after the accident

121. For times of less than one year after the accident, the reference absorbed dose rate in air was calculated assuming that the radioactive deposit was a plane source below a soil slab with a mass per unit area of 0.5 g cm^{-2} [E7]. During the first few months after the accident, the dose rate in air varied according to the radionuclide composition of the activity deposited, which, as shown in Table 6, varied according to direction and distance from the reactor. As an example, Figure XIII illustrates the variations in the contributions to the absorbed dose rate in air of various radionuclides from a contaminated area of the Russian Federation [G1]. In that case, the radiocaesiums became the greatest contributors to the dose rate in air only one month after the accident, because the short-lived radio-

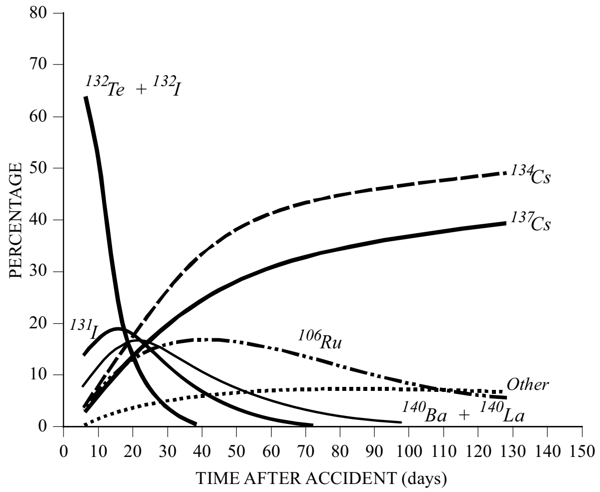


Figure XIII. Contributions of radionuclides to the absorbed dose rate in air in a contaminated area of the Russian Federation during the first several months after the Chernobyl accident [G1].

nuclides and the refractory elements were less important than in areas closer to the reactor. As shown in Figure XIV, the short-lived radioisotopes of refractory elements, such as ^{95}Zr, ^{106}Ru, and ^{141}Ce, played an important role in the doses from external irradiation received during the first year after the accident in areas close to the reactor site [M3]. Following decay of the short-lived emitters, the annual doses per unit ^{137}Cs deposition were similar in all areas, although a slight decrease was observed with increasing distance from the reactor [J1]. Table 31 presents published estimates of normalized effective doses from external irradiation for various periods after the accident and for rural and urban areas in the three countries that were most affected by the accident. The effective doses from external irradiation are estimated to be higher in rural areas than in urban areas by a factor of about 1.5. During the first year after the accident, average values of the normalized effective dose are estimated to have ranged from 11 µSv per kBq m^{-2} of ^{137}Cs for urban areas of the Russian Federation to 24 µSv per kBq m^{-2} of ^{137}Cs for rural areas of Ukraine.

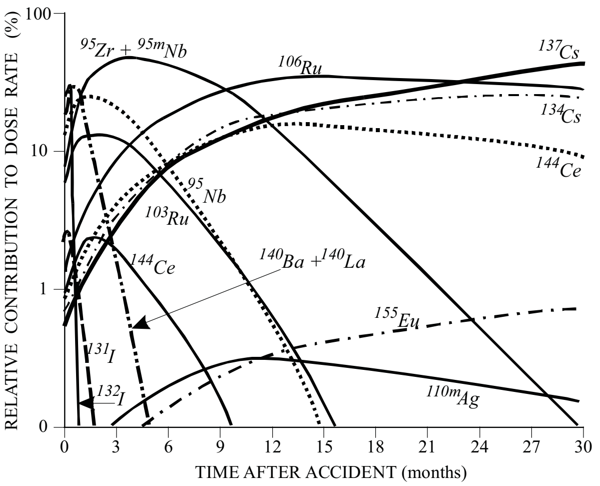


Figure XIV. Contributions of radionuclides to the absorbed dose rate in air in areas close to the Chernobyl reactor site [M3].

122. In summary, during the first year after the accident, the average values of the normalized effective dose are estimated to have been 15–24 µSv per kBq m^{-2} of ^{137}Cs for rural areas and 11–17 µSv per kBq m^{-2} of ^{137}Cs for urban areas, the values for Belarus and Ukraine being higher than those for the Russian Federation because of their closer proximity to the reactor. These values are in agreement with the value of 10 µSv per kBq m^{-2} of ^{137}Cs used by the Committee in the UNSCEAR 1988 Report [U4] for the normalized effective dose equivalent, because most of the data used to derive the 1988 value came from countries further away from the reactor than Belarus, the Russian Federation and Ukraine.

(b) Doses from external irradiation received after the first year following the accident

123. At times greater than one year after the accident, the absorbed dose rate in air came essentially from the gamma radiation from ^{134}Cs and ^{137}Cs. The models used in the three countries (Belarus, the Russian Federation and Ukraine) to derive the variation with time of the normalized absorbed dose rate in air at a height of 1 m above undisturbed ground in the settlements of the contaminated areas are somewhat different. In Belarus, a Monte Carlo method was used; the vertical profile of ^{134}Cs and ^{137}Cs in soil was simulated by a set of infinite isotropic thin sources placed at different depths of soil and an exponential decrease with depth, with an initial relaxation length of 0.5 g cm^{-2} and a linear increase of that value with time after the accident [K38]. In the Russian Federation, the vertical migration of ^{137}Cs to deeper layers of soil was taken into account using a time-varying function r(t), which represents the ratio of the absorbed dose rates in air at a height of 1 m above ground at times t after deposition and at the time of deposition (t = 0), the latter being calculated over flat, undisturbed ground. The variation with time of r(t) may be described as

$$r(t) = a_1\, e^{-\ln 2t/T_1} + a_2\, e^{-\ln 2t/T_2}$$

with $T_1 = 1.5$ a, $T_2 = 20$ a, and a_1 and a_2 equal to 0.4 and 0.42, respectively [B26, M17].

124. In Ukraine, the variation of the normalized absorbed dose rate in air was determined both on the basis of routine measurements of exposure rate at eight reference sites and modelling of the vertical migration of ^{137}Cs. The second approach used the time-varying function given in the above equation but with different parameter values: $T_1 = 0.5$ a, $T_2 = 10$ a and a_1 and a_2 equal to 0.18 and 0.65, respectively [M16]. The difference in the estimates obtained for r(t) in the Russian Federation [M17] and in Ukraine [M16] is difficult to explain; it may be partly due to the fact that the measurements were made in different conditions according

to the type of fallout (wet or dry), the distance from the reactor and the type of soil. The values obtained in the three countries for the normalized absorbed dose rate in air are given in Table 32 for each year between 1987 and 1995. The variation with time is fairly similar in the three countries.

125. Average external normalized effective doses for the populations living in contaminated areas are derived from the reference values of normalized absorbed dose rates in air presented in Table 32 and the overall coefficients from dose in air to effective dose presented in Table 30. Results for several time periods are shown in Table 31. Values for rural areas of Belarus for the 1996–2056 time period are estimated in this Annex to be the same as those for the Russian Federation and Ukraine in rural areas; on the basis of data in Table 30, values for urban areas of Belarus are taken to be the same as in rural areas of that country. The selected values of the average normalized external effective doses for urban and rural populations are shown in Table 33. On average, the external doses received during the first 10 years after the accident represent 60% of the lifetime doses (Table 33). The normalized lifetime doses are estimated to range from 42 to 88 μSv per kBq m^{-2} of ^{137}Cs. These values are somewhat lower than the value of 86 μSv per kBq m^{-2} of ^{137}Cs used by the Committee in the UNSCEAR 1988 Report for the normalized effective dose equivalent. This may be due to the fact that in the UNSCEAR 1988 Report, the Committee used the conservative assumption that the vertical profile of ^{137}Cs in soil would be permanently fixed one year after the time of deposition.

126. Average effective doses from external irradiation received during the first 10 years after the accident are estimated to range from 5 mSv in the urban areas of the Russian Federation to 11 mSv in the rural areas of Ukraine. The distributions of the collective effective doses from external irradiation according to region of the country, dose interval, and ^{137}Cs deposition density are presented in Tables 34–36 for Belarus, the Russian Federation and Ukraine. These distributions have been estimated from the databases of radionuclide depositions that are available for each settlement of the contaminated areas of Belarus, the Russian Federation and of Ukraine [B37, L44, M17, S46].

127. The variability of individual external doses can be estimated from the analysis of TLD measurements. Figure XV illustrates the relative distribution of external doses in 1991 and 1992 for 906 inhabitants of 20 Belarusian villages in which the ^{137}Cs deposition density ranged from 175 to 945 kBq m^{-2} [G9, G10]. The individual doses were normalized to the median dose in each settlement. It was found that a log-normal distribution with a geometric standard deviation of 1.54 provides a good approximation of the normalized individual doses from external irradiation. The calculated doses that are recorded in the dose catalogues at that time were in good agreement with the measured median doses, the maximum discrepancy being ±30%.

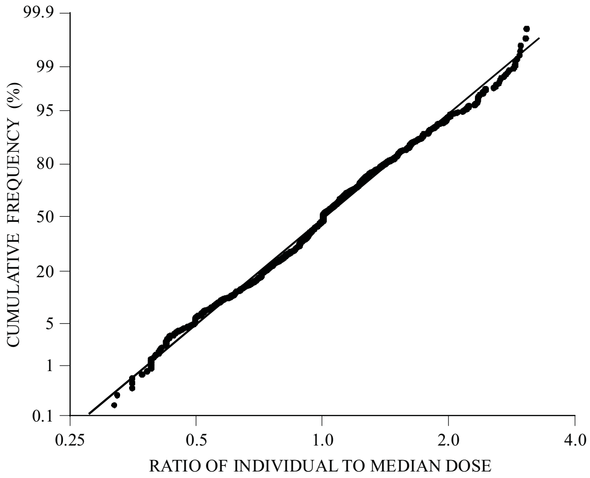


Figure XV. Distribution of ratios of measured external individual doses to median settlement dose for 906 inhabitants of 20 rural settlements of Gomel region in 1991-1992 *(geometric standard deviation: 1.54).*

128. Figure XVI illustrates the distribution of external doses obtained in 1987 in a smaller survey involving the inhabitants of the village of Stary Vyshkov in the Russian Federation [S25]. In that particular case, it was found that a normal distribution with a coefficient of variation of about 1.4 could be used. Individuals who received doses in the upper or lower tenths of the distribution were examined further. The two characteristics found to be important were occupation and the construction of the building in which the individuals spent a large proportion of time. None of the individuals living or working in stone or brick buildings received external doses in the upper tenth percentile of the dose distribution [S25]. In addition, the external dose received as a function of age was also studied for the inhabitants of that Russian village. The results, shown in Figure XVII, indicate a great variability in external dose,

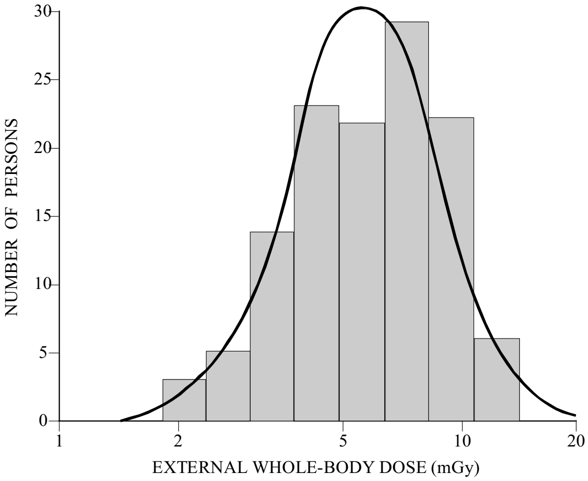


Figure XVI. Distribution of external whole-body doses among 124 residents of Stary Vyshkov, Russian Federation, in 1987 [S25]. *The fitted normal curve is superimposed.*

with an overall trend that suggests an increase in external dose with increasing age [S25]. This may reflect differences in occupational activity, since young people would be expected to spend a large proportion of time indoors at school and, consequently, to receive low external doses, while old people generally spend much time outdoors or inside lightly shielded buildings [S25].

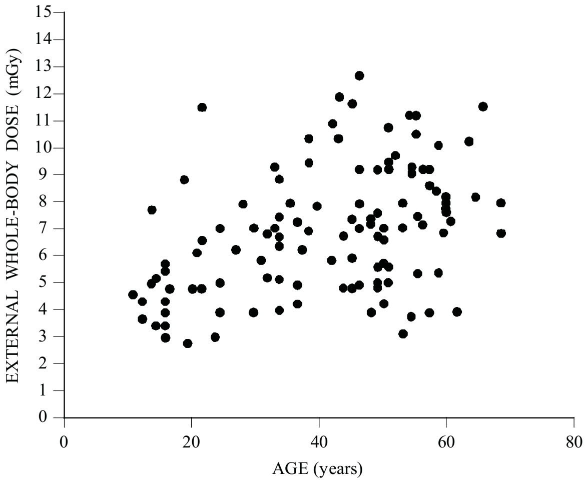


Figure XVII. Variation with age of external whole-body doses among residents of Stary Vyshkov, Russian Federation, in 1987 [S25].

129. The effect of decontamination procedures on external dose was also studied by the analysis of daily external doses calculated from TLD measurements made before and after decontamination of the Belarusian village of Kirov [S25]. Decontamination procedures included replacing road surfaces, replacing roofs on buildings, and soil removal. The results, presented in Table 37, suggest that the decontamination measures were most effective for schoolchildren and field workers (with dose reductions of 35% and 25%, respectively) but had a limited effect on other members of the population [S25]. Similar estimates have been obtained with regard to the decontamination of Russian settlements in 1989 [B38]. The average external dose ratio measured after and before decontamination was found to range from 0.70 to 0.85 for different settlements [B38].

130. The averted collective dose attributable to decontamination procedures was estimated to be about 1,500 man Sv for the first four years after the accident, taking into account the fact that decontamination was only conducted in areas with a ^{137}Cs deposition density greater than 555 kBq m^{-2} and assuming that the doses were reduced by about 20% as a result of the decontamination procedures [A10, I30].

2. Doses from internal exposure

131. The doses from internal exposure came essentially from the intake of ^{131}I and other short-lived radioiodines during the first days or weeks following the accident, and subsequently, from the intake of ^{134}Cs and ^{137}Cs. Other long-lived radionuclides, notably ^{90}Sr and ^{239,240}Pu, have so far contributed relatively little to the internal doses, but they may play a more important role in the future. Following the Chernobyl accident, about 350,000 measurements of ^{131}I in the thyroids of people [G7, L10, S17] and about 1 million measurements of ^{134,137}Cs whole-body contents [B14, D3, L21] were conducted in the three republics by means of gamma radiation detectors placed outside the body. In addition, thousands of analyses of ^{90}Sr and hundreds of analyses of ^{239}Pu were performed on autopsy samples of tissues.

132. The assessment of the internal doses from radioiodines and radiocaesiums is based on the results of the measurements of external gamma radiation performed on the residents of the contaminated areas. Usually, individuals were measured only once, so that only the dose rate at the time of measurement can be readily derived from the measurement. To calculate the dose, the variation with time of the dose rate needs to be assessed. This is done by calculation, taking into account the relative rate of intake of the radionuclides considered, both before and after the measurement, and the metabolism of these radionuclides in the body, which in the case of thyroid doses from radioiodines may have been modified by the intake of stable iodine for prophylactic purposes. The age-dependent values recommended by the ICRP [I36] for the thyroid mass and the biological half-life of ^{131}I in the thyroid were generally used in thyroid dose assessments based on measurements, although there is evidence of mild to moderate iodine deficiency in some of the contaminated areas [A16].

(a) Thyroid doses from radioiodines and tellurium-132

133. The same methodology as described in the preceding paragraph was used in the three countries to reconstruct the thyroid doses of the persons with thyroid measurements [W7]. There were, however, practical differences related to the quantity and quality of the thyroid measurements and the assumptions used to derive the temporal variation of the radioiodine intake. For the individuals who were not measured but who lived in areas where many persons had been measured, the thyroid doses usually are reconstructed on the basis of the statistical distribution of the thyroid doses estimated for the people with measurements, together with the knowledge of the dietary habits of the individuals for whom the doses are reconstructed. Finally, the thyroid doses for people who lived in areas with very few or no direct thyroid measurements within a few weeks after the accident are being reconstructed by means of relationships using available data on ^{131}I or ^{137}Cs deposition, exposure rates, ^{137}Cs whole-body burdens, or concentrations of ^{131}I in milk. The largest contribution to the thyroid dose was from the consumption of fresh cows' milk contaminated with ^{131}I. Short-lived radioiodines (^{132}I and ^{133}I) in general played a minor role for the populations that were not evacuated within a few days after the accident; the contribution of the short-lived radioiodines and of ^{132}Te is estimated to have been up to 20% of the ^{131}I thyroid dose if the radionuclide intake occurred only through inhalation and of the order of 1% if the consumed foodstuffs (milk in particular) were contaminated [K16]. Although many initial estimates of

thyroid doses are available, they need to be refined using all the relevant and scientifically reviewed information that is available [L42, L43]. In order to obtain better information on the pattern of deposition density of ^{131}I, measurements of the ^{129}I concentrations in soil are envisaged [P25, S45].

134. The influence of having taken stable iodine for prophylactic purposes has usually not been taken into account in the determination of thyroid doses. Based on a survey conducted in 1990 of 1,107 persons living in contaminated areas, the number of persons who indicated that they actually took potassium iodide (KI) for prophylactic purposes is about one quarter of the population [M5]. Forty-five percent of those who took KI indicated that they took it only once, 35% more than once, and 19% could not remember details of their KI prophylaxis [M5]. The exact day that administration of KI was begun was poorly recalled by the subjects, making it difficult to use these data for dose reconstruction purposes. In another survey, conducted in the three most contaminated districts of the Gomel region of Belarus, it was found that 68% of the children who consumed fresh cow's milk took KI pills between 2 and 4 May 1986 [S43]. However, in a survey performed in 1992 on about 10,000 individuals from 17 Ukrainian districts of the Chernigov region, only about 1% of the respondents reported that they took stable iodine between 1 May and 20 May 1986 [L25].

135. For several reasons, thyroid dose estimates were made independently of ^{137}Cs measurements and not only in areas where the ^{137}Cs deposition density exceeded 37 kBq m^{-2}: (a) the thyroid measurements were carried out within a few weeks after the accident, that is, in large part before an accurate and detailed pattern of ^{137}Cs deposition density was available; (b) the ^{131}I to ^{137}Cs activity ratio in fallout was markedly variable, especially in Belarus (Figure XVIII); (c) the milk that was consumed within a few weeks after the accident was not necessarily of local origin, at least in urban areas; and (d) there is a large variability of the individual thyroid doses according to age and dietary habits. The thyroid dose estimates reported in the scientific literature are for populations with thyroid measurements, for populations that resided at the time of the accident in ill-defined "contaminated areas", and for the entire populations of the three republics.

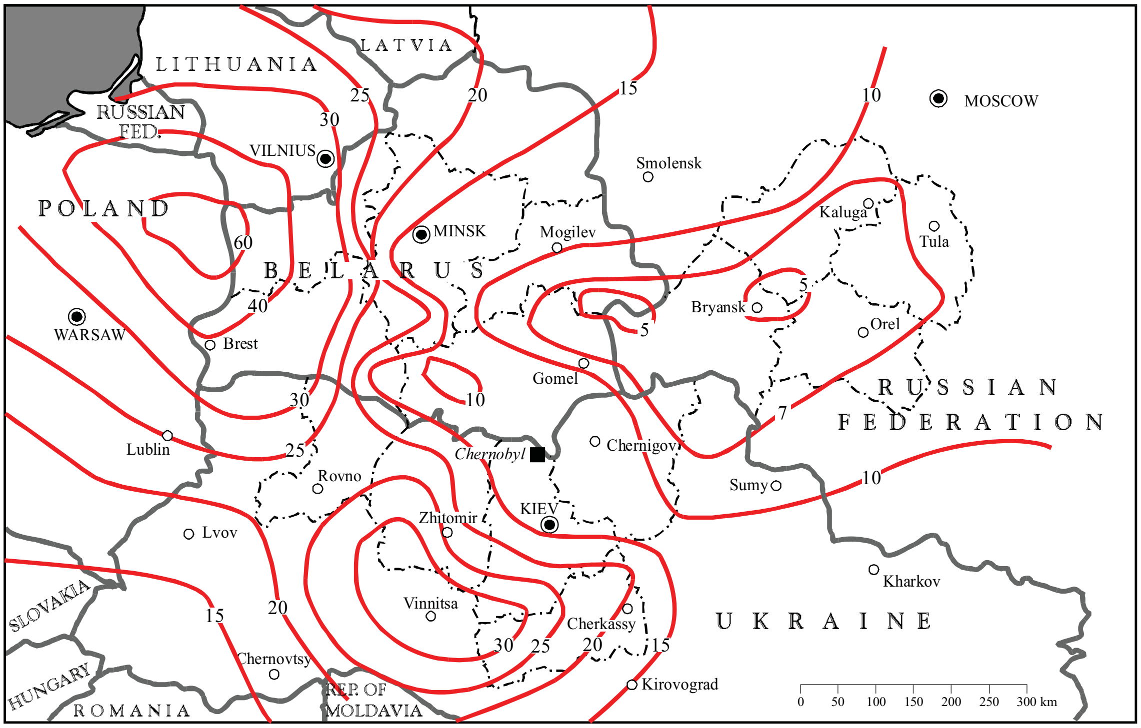


Figure XVIII. Estimated pattern of iodine-131/caesium-137 activity ratio over the European territory of the former USSR resulting from the Chernobyl accident [S30]. *(Values decay corrected to 1 May 1986).*

136. The ratio of ^{131}I to ^{137}Cs deposited by dry processes (i.e. in the absence of precipitation) in Poland was assessed from measurements of air concentrations [K39]. From 28 April to 1 May, the measured time-integrated concentrations of ^{131}I and ^{137}Cs were 187 and 18.2 Bq d m^{-3}, respectively. This ratio of about 10 for the time-integrated concentrations of ^{131}I and ^{137}Cs is consistent with that found in a previous estimation [Z5]. The measured physico-chemical forms of ^{131}I were 62% aerosol-bound, 34% elemental, and 4% organic. Assuming that (a) all of the ^{137}Cs is aerosol-bound, (b) the deposition velocity of elemental iodine is five times greater than that of the aerosol-bound fraction, and (c) the deposition velocity of organic iodine is negligible, the ratio of ^{131}I to ^{137}Cs deposition can be estimated to be 23 [K39]. The measurements of ^{131}I and ^{137}Cs in soil sampled in a few locations in central and southern Poland yield a ratio of 20 (95% CI: 20−40). These values are in agreement with both

the ratio derived from air concentrations and the values shown in Figure XVIII. Measurements of deposition are lacking for the northeastern part of Poland, but the measured concentrations in milk indicate that the ratio of ^{131}I to ^{137}Cs deposition was greater there than in central and southern Poland, again in agreement with Figure XVIII. There are also other reports on the composition of ^{131}I species in the air in different countries. Some of them were presented in the UNSCEAR 1988 Report [U4]. The results indicate that the distribution of the physico-chemical forms changed with time, distance, and weather conditions. Because the transfer of radioiodine from the air to vegetation is highly influenced by its chemical forms, it is important to consider the distribution of iodine species in the assessment.

137. ***Belarus.*** The main contaminated areas of Belarus are located in the Gomel and Mogilev regions. Within a few weeks after the accident, direct thyroid measurements (i.e. measurements of gamma radiation emitted by the thyroid using detectors placed outside the body) were made on approximately 130,000 persons, including 39,500 children, living in the most contaminated areas of Gomel and Mogilev regions, as well as in the city of Minsk [G6]. The content, at the time of measurement, of ^{131}I in the thyroid of these 130,000 persons was derived from the direct thyroid measurements. The thyroid dose estimation was then performed for the measured individuals, supplementing the results of the direct thyroid measurements with standard radio-ecological and metabolic models, for ^{131}I intake with inhalation and with ingestion of fresh milk following a single deposition of fallout on pasture grass [G6, S44]. Unfortunately, most of the thyroid measurements are of poor quality, as they were made by inexperienced people with uncollimated detectors. The uncertainties in the thyroid dose estimates obtained in this manner in Belarus are reported to be characterized by a geometric standard deviation of up to 1.7 [G7]. A detailed breakdown of the thyroid dose distribution for approximately 32,000 children with thyroid measurements is presented in Table 38. In each age category, the thyroid dose estimates are found to lie in a very wide range (from <0.02 Gy to >2 Gy). As shown in Figure XIX, doses to adults also show a large variability, even if the samples are taken from a single village or town [G6].

138. Limited information is available on *in utero* thyroid doses. In a study of 250 children born during the period from May 1986 to February 1987 from mothers who lived at the time of the accident in areas with ^{137}Cs deposition densities greater than 600 kBq m^{-2} in Gomel region (222 mothers), in Mogilev region (14 mothers) and in Pripyat town (14 mothers who were evacuated to Belarus), thyroid doses were estimated to range up to 4.3 Gy, with 135 children exposed to less than 0.3 Gy, 95 children between 0.3 and 1.0 Gy, and 20 children with doses greater than 1.0 Gy [I37]. Uncertainties in the estimated doses were characterized by a geometric standard deviation of 1.7 to 1.8.

139. Average and collective thyroid doses for the rural and urban populations of the contaminated areas of the Gomel and Mogilev regions were derived from an analysis of dose estimates obtained from direct thyroid measurements [I28]. The results, presented in Table 39 for children 0–7 years old and for the total population, show that the thyroid doses are about two times greater in rural areas than in urban areas and also two times greater in Gomel region than in Mogilev region.

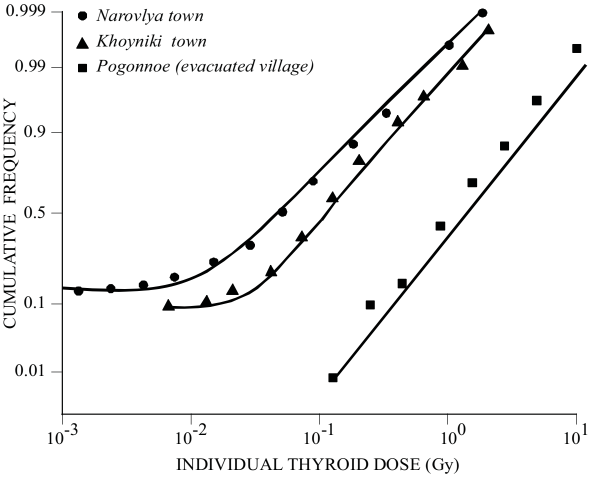


Figure XIX. Cumulative distribution of individual thyroid doses for adults of selected towns and villages of Belarus [G6].

140. Because very few or no thyroid measurements were available for many villages and towns, whereas ^{137}Cs deposition densities were measured in practically all inhabited areas of Belarus, a model was developed to establish a relationship between the ^{137}Cs deposition densities, F(^{137}Cs), and the mean thyroid doses to adults, D_{ad}, in areas where abundant thyroid measurements had been performed. This model enabled the estimation of thyroid dose to be made for the populations of any area in Belarus. In Figure XX, the values of D_{ad} are plotted against those of F(^{137}Cs) for 53 villages of the Khoyniki district. A proportional relationship between the ^{137}Cs deposition density and the mean thyroid dose to adults seems to be inadequate; however, there is a weak tendency shown by the solid line, although characterized by large uncertainties. Similar relationships were observed for all areas of Belarus where abundant thyroid measurements had been performed. That there is no proportional relationship between D_{ad} and F(^{137}Cs) in Belarus is likely to be partly due to the fact that the fraction of ^{131}I intercepted by pasture grass differs according to whether deposition occurs with or without rainfall and varies also as a function of rainfall intensity. The fraction of ^{131}I intercepted by pasture grass is greater when the deposition occurs in the absence of rainfall (usually associated with low levels of deposition) than when deposition occurs with rainfall (generally associated with high levels of deposition). Because of this, the thyroid dose per unit ^{137}Cs deposition density is found to decrease as the ^{137}Cs deposition density increases. A confounding factor is that the ratio of ^{131}I to ^{137}Cs in deposition also varied according to whether deposition occurred in the presence or absence of rainfall. However, similar relationships are observed when the thyroid dose is plotted against either ^{131}I or ^{137}Cs deposition density, suggesting that the variation in the interception coefficient is the dominant factor.

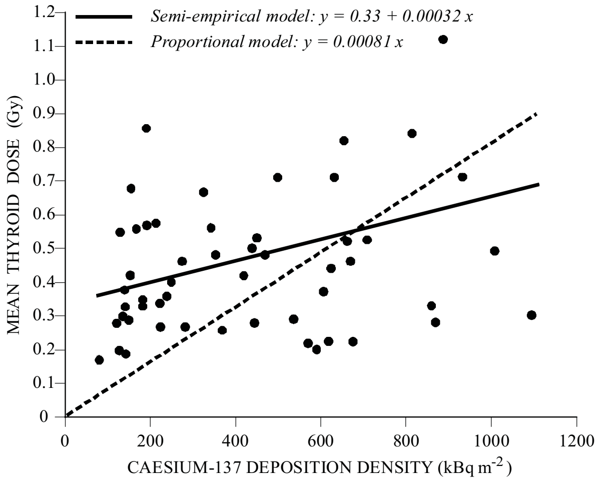


Figure XX. Thyroid dose to adults in relation to caesium-137 deposition density in the district of Khoyniki (Gomel region, Belarus) [G17].

141. Using these relationships for areas with no or few direct thyroid measurements, estimates of collective thyroid dose have been calculated for the entire population of each region of Belarus and for the entire population of the country [G7]. The collective thyroid dose to the entire population of Belarus is roughly estimated to be about 500,000 man Gy (Table 40).

142. ***Russian Federation.*** The main areas of contamination in the Russian Federation are located 150–250 km to the northeast of Chernobyl in the Bryansk region and at a 500 km distance in the Kaluga-Tula-Orel regions. The ratio of ^{131}I to ^{137}Cs varied little in this area, which indicated that the contamination originated from a single plume. The plume arrived 1–2 days after release from the reactor. During this time period, most of the short-lived iodine isotopes had decayed. Rainfall in the area decreased the concentrations in air and reduced the inhalation intake. Therefore, the dose to thyroid was due primarily to ^{131}I intake with milk and leafy vegetables, and the pattern of doses was similar throughout the region.

143. About 45,000 direct thyroid measurements were made in May-July 1986 in the Bryansk, Kaluga, Tula and Orel regions [B39, Z1]. These measurements showed a maximum on 16 and 17 May of up to 300 kBq in the thyroid of some individuals in the villages of Barsuki and Nikolayevka in the Krasnogorsk district of the Bryansk region. The ^{137}Cs deposition at these locations was 2.6–3 MBq m^{-2} [Z1]. In other areas, the content of ^{131}I in the thyroid was considerably less, owing to lower contamination and also to earlier implementation of protective measures, including the ban on consumption of local milk and leafy vegetables and the administration of stable iodine. Activities of ^{131}I in the thyroid were calculated from the results of direct thyroid measurements and were corrected for the contribution of the gamma radiation due to radiocaesium incorporated in the entire body.

144. In the absence of protective measures, the temporal variation of the ^{131}I intake, taking into account inhalation and the ingestion of contaminated milk, is calculated from standard radio-ecological models shown in Figure XXI (left panel). However, for the purposes of dose reconstruction, a simplified representation has been adopted (Figure XXI, right panel) [B14]. The thyroid mass was determined from autopsies in the Novozybkov district hospital in the Bryansk region. The average value for adults was 26.7 g, suggesting a mildly endemic goiter area. The Tula and Orel regions are not in endemic areas, and as direct measurements were unavailable, the standard thyroid mass for adults of 20 g was used in dose calculations [Z1].

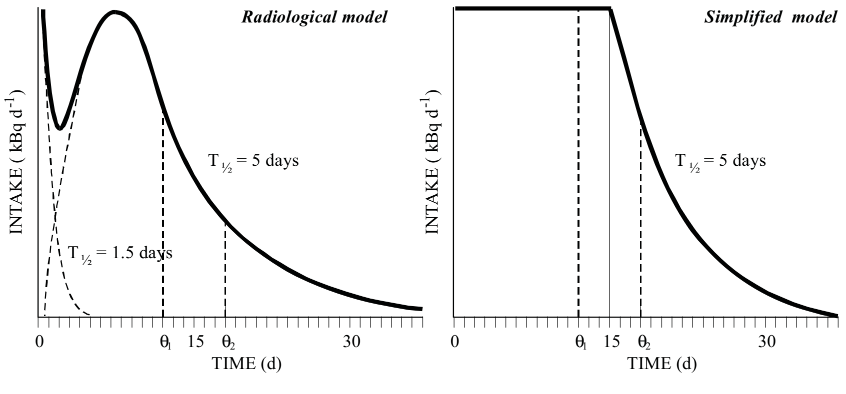


Figure XXI. Models of iodine-131 intake to inhabitants of contaminated areas in Russia [B14].

145. Thyroid doses were estimated in this manner for six age groups: <1, 1–2, 3–5, 7–11, 12–17 and >18 years. Within each age group the distribution of dose was asymmetrical, approximately log-normal. The maximum individual doses often exceeded the mean dose by a factor of 3–5. The variations between age groups were different for towns and villages, reflecting not only the age-related iodine metabolism but also differences in social and nutritional habits. As presented in Table 41, the average thyroid doses for children less than one year old were greater than those for adults by factors of 13 in towns and 5 in villages [B14, Z1].

146. Where measurements were insufficient or lacking, correlations were used to estimate the thyroid doses. The uniformity of contamination allowed correlation analyses to be used to relate the thyroid doses to the deposition of ^{137}Cs, the

air kerma rate on 10–12 May 1986, the concentrations of ^{131}I in milk, and the body content of ^{137}Cs in adults measured within a few months after the accident. The analysis of the results of the direct thyroid measurements for inhabitants of the Kaluga region showed that the thyroid doses of people who did not consume local milk was about 15% of the thyroid doses received by the people who consumed local milk. The type and number of data available in the Russian Federation are presented in Table 42.

147. The analysis of the direct thyroid measurements and of data from personal interviews for 600 inhabitants of the Bryansk region showed a significant correlation with milk consumption. From 80% to 90% of ^{131}I intake appeared to be derived from this source and only 10% to 20% from vegetables and inhalation. Thus, estimates of doses to individuals could be derived by normalizing 80% of the average dose for the settlement by the actual volumes of milk consumed (litres per day times days) relative to the average consumed volume.

148. Estimates of thyroid doses in contaminated areas of the Russian Federation are presented in Table 43. In areas where there were no limitations on ^{131}I intake (e.g. Plavsk district of Tula region), the thyroid dose for children less than 3 years old reached 0.35 to 0.7 Gy, on average, with individual doses up to 4 Gy. In the most contaminated areas of the Orel region, the thyroid doses were approximately 0.3 Gy, on average, for young children. The highest doses were received by inhabitants of the most contaminated areas of the Bryansk region even though local milk consumption was banned in those areas in early May 1986. In some villages average doses in children exceeded 1 Gy and individual doses exceeded 10 Gy. Average thyroid doses of rural inhabitants were higher than those received by urban populations in areas with similar radioactive contamination. The age distribution of the collective dose for the population of the Bryansk region is presented in Table 44. About 40% of the collective thyroid dose in rural areas and 60% of the collective thyroid dose in urban areas were received by children under 15 years of age.

149. ***Ukraine.*** Over 150,000 direct thyroid measurements of the radioiodine content of the thyroid gland were made in May-June 1986 in the areas of Ukraine closest to Chernobyl. Most of the thyroid measurements were made in eight districts surrounding Chernobyl and the town of Pripyat: Polesskoe, Ivanov, Chernobyl and Pripyat in the Kiev region; Kozeletsk, Repkine and Chernigov in the Chernigov region; and Narodichi and Ovruch in the Zhitomir region [L12]. Between 30% and 90% of the children and 1% and 10% of the adults from these areas were measured [L2, L11, L12, R4]. When the quality of these measurements was reviewed, over 80% were found to be of acceptably high quality [L13, L14].

150. Preliminary estimates of the thyroid doses received by the persons with direct thyroid measurements were made using standard methods [A3, I13]. Except for the city of Kiev, where the ^{131}I concentrations in air, water and milk were monitored extensively [L15], very few measurements of ^{131}I in the environment are available from Ukraine. Two models have been used to describe the variation of the temporal intake of ^{131}I. According to the most conservative model, a single intake of ^{131}I was assumed to have occurred on the first day of the accident, and a single exponential is used to describe the iodine retention in the thyroid gland. The more realistic model for calculating thyroid doses assumes that ^{131}I intake occurred during the entire period of stay in the contaminated areas [L12]. The intake function was determined assuming a single initial contamination event by ^{131}I in an area. A two-exponential function is used to represent the dynamics of intake by milk consumption. The effective decay constants from grass and milk are 0.15 and 0.63 d^{-1}, respectively [A3]. The period of intake was taken to be the period until relocation or, if there was no relocation or the information is lacking, the whole period until ^{131}I decay.

151. Results of the thyroid dose evaluations for children and adults of the Ukraine indicate that the highest absorbed doses (1.5–2.7 Gy) were received by children of the Narodichi and Ovruch districts of Zhitomir region and of Pripyat and the Polesskoe districts of Kiev region. Doses to children 7–15 years old were, in general, 2.5 times lower than doses to the 0–7-year-old group. The adult doses were lower by a factor of 2–8 [L2, L12, R4]. According to the conservative, single-exponential model, there were 38,000 children (>40%) with doses lower than 0.3 Gy and 79,500 (nearly 90% of children) with doses lower than 2 Gy. Use of the more realistic model generally shifts the distribution to lower doses. In this case, 63% of children had doses below 0.3 Gy [L12]. The distribution of thyroid doses in a settlement usually was found to be log-normal.

152. The estimation of doses to individuals living in the city of Kiev was performed using direct thyroid measurements for approximately 5,000 residents and measured ^{131}I concentrations in air, water and milk during May-June 1986 [L16, L17]. The individual thyroid doses were found to vary by an enormously wide range of up to four orders of magnitude [L15]. The average thyroid doses to individuals of five age groups were as follows: 0.10 Gy (birth years 1983–1986), 0.06 Gy (1979–1982), 0.2 Gy (1975–1978 and 1971–1974), and 0.04 Gy (those born before 1974) [L15].

153. To estimate the thyroid doses received by the persons without direct thyroid measurements living in areas other than the city of Kiev, two procedures were used, depending on the abundance of the thyroid measurements in the area considered. In the three regions where most of the thyroid measurements were performed (Chernigov, Kiev and Zhitomir), the following empirical relationship between the measured thyroid doses, D, and the ^{137}Cs deposition density, as well as the location relative to the Chernobyl reactor, was determined to be $D(n) = K\,a^t$ [L10, L25], where $t = e^{-bn}$, D is the thyroid dose (Gy), n is the age of the individual (years), and K is a scaling parameter (Gy). The parameters a (dimensionless) and b (a^{-1}) describe the age dependence of the thyroid dose in the locality considered.

154. The parameter values for K, a, and b were established for the towns and villages of each district of the three regions. As examples, Table 45 presents the values obtained for three districts of the Chernigov region as well as the mean thyroid

doses for infants and adults [L25], while the measured individual doses are compared in Figure XXII with the calculated mean thyroid doses for various age groups in Rudka village of the Chernigov district [L25]. As is the case in Belarus and the Russian Federation, the mean thyroid doses in villages are about twice those in urban areas (Table 45). However, the variability of the individual doses, within a given village and a given age group, is very great (Figure XXII).

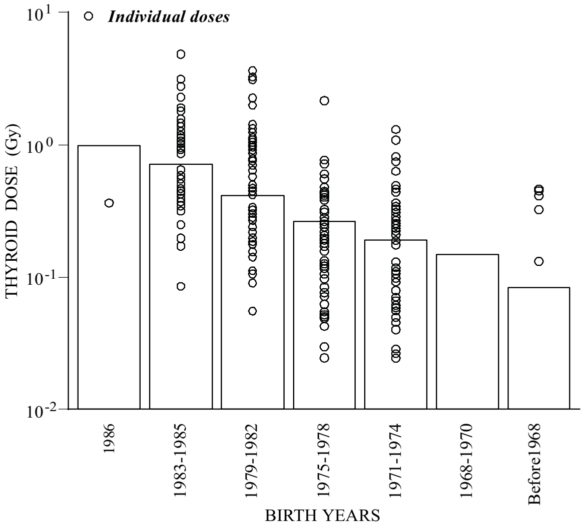


Figure XXII. Comparison of individual doses estimated from thyroid measurements and of calculated mean doses (histogram) for the Ukrainian village of Rudka [L25].

155. Another method of thyroid dose assessment was used for the regions of Cherkasy and Vinnytsia, where very few thyroid measurements were carried out. Those regions were subdivided into sectors and segments with relatively uniform ^{131}I intake functions [L10]. The relationships established for areas with thyroid measurements were then extrapolated to other areas.

156. The age-dependent thyroid dose distribution obtained for the population of the five regions (Cherkasy, Chernigov, Kiev, Vinnytsia and Zhitomir) is given in Table 46. Most of the thyroid doses are estimated to be less than 0.3 Gy. Doses exceeding 2 Gy are found only among children less than 4 years old [L10]. An estimate of the collective thyroid dose to residents of Ukraine is presented in Table 47.

(b) Effective doses from caesium-134 and caesium-137

157. Internal effective doses from ^{134}Cs and ^{137}Cs have been estimated by two methods: (a) estimation of dietary intake from measured concentrations in foods and standard consumption assumptions and (b) whole-body counting. The foodstuffs that contribute the most to the effective dose are milk, meat, potatoes and mushrooms [F4]. From 1986 to 1990, the internal doses were calculated from the measured ^{137}Cs concentrations in milk and potatoes, assuming that the intake of radiocaesium by ingestion is adequately represented by consumption rates of 0.8 l d^{-1} of milk and 0.9 kg d^{-1} of potatoes. The concentrations used to calculate the doses were those corresponding to the 90th percentiles of the distributions [A12]. The relationship between the 90th percentiles to the average ^{137}Cs concentrations in milk and potatoes was 1.7±0.1 [B9]. Beginning in 1991, the average ^{137}Cs concentrations in milk and potatoes, rather than the 90th percentiles, were used to estimate the effective doses from internal irradiation.

158. Calculated internal doses assuming consumption only of locally produced foods (no imported, uncontaminated foods) have been recognized to overestimate actual doses. The dose estimates calculated in this manner are used only for decision-making purposes. The ratios of calculated doses using the 90th percentiles of the distributions to the doses determined by whole-body counting range from 2.5 to 25 for most settlements in the zone of strict control (where the ^{137}Cs deposition density is greater than 555 kBq m^{-2}), with a median value of 7 [B9]. In areas with lower ^{137}Cs deposition density, where most of the consumed foodstuffs are of local origin, this ratio is estimated to be in the range 1.5−15, with a median of 4. For this reason, the internal effective dose estimates provided currently in the official dose catalogues in Belarus and the Russian Federation are based on whole-body measurements. However, the dose estimates presented in the Ukrainian dose catalogues are still based on the assessment of the dietary intakes.

159. The transfer of radiocaesium from soil to milk depends substantially on the type of soil. For example, in Ukrainian territory, as a result of radio-ecological monitoring carried out in 1991, four zones with typical values of soil-milk transfer coefficient for radiocaesium ranging from less than 1 to greater than 10 Bq l^{-1} per kBq m^{-2} were delineated [K23]. The corresponding normalized effective doses from internal irradiation are shown in Table 48 for the first 10 years after the accident; the estimated normalized effective doses for the zone with highest values of the transfer coefficient are about 20 times greater than those obtained in the zone with the lowest values of the transfer coefficient. The territories with peat-swampy soil that are characterized with the highest values of soil-milk transfer coefficient are mainly located in the northern part of the Rovno and Zhitomir regions (Ukraine) and in the eastern part of the Brest region and the southwestern part of the Gomel region (Belarus).

160. In the Russian Federation, normalized doses were estimated for the sodic-podzol sand soil found in some areas of the Bryansk and Kaluga regions and for the chernozem soil found in the Tula and Orel regions [B25, R9]. Here again, the values of the transfer coefficients and of the normalized effective doses vary by factors of 10−20 (Table 49).

161. Estimated internal effective doses, normalized to unit deposition density of ^{137}Cs (1 kBq m^{-2}), are given in Table 50 for various periods after the accident and for areas with different degrees of contamination in the Russian Federation. More detailed information for the population of Belarus is presented in Table 51. It is

recognized that the internal effective doses normalized per unit deposition density of ^{137}Cs have to be treated with caution, because of the large differences in the transfer of ^{137}Cs from soil to milk and because of the influence of protective measures. Estimates of projected doses from internal exposures are highly uncertain, as they depend on local soil conditions for the transfer to foodstuffs, on the composition of the diet, and on the extent to which local foods are supplemented by imported foods [Z4]. In particular, it is to be noted that the importance of forest products (mushrooms, berries, wild game) increases with time, since the ^{137}Cs concentration in these products generally have longer ecological half-times than food products from agricultural systems (milk, vegetables, meat from domestic animals) [K7, S16]. Average internal effective doses received during the first 10 years after the accident are estimated to range from 4 mSv in the rural areas of Tula region in the Russian Federation to 13 mSv in the rural areas of Bryansk region in the Russian Federation. On average, the internal doses received during the first 10 years after the accident represent 90% of the lifetime doses (Table 50). The distributions of the collective effective doses from internal irradiation according to the region of the country, dose interval, and ^{137}Cs deposition density are presented in Tables 34–36 for Belarus, the Russian Federation and Ukraine.

162. Several measures were taken to reduce the internal exposure to the residents of the contaminated areas. During the first year after the accident, the most important measures were taken in the territories of strict control (territories with a ^{137}Cs deposition density exceeding 555 kBq m^{-2}). In Belarus, the resulting factor of decrease in the internal dose was estimated to be 3.2–3.4 [S24], while in the Bryansk region it was about 3.6. In the following years, the corresponding factors of decrease were maintained at approximately the same levels: 4.1 [I30] and 3.7 [I22], respectively. Therefore, the averted collective dose for the strict control zone (inhabited by 273,000 residents) can be assessed to be 6,000 man Sv. For the territories with a ^{137}Cs deposition density from 185 to 555 kBq m^{-2} (inhabited by about 1,300,000 people), the factor of decrease in the internal dose was estimated to be approximately 2 [S24], resulting in an averted dose of 7,000 man Sv. Thus, the averted collective dose for about 1,500,000 residents of the areas contaminated with a ^{137}Cs level exceeding 185 kBq m^{-2} was assessed at nearly 13,000 man Sv. It should be noted that self-imposed measures also led to a decrease in the internal doses [L21].

163. Within the framework of the Chernobyl Sasakawa Health and Medical Cooperation Project, about 120,000 children, aged 0–10 years at the time of the accident, were examined in two Belarusian centres, two Ukrainian centres and one Russian centre [N2, S2, S7]. The examinations were essentially of a medical nature but included a measurement of the whole-body concentration of ^{137}Cs. Average values were similar from centre to centre and from year to year, with an overall average of about 50 Bq kg^{-1} of ^{137}Cs; the corresponding internal effective dose rate from ^{137}Cs is about 0.1 mSv a^{-1}.

164. The Ministry of the Environment, Protection of Nature, and Reactor Safety of Germany also organized a campaign of whole-body counting in Belarus, the Russian Federation and Ukraine. About 300,000 persons were monitored from 1991 to 1993 for their ^{137}Cs whole-body content [H1, H4, H5]. For 90% of the persons monitored, the internal effective dose rates from ^{137}Cs were found to be less than 0.3 mSv a^{-1}. The analysis of the results for Kirov, in Belarus, shows that the population monitored could be classified in one of five groups, according to the nature of their diet and the origin of the consumed milk, with increasing ^{137}Cs content from one group to the next; the dietary characteristics of those groups are defined as (a) no milk, no forest products; (b) local milk, no forest products; (c) non-local milk, forest products; (d) local milk, forest products but no wild game; and (e) local milk and forest products including wild game [S25].

(c) Internal doses from strontium-90

165. Because of the relatively small release of ^{90}Sr and because a large fraction of the ^{90}Sr activity released was deposited within the 30-km zone, internal doses from ^{90}Sr are relatively small. It is estimated that the ^{90}Sr contribution to the effective dose from internal exposure does not exceed 5%–10%, according to intake calculations based on measurements of ^{90}Sr concentrations in foodstuffs, as well as measurements of ^{90}Sr in human bones [B15].

(d) Lung doses from transuranics

166. The fuel particles that deposited on the ground contained alpha-emitting transuranics, such as ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am, as well as beta-emitting transuranics, such as ^{241}Pu. Lung doses from transuranics may be caused by inhalation of radioactive particles during the passage of the cloud and following resuspension of deposited materials. A pathway of concern is the potential hazard from the resuspension from soil to air of radioactive aerosols containing ^{239}Pu. In an assessment of the equivalent doses to lungs for agricultural workers, it was concluded that even at sites inside the 30-km zone, lifetime committed equivalent doses to the lungs per year of work will not exceed 0.2 mSv for most individuals [J1]. In the future, the relative importance of ^{241}Am among the alpha-emitting transuranics is going to increase as a result of the decay of its shorter-lived parent, ^{241}Pu.

D. INHABITANTS OF DISTANT COUNTRIES

167. Information on doses received by populations other than those of Belarus, the Russian Federation and Ukraine is not as complete. In the UNSCEAR 1988 Report [U4], the Committee estimated first-year thyroid and effective doses for most of the countries of the northern hemisphere and lifetime effective doses for three latitude bands (northern, temperate and southern) of the northern hemisphere. These data have been used in this Annex to estimate crude average thyroid and bone-marrow doses received by the populations considered in

epidemiological studies of thyroid cancer and of leukaemia. These populations usually resided in areas where the deposition densities of ^{137}Cs resulting from the Chernobyl accident were the highest (except for contaminated areas of Belarus, the Russian Federation and Ukraine).

1. Thyroid doses

168. Populations of Croatia, Greece, Hungary, Poland and Turkey have been considered in epidemiological studies of thyroid cancer [S12]. The average thyroid doses received by those populations have been estimated, using the approximation that the population-weighted average thyroid dose is three times that to adults. Results are presented in Table 52. The estimates of average thyroid dose range from 1.5 to 15 mGy.

2. Bone-marrow doses

169. Populations of Bulgaria, Finland, Germany, Greece, Hungary, Romania, Sweden and Turkey have been considered in epidemiological studies of leukaemia [S12]. The average bone-marrow doses received by those populations have been estimated from data in the UNSCEAR 1988 Report [U4], using the approximation that the bone-marrow dose is numerically equivalent to the effective dose equivalent from all radionuclides for external irradiation and from radiocaesium for internal irradiation. The values of effective dose equivalents per unit ^{137}Cs deposition density that are calculated in the UNSCEAR 1988 Report for the populations of three latitude bands have been assigned in this Annex to the populations of the countries considered, as appropriate. In each country, the ^{137}Cs deposition density corresponding to the region of highest fallout has been selected, when that information is provided in the UNSCEAR 1988 Report. The resulting estimates of average bone-marrow dose for the populations considered range from about 1 to 4 mGy (Table 52).

E. COLLECTIVE DOSES

170. In this Section, the collective doses received by the populations of the contaminated areas of Belarus, the Russian Federation and Ukraine are summarized.

1. Collective doses from external exposure

171. The collective effective doses from external exposure received by the inhabitants of the contaminated areas during the first 10 years after the accident have been estimated using the average ^{137}Cs deposition densities in each district and estimated average annual effective doses from external exposure in each district. Detailed estimates of the collective effective doses and of their distributions are presented in Tables 34–36 for Belarus, the Russian Federation and Ukraine. The totals for each country are presented in Table 53, while the distribution of the collective effective doses for the three republics is summarized in Table 54. The total collective effective dose received during the first 10 years after the accident by the approximately 5.2 million people living in the contaminated areas of Belarus, the Russian Federation and Ukraine is estimated to be 24,200 man Sv. Assuming that this collective dose represents 60% of the lifetime collective dose, on the basis of the data presented in Table 33, the lifetime collective dose from external irradiation received by the inhabitants of the contaminated areas of the three republics would be 40,300 man Sv.

2. Collective doses from internal exposure

172. ***Collective effective doses.*** The collective effective doses from internal exposure received by the inhabitants of the contaminated areas during the first 10 years after the accident have also been estimated using the average ^{137}Cs deposition densities in each district and estimated average annual effective doses from internal exposure in each district. They are found to be about 5,500 man Sv for Belarus [D3], 5,000 man Sv for the Russian Federation and 7,900 man Sv for Ukraine [L7]. Detailed estimates of the collective effective doses and of their distributions are presented in Tables 34–36 for Belarus, the Russian Federation and Ukraine. Whether those estimates were obtained using similar methodologies has not been thoroughly clarified. From the data presented in Table 50, the doses from internal exposure received during the first 10 years after the accident represent about 90% of the lifetime doses. The collective effective doses from internal exposure received by the population of the contaminated areas can thus be estimated to be about 18,400 man Sv for the first 10 years after the accident and about 20,400 man Sv over lifetime; this corresponds to an average lifetime effective dose of 3.9 mSv.

173. ***Collective thyroid doses.*** Estimated collective thyroid doses, as reported for populations of Belarus, the Russian Federation and Ukraine, are presented in Table 40. Collective thyroid doses are estimated to be about 550,000, 250,000 and 740,000 man Gy for the entire populations of Belarus, the Russian Federation and Ukraine, respectively.

3. Total collective doses

174. Estimated collective effective doses received during the 1986–1995 time period by the inhabitants of the contaminated areas of Belarus, the Russian Federation and Ukraine are presented in Table 53. The collective effective doses that were delivered during the first 10 years after the accident are estimated to be about 24,200 man Sv from external exposure and 18,400 man Sv from internal exposure, for a total of 42,600 man Sv and an average effective dose of 8.2 mSv. Assuming that the doses delivered during the first 10 years represent 60% of the lifetime dose for external exposure and 90% of the lifetime dose for internal exposure, the estimated lifetime effective doses for the populations of the three countries living in contaminated areas are about 40,300 man Sv from external exposure and 20,400 man Sv from internal exposure, for a total of about 60,700 man Sv. This total corresponds to an average lifetime effective dose of 12 mSv.

175. These figures do not include the collective thyroid doses, which were delivered in their totality during 1986, and which are estimated to be 1,500,000 man Gy in total for the three countries. Taking the population size of the three republics to be 215 million, the average thyroid dose is found to be 7 mGy. Much larger thyroid doses, however, were received by a small fraction of the population. For example, the distribution of the thyroid doses received in Ukraine is such that very low thyroid doses were received in a large part of the country, while average thyroid doses greater than 500 mGy were received in twelve districts.

F. SUMMARY

176. Doses have been estimated for: (a) the workers involved in the mitigation of the accident, either during the accident itself (emergency workers) or after the accident (recovery operation workers) and (b) members of the general public who either were evacuated to avert excessive radiation exposures or who still reside in contaminated areas, which are found mainly in Belarus, in the Russian Federation and in Ukraine. A large number of radiation measurements (film badges, TLDs, whole-body counts, thyroid counts, etc.) were made to evaluate the radiation exposures of the population groups that are considered.

177. The highest doses were received by the approximately 600 emergency workers who were on the site of the Chernobyl power plant during the night of the accident. The most important exposures were due to external irradiation, as the intake of radionuclides through inhalation was relatively small in most cases. Acute radiation sickness was confirmed for 134 of those emergency workers. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy. Ninety-three patients received higher doses and had more severe acute radiation sickness: 50 persons with 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 from beta exposures evaluated for eight patients with acute radiation sickness ranged from 10 to 30 times the whole-body doses from external irradiation.

178. About 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators (recovery operation workers), 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, of a town for reactor personnel, and of waste repositories. These tasks were completed by 1990.

179. A registry of recovery operation workers was established in 1986. This registry includes estimates of doses from external irradiation, which was the predominant pathway of exposure for the recovery operation workers. The registry data show 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 is, however, difficult to assess the validity of the results that have been reported for a variety of reasons, including (a) the fact that different dosimeters were used by different organizations without any intercalibration; (b) the high number of recorded doses very close to the dose limit; and (c) the high number of rounded values such as 0.1, 0.2, or 0.5 Sv. Nevertheless, it seems reasonable to assume that the average effective dose from external gamma irradiation to recovery operation workers in the years 1986–1987 was about 0.1 Sv.

180. The doses received by the members of the general public resulted from the radionuclide releases from the damaged reactor, which led to the ground contamination of large areas. The radionuclide releases occurred mainly over a 10-day period, with varying release rates. From the radiological point of view, the releases of ^{131}I and ^{137}Cs, estimated to have been 1,760 and 85 PBq, respectively, are the most important to consider. Iodine-131 was the main contributor to the thyroid doses, received mainly via internal irradiation within a few weeks after the accident, while ^{137}Cs was, and is, the main contributor to the doses to organs and tissues other than the thyroid, from either internal or external irradiation, which will continue to be received, at low dose rates, during several decades.

181. The three main areas of contamination, defined as those with ^{137}Cs deposition density 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. The Central area is within about 100 km of the reactor, predominantly to the west and northwest. The Gomel-Mogilev-Bryansk contamination area is centred 200 km to the north-northeast of the reactor at the boundary of the Gomel and Mogilev regions of Belarus and of the Bryansk region of the Russian Federation. The Kaluga-Tula-Orel area is located in the Russian Federation, about 500 km to the northeast of the reactor. All together, territories from the former Soviet Union with an area of about 150,000 km^2 were contaminated. About five million people reside in those territories.

182. Within a few weeks after the accident, approximately 116,000 persons were evacuated from the most contaminated areas of Ukraine and of Belarus. 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 were evacuated essentially within 48 hours after the accident, the population-weighted average thyroid dose is 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 is estimated to be 0.47 Gy. Doses to organs and tissues other than the thyroid were, on average, much smaller.

183. Thyroid doses have also been estimated for residents of the contaminated areas who were not 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 is estimated to be 7 mGy.

184. Following the first few weeks after the accident when ^{131}I was 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 have resulted essentially from external exposure from ^{134}Cs and ^{137}Cs deposited on the ground and internal exposure due to contamination of foodstuffs by ^{134}Cs and ^{137}Cs. Other, usually minor, contributions to the long-term radiation exposures include the consumption of foodstuffs contaminated with ^{90}Sr and the inhalation of aerosols containing isotopes of plutonium. Both external irradiation and internal irradiation due to ^{134}Cs and ^{137}Cs result in relatively uniform doses in all organs and tissues of the body. The average effective doses from ^{134}Cs and ^{137}Cs that were received during the first 10 years after the accident by the residents of contaminated areas are estimated to be about 10 mSv. The median effective dose was about 4 mSv and only about 10,000 people are estimated to have received effective doses greater than 100 mSv. The lifetime effective doses are expected to be about 40% greater than the doses received during the first 10 years following the accident.

III. EARLY HEALTH EFFECTS IN REACTOR AND EMERGENCY WORKERS

185. The first information on the early manifestations and outcomes of acute radiation sickness 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 [I2]. A detailed and comprehensive review of these effects was included in the UNSCEAR 1988 Report (Appendix to Annex G, “Early effects in man of high doses of radiation”) [U4]. This Chapter describes the health effects observed in this group in the years since the accident. Dose estimations for those working at the Chernobyl nuclear power plant on 26 April, 1986, are given in Section II.A.1.

186. Among the staff members of the reactor and emergency workers at the site at the time of the accident, a total of 237 were initially examined for signs and symptoms of acute radiation sickness, defined here as having at least minimal bone-marrow suppression as indicated by depletion of blood lymphocytes. This diagnosis was later confirmed in 134 patients, the others being designated as unconfirmed. A computerized questionnaire for patients with acute radiation sickness was developed in 1990 [F11] and later extended, incorporating other nuclear accidents [F3]. The fate of the whole group of 237 patients has been monitored up to the present, although not always systematically, with accurate data available for most patients for the acute phase and incomplete information available for the follow-up period of 1986–1996.

187. The definition of acute radiation sickness is well established and based on clinical observations and the degree of pancytopenia [B22, K26]. A reliable assessment of the severity of acute radiation sickness from mild (Grade I) to severe (Grade IV) is possible at three days following exposure. To predict the likelihood of bone marrow recovery, damage to the stem cell pool must be determined [F12]. Seven to ten days after exposure, patients in whom prolonged myelosuppression was diagnosed were selected for bone marrow transplantation.

188. Among 37 patients considered for transplantation treatment, all had severe radiation damage to the skin and, in 15 cases, gastrointestinal tract symptoms. Cutaneous lesions and/or oropharyngeal mucositis were the primary causes of death in the majority of these patients who later died as an immediate consequence of the accident. As might be expected, there was a clear relationship between the extent of local skin radiation injury, the grade of acute radiation sickness and mortality. Patients not selected for bone marrow transplantation received supportive therapy such as transfusions and antibiotics.

189. A total of 13 patients with estimated whole-body doses of 5.6 to 13 Gy received bone marrow transplants at the Institute of Biophysics of the Ministry of Health and Clinical Hospital, Moscow [B40]. Two transplant recipients, who received estimated radiation doses of 5.6 and 8.7 Gy, were alive more than three years after the accident. The others died of various causes, including burns (n = 5), interstitial pneumonitis (n = 3), graft-vs-host disease (n = 2), and acute renal failure and respiratory distress syndrome (n = 1).

190. Stable chromosome aberrations in circulating stem cells, indicating residual damage in the stem and progenitor cells, were used for retrospective dosimetry [K45]. Unstable chromosome aberrations seemed to be a less reliable proxy for average whole-body dose unless evaluated shortly after exposure [T15].

191. The distribution of patients with acute radiation sickness by severity of disease and range of absorbed dose from whole-body gamma radiation is given in Table 11. Among the 134 cases, 28 died within the first four months of the accident. The causes of death are listed in the UNSCEAR 1988 Report, Appendix to Annex G, “Early effects in man of high doses of radiation” [U4]. In the early period (14–23 days after exposure), 15 patients died of skin or intestinal complications and 2 patients died of pneumonitis. In the period 24–48 days after exposure, six deaths from skin or lung injury and two from secondary infections following bone-marrow transplantation

occurred. Between 86 and 96 days following the accident, two patients died from secondary infections and one patient from renal failure [U4]. Underlying bone marrow failure was the main contributor to all of these deaths.

192. There have been eleven deaths between 1987 and 1998 among confirmed acute radiation sickness survivors who received doses of 1.3–5.2 Gy. The causes of death are presented in Table 55. There were three cases of coronary heart disease, two cases of myelodysplastic syndrome, two cases of liver cirrhosis, and one death each of lung gangrene, lung tuberculosis and fat embolism. One patient who had been classified with Grade II acute radiation sickness died in 1998 from acute myeloid leukaemia.

193. At exposures below 6 Gy, the bone-marrow depletion was not the direct cause of death when prompt and adequate treatment of the complications could be provided. The therapy decreased the incidence and severity of infectious complications and haemorrhagic manifestations [G21, S33, W2].

194. Inflammation of the oropharynx (mucositis) was apparent even at relatively low doses (1–2 Gy) of gamma radiation 4–6 days following exposure. An unknown influence of beta radiation could explain these findings. The incidence of mucositis increased and reached 100% in patients receiving gamma doses of 6–13 Gy. The pathogenesis of the oropharyngeal syndrome is complex, as it is determined by the initial radiation damage to the skin and mucosa and further complicated by infections of viral, bacterial and fungal species. Recovery of the mucosal epithelium was observed even in severe acute radiation sickness survivors, which is typical of beta radiation effects [G22, P10]. Acute gastrointestinal symptoms were observed in 15 Chernobyl accident victims and were the most severe symptoms in 11 patients who received doses higher than 10 Gy.

195. Radiation skin burns were observed in 56 patients, including 2 patients with combined radiation-thermal burns. Alopecia, onycholysis, mucositis, conjunctivitis and acute radiation ulcers were seen. There was a clear correlation between extent of skin injury and severity of acute radiation sickness. Skin damage varied from patient to patient in terms of occurrence, severity, course and extent. The clinical course of skin damage was shown to be dependent on the skin exposure conditions, the beta/gamma ratio, and the radionuclide contamination on skin and clothing and in the environment [B29]. Absorbed doses in skin exceeded bone marrow doses by a factor of 10–30 in some victims, corresponding to doses up to 400–500 Gy. From detailed analysis of clinical morphology data, it can be stated that severe skin injury by beta radiation of moderate energy (1–3 MeV) could be a major cause of death if the damaged area exceeds 50% of the body surface. Relatively smaller areas of injury (10%–15% of body surface) from high-energy beta exposure (^{134}Cs, ^{137}Cs, ^{106}Ru, ^{90}Y, ^{90}Sr) with early development of necrosis-ulceration require surgery and can cause long-term disability [B29, G21, N3]. Surgical treatment was provided to fifteen acute radiation sickness survivors with extensive cutaneous radiation injuries, including ulcerations and fibrosis, at University of Ulm between 1990 and 1996. Follow-up of these survivors has not shown a single case of skin cancer.

196. Cataracts, scarring and ulceration are the most important causes of persistent disability in acute radiation sickness survivors. The consequence of severe skin ulceration is cutaneous fibrosis, which has been successfully treated with low-dose interferon [P26]. The recovery of physical ability is related to the severity of the initial symptoms of acute radiation sickness. To limit occupational radiation exposures of the acute radiation sickness survivors, legal measures adopted in the Russian Federation and other countries of the former Soviet Union have restricted their activities or caused them to change their occupations.

197. Sexual function and fertility among acute radiation sickness survivors was investigated up to 1996 [G2]. In the majority of cases, functional sexual disturbances predominated, while fourteen normal children were born to acute radiation sickness survivor families within the first five years after the accident (in one family, the first newborn died from sepsis, but a second, healthy child was born subsequently).

198. Patients with acute radiation sickness Grades III and IV were severely immunosuppressed. Whereas haemopoietic recovery occurs within a matter of weeks or, at most, months, full reconstitution of functional immunity may take at least half a year, and normalization may not occur for years after exposure. This does not necessarily mean that after the acute phase, i.e. the first three months, recovering patients display major immunodeficiency, and it is not surprising that studies of immune status did reveal pattern of changes in the blood cell concentrations without clinical manifestations of immunodeficiency [N3]. Nineteen parameters of the immune system were investigated five and six years after the accident in acute radiation sickness survivors (1–9 Gy) and in persons without acute radiation sickness (0.1–0.5 Gy) as well. For higher doses of radiation, T-cell immunity may show protracted abnormalities; however, these abnormalities are not necessarily associated with clinically manifest immunodeficiency.

IV. REGISTRATION AND HEALTH MONITORING PROGRAMMES

199. In order to mitigate the consequences of the Chernobyl accident, registration followed by continuous monitoring of the exposed populations was one of the priorities set by the Ministry of Health of the former Soviet Union. In the summer of 1986, Chernobyl registries were established for continuous monitoring of the health status of the exposed populations [M7, T12, W1]. Specialized population-based disease registers were created to monitor haematological tumours [I10, W1]. These activities have continued in Belarus, the Russian Federation and Ukraine since the dissolution of the USSR in 1991, with financial and technical support from many countries of the world.

200. Following the first reports of an increased incidence of thyroid cancer in children exposed to the radioactive fallout during the early 1990s [B18, K11, P8], thyroid cancer registries were developed in Belarus, the Russian Federation and Ukraine [D2, R2, T4]. More recently, specialized childhood cancer registries began to be developed in these countries [V7].

201. Considering the potential long-term health consequences of the Chernobyl accident, the existing general population cancer surveillance systems in Belarus, the Russian Federation and Ukraine have attracted particular attention. International researchers started to assess the functioning of these systems as well as their quality and completeness in comparison with the cancer registries in many Western countries and to evaluate their potential for research purposes [S6, W10]. To provide a basis for interpreting the health effects reported from epidemiological studies, this Chapter reviews the available information on registers and their follow-up.

A. REGISTRATION AND MONITORING OF EXPOSED POPULATIONS

1. The Chernobyl registries

202. In May 1986, the Ministry of Health of the USSR convened a conference of Soviet experts on the treatment and follow-up of radiation-exposed individuals [M7]. This conference recommended the establishment of a special registry to assist in the delivery of primary health care, treatment, and follow-up and to provide a basis for the long-term monitoring of the Chernobyl-exposed populations. Governmental orders issued by the Ministry of Health in 1987 provided the basis for creating the All-Union Distributed Clinico-Dosimetric Registry and for appointing the Medical Radiological Research Centre at Obninsk as the institution responsible for the development and maintenance of this registry [T12]. Compulsory registration and continuous monitoring of the health status was introduced for four population groups (primary registration groups): group 1, persons engaged in the recovery operations following the accident (liquidators); group 2, persons evacuated from the most contaminated areas (^{137}Cs deposition >1,480 kBq m^{-2}); group 3, residents of highly contaminated areas (^{137}Cs deposition >555 kBq m^{-2}); and group 4, children born after the accident to those registered in groups 1–3.

203. For the purpose of data collection, registries were established at the national, regional and district levels, as well as in certain ministries that provide health care for their employees independent of the general health care network. Four special data collection forms were introduced [M7, W1]: registration, clinical examination, dosimetry and correction form.

204. Persons were registered in the All-Union Registry upon presentation of their official documents of work or residence in the Chernobyl zone, mainly during the compulsory annual medical examination in the outpatient department of the district hospital responsible for their place of residence (see Section IV.A.2). In return, each person obtained a special registration document enabling him/her to obtain special Chernobyl-related social benefits. At the time of the dissolution of the USSR, the All-Union Registry had accumulated data on 659,292 persons, 43% of whom were recovery operation workers (group 1), 11% of whom were persons evacuated from the most contaminated areas (group 2), and 45% of whom were persons living in contaminated areas (group 3); the remaining 1% were children of groups 1–3 (group 4) [W7].

205. Since 1992, the national Chernobyl registries have continued to operate, but independently, with only basic data items in common. Although the registries continue to employ the general registration techniques and categories developed during the Soviet era, they have evolved separately in terms of the population groups and/or data items that are covered, data quality, dose-reconstruction methodology and follow-up mechanisms [W12]. This must be kept in mind when interpreting and comparing results from the three countries most heavily exposed as a consequence of the accident.

206. Successive publications using Chernobyl registry data sources show ever-increasing numbers of persons registered. Whereas at the beginning, the Chernobyl registry of Belarus contained information on 193,000 persons, 21,100 of whom were reported to have worked as recovery operation workers [W7], at the beginning of 1995 this number had risen to 63,000 [O2]. Similarly, the number of persons registered in the Russian National Medical and Dosimetric Registry as belonging to one of the four primary registration groups has increased steadily over the years (Figure XXIII). The legal statute regulating medical criteria for disability and invalidity has changed over the years, and as a result the number of individuals included in the registries has increased [O4, W7].

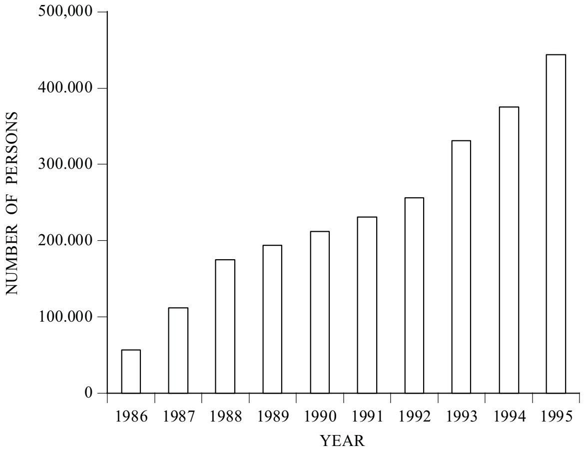


Figure XXIII. Number of persons registered in the Russian National Medical and Dosimetric Registry as exposed to ionizing radiation as a consequence of the Chernobyl accident [I14].

207. All persons included in the Chernobyl registries continue to receive active follow-up. This follow-up was centralized for a number of years in the former Soviet Union. Subsequently it has been performed in the three successor countries. Originally, the Chernobyl registration process was grafted onto an existing infrastructure, but the follow-up of the exposed populations is more specific and concerns all age ranges, including retired persons, who would not normally have received medical follow-up, since this is confined to the working population.

208. Compulsory annual medical examinations are conducted by a general practitioner in the outpatient department of the district hospital at the official place of residence. The information ascertained during these examinations is systematically reported to the Chernobyl registry by means of the specially devised clinical examination form [T12, W1]. In case a more severe health condition is suspected, the patient is referred to specialized health-care institutions for diagnosis and treatment.

2. Specialized registries

209. In addition to the Chernobyl registries, the Russian Federation keeps specialized registries of Chernobyl-exposed populations. Whereas the primary information on persons included in these registries is systematically reported to the Russian National Medical and Dosimetric Registry, the specialized registries generally contain more detailed information on exposure and follow-up.

210. The follow-up mechanisms for the specialized registries follow the same principles as those for the Chernobyl registries. However, medical services and annual medical examinations are provided at special medical facilities of the respective Ministry. The provision and quality of services at these special facilities are generally considered to be better than those offered by the general health-care network [W10]. Follow-up in the special medical facilities ceases with termination of employment (other than retirement), after which the person returns to the general health-care regime.

211. The *Registry of Professional Radiation Workers* is maintained by the Institute of Biophysics in Moscow. It contains information on 22,150 professional radiation workers who participated in recovery work. Approximately 18,600 of them currently live in the Russian Federation, and 13,340 worked in the Chernobyl area in 1986–1987. The radiation doses for these workers were monitored with personal dosimeters. The Registry currently contains doses for approximately 50% of the workers; doses for the remainder are being collected and entered into the database.

212. Medical examinations of persons included in the *Registry of Professional Radiation Workers* are carried out in about 70 medical facilities of the Ministry of Health. The oncology service of the Institute of Biophysics verifies the diagnosis of all cases of cancer and extracts information from case histories. Before 1993, no information was collected on the date of diagnosis or cause of death. Of the 22,150 workers registered at the beginning, only 18,430 are currently being followed [T13].

213. The *Registry of Military Liquidators,* operated by the Military Academy at St. Petersburg, contains information on persons from all over the former USSR who were drafted by the Ministry of Defence to help in the recovery work after the accident. Their doses were mainly determined through time and motion studies. Information on places and dates of work in the Chernobyl area has been recorded in the registers. The medical follow-up of the approximately 15,000 servicemen included in the registry is carried out at local polyclinics and specialized dispensaries of the Ministry of Defence. Another group of approximately 40,000 persons who were sent to work in the Chernobyl area by the Ministry of Defence are followed in the general civilian network of health care.

214. Among the recovery operation workers, there are about 1,250 helicopter pilots and crew. All individuals with doses of more than 250 mGy were hospitalized for careful medical examination as soon as their work was finished. No sign of radiation sickness was found. A list of persons is maintained by the Russian Aviation Medicine Institute [U15]. The Aviation Medicine Institute carries out periodic examinations of helicopter pilots; results have been published on groups of 80 to 200 of them, including military pilots and crew members who flew over Unit 4 of the Chernobyl reactor in April and May 1986 [U15].

B. REGISTRATION OF MORTALITY AND DISEASE IN THE GENERAL POPULATION

1. Mortality

215. Mortality statistics are one of the main measures of health outcome used in epidemiological studies. In the countries of the former USSR, and throughout the world, registration of death is the responsibility of vital statistics

departments. For each death, a medical death certificate (medical document) is completed by the attending physician or by a medically trained person. The death is then registered at the district vital registration department by completing a death registration act (legal document), which provides authorization for burial. The medical death certificate in use in the countries of the former USSR has followed international recommendations since the 1980s [W10]. The quality of the death certificates depends on the competency of the person completing them, and the validity of the death certificates has probably changed over time.

216. A copy of the death registration act is forwarded to the regional vital registration department, which is in charge of the coding and the preparation of annual regional mortality statistics. The cause of death is coded using a slightly modified version of the Ninth Revision of the International Classification of Diseases B-List [S6]. Regional mortality statistics are submitted to the national statistical authority for the compilation of annual national mortality statistics.

217. As part of a general policy of censorship of demographic and health statistics, the use of mortality statistics for research purposes was severely restricted during the Soviet era [R1]. The main use of the mortality statistics was health planning. Since the dissolution of the Soviet Union into independent countries, however, such data have been readily available.

2. Cancer incidence

218. Cancer diagnosis and treatment were the responsibility of oncological dispensaries throughout the Soviet Union. Cancer patients were followed by the district hospital at the official place of residence. Certain malignant neoplasms, such as haematological neoplasms, childhood cancers, and certain rare tumours, e.g. brain and eye, are diagnosed and treated outside the network of oncological dispensaries [W10].

219. Based on the existing oncological infrastructure, cancer registration was made compulsory in 1953 throughout the USSR [N6]. The cancer registration process, which still applies today in the successor countries, involves the passive reporting of newly diagnosed cancer cases and information on their follow-up to regional cancer registries at the regional oncological dispensaries in the patient’s place of residence [W10].

220. The patient cards maintained at the regional cancer registries are continuously updated with the information received from the cancer registration documents. After a cancer patient dies, the card is removed from the active cancer registry for storage in archives. Information on cancer deaths is gathered at regular intervals from the vital registration departments, and trace-back procedures are initiated for persons not registered during their lifetimes.

221. Annual cancer statistics are compiled at both the regional and national levels. Two basic reports are compiled manually each year. The cancer incidence report provides the number of cases according to sex, age group and cancer site, and the cancer patient report provides basic information on prevalence as well as on the diagnosis, treatment and survival of the patient. Death certificates and autopsy reports as information sources have been used since 1961, but the registration of leukaemia became compulsory only in 1965 [R1]. Thus, cancer statistics that meet the Western definition of cancer registries have existed only since 1966 in the countries of the former Soviet Union [W10].

3. Specialized cancer registries

222. Haematological cancer registries were set up in Belarus, the Russian Federation and Ukraine shortly after the accident, but thyroid cancer registries only started to appear during the early 1990s, after first reports of an increase in thyroid cancer following the Chernobyl accident. Specialized childhood cancer registries were set up only recently because the quality of the general registration was questionable [V7].

223. These specialized cancer registries are for cancers that are mainly diagnosed outside the network of regional oncological dispensaries. The registration of these cancers in the national cancer registries is likely to be less complete than for cancers directly diagnosed and registered in the oncological dispensaries. An important difference between the national cancer registries and the specialized cancer registries is that case ascertainment is passive in the former and active in the latter. Active reporting systems generally achieve a higher degree of completeness, as cancer registry personnel directly and systematically abstract the information from the source. Furthermore, specialized cancer registries generally record more detailed information on the clinical features of the tumour than do general cancer registries.

(a) Haematological cancer registries

224. In Belarus, the *National Register of Blood Diseases* is operated by the Institute of Haematology and Blood Transfusion in Minsk. Although activities only started in 1987, data since 1979 have been collected retrospectively. The registry covers the entire population of Belarus and receives details of cases of leukaemia, lymphoma and related blood diseases from haematological departments and oncological dispensaries and from autopsies. Information in this registry has, however, only recently been computerized.

225. The *Registry of Leukaemia and Lymphomas* in the Bryansk region (Russian Federation) records all relevant cases in all ages in this region, including a retrospective assessment since 1979. Before 1986, however, the registry is reported to be incomplete [W1].

226. Little is known about the *Ukrainian Registry of Haemoblastosis* (term used in the Russian language) that covers leukaemia, lymphomas and related non-malignant diseases, such as polycythaemia vera, aplastic anaemia and sideroblastic anaemia. The registry is operated by the Ukrainian Centre for Radiation Medicine and is designed to record all cases of haemoblastosis in the Ukrainian resident population [W1].

(b) Thyroid cancer registries

227. In Belarus, the *Thyroid Surgery Registry* is operated by the Scientific and Practical Centre for Thyroid Tumors at the Institute of Medical Radiology and Endocrinology, Minsk [D2, P2]. This registry includes only patients with thyroid disorders treated at the Centre. A comparison between the registry data and data obtained from pathologists indicated that it is incomplete for thyroid cancers diagnosed during adolescence and adulthood, as these are mostly diagnosed and treated at the regional level [C6]. The number of thyroid cancer cases reported from Belarus in different scientific publications varies according to the age range considered and depends on whether case series were abstracted from the *Thyroid Surgery Registry* only [P2], whether they were complemented by incidence data [B11], or whether only cases known to the national cancer registry were used [K40].

228. In the Russian Federation, the *Thyroid Cancer Registry* has been created for the Bryansk and Tula regions; it includes data on all cases of thyroid cancer since 1981 [R2]. In Ukraine, a clinical morphological register of thyroid cancers has been created at the Institute of Endocrinology and Metabolism in Kiev [T4]. This registry includes data on all thyroid cancer cases in which the patients were under the age of 18 years at the time of the Chernobyl accident, as well as retrospective data since 1986. Information is gathered from two sources: (a) data on all cases treated at the surgery department of the Institute of Endocrinology and (b) data on thyroid cancer cases from the national cancer registry, diagnosed throughout Ukraine. In 1986–1994, one third of the total of 531 cases recorded was identified from surgical records. Data quality and the amount of detail available in this registry is likely to vary, depending on the data sources. Also, thyroid cancer cases occurring in the Chernobyl-contaminated areas are more likely to undergo surgery in Kiev than cases occurring in other areas.

(c) Childhood cancer registries

229. Publications on childhood thyroid cancer or haematological malignancies generally are based on data from the corresponding specialized cancer registries [D2, I10, I31, T4] or, in the case of childhood thyroid cancers, from population screening programmes [I26, T5]. A new specialized registry, the *Belarusian Childhood Cancer Registry*, was created at the Institute of Oncology and Medical Radiology in 1996. Data are reported from centres diagnosing and treating children. Similarly, childhood cancer registries are also being created for the Bryansk and Tula regions of the Russian Federation [R2].

(d) Registers of hereditary disorders and congenital malformation

230. A national monitoring system for hereditary diseases exists in Belarus at the Institute for Hereditary and Congenital Diseases [L8]. Reporting is compulsory since 1979 for anencephaly, spina bifida, cleft lip and palate, polydactyly, limb reduction defects, oesophageal and anorectal atresia and Down's syndrome. In addition, reporting of multiple congenital malformations became compulsory in 1983. Morphogenesis defects in embryos and early fetuses have been recorded since 1980.

231. The comparability of registries of congenital malformations with similar registries from countries outside the former Soviet Union is generally considered to be poor owing to the great variation in definitions of the included parameters. Differences are found in defining the geographical location (e.g. place of residence of the mother or place of birth of the child), in the definition and coding of the diagnosis, and in coverage (live births, stillbirths, induced abortions, fetal deaths, spontaneous abortions) [L8, L20]. There has been no independent assessment of the quality and completeness of this registry, in particular for the period before the Chernobyl accident.

C. QUALITY AND COMPLETENESS OF REGISTRATION

1. Registers of exposed populations

232. The ever-increasing number of persons registered in the Chernobyl registries raises the crucial question of whether and when the registration of the exposed population groups can ever be reasonably complete. The legal statute regulating medical criteria for disability and invalidity in citizens of the Russian Federation was promulgated in 1991. According to this law, the causal association between the Chernobyl accident and disease, death, or invalidity can be established independently of the absorbed dose received or the health status of the person before the accident. As a result of this law, the number of individuals included in the register has increased over the past years [O4, W7]. Some registration increases occur as the people exposed as a result of the accident grow older, become ill, and seek registration to obtain social benefits. Any difference between the health status of exposed persons registered in recent years in the Chernobyl registries and that of exposed persons registered in earlier years could introduce bias into epidemiological studies using these data. However, preliminary analysis in Belarus and the Russian Federation appears to indicate that the health status distribution of the newly registered workers is similar to that of the workers registered previously [P18].

233. To obtain a more reliable and complete enumeration of a cohort of Chernobyl recovery workers for epidemiological purposes, Estonian researchers used four independent data sources:

(a) records of military personnel, both regular personnel and reservists, who were sent to the Chernobyl area;
(b) The Estonian Chernobyl Radiation Registry;
(c) members of the Estonian Chernobyl Committee, a non-governmental organization that aims to obtain compensation and health-care benefits for the recovery workers;

(d) files from the Ministry of Social Welfare of Estonia, which had conducted an independent registration of recovery operation workers for social benefits.

By using multiple data sources, the information on 83% of the 4,833 Estonian men who worked in the Chernobyl area could be ascertained from two or more sources [T6].

234. It remains unclear to what extent a verified diagnosis in the more specialized institutions is actually reported to the Chernobyl registries. One study indicated that almost half of the leukaemia diagnoses in the Russian Federation Chernobyl registry were not confirmed [O1]. By contrast, in Belarus, where a national registry of haematological malignancies was created following the Chernobyl accident, this information has been periodically reported to the Chernobyl registry in recent years.

235. Caution should be observed when comparing the mortality experience in the Chernobyl registry populations with national background mortality rates. The Chernobyl registries obtain mortality information from next-of-kin whenever the person under observation does not present himself/herself for the annual medical examination and/or from official death certificates, which are screened for information. The Chernobyl registry does not use the coding rules implemented by the official demographic authorities but often uses the existing medical information to code the appropriate cause of death in the Chernobyl registry. As a result, the mortality information available in the Chernobyl registries is often more specific and has a higher degree of completeness than official demographic sources.

236. Understanding the registration processes, coding and quality changes over time is essential for researchers to appropriately conduct and interpret epidemiological studies using Chernobyl related data. More research is needed to document the methods of data collection and the quality of data collected in the framework of the Chernobyl registries.

2. Registers of the general population

237. ***Mortality.*** Very little information exists on the quality of mortality statistics from countries of the former Soviet Union. During the late 1970s, a study was conducted to compare the quality of cause-of-death coding in seven countries, including the USSR [P22]. The results showed that for a standard set of 1,246 causes of death related to cancer there were no differences in the quality of coding in the USSR and in the other participating countries. However, for this particular study, an expert pathologist performed the coding in the USSR, whereas in the rest of the countries a vital statistics official did the coding. A study is currently under way comparing the coding for the same 1,246 cause-of-death series as performed by the actual coders of a number of regional vital registration departments in Belarus, the Russian Federation and Ukraine.

238. Mortality rates in the three countries declined in 1984–1987, increased in 1987–1994 [L38], and were more stable in recent years [L37]. International comparisons of mortality statistics show higher rates for deaths from cardiovascular disease and violence in the Russian Federation. [M8]. Although differences in data quality cannot be excluded entirely, recent evidence suggests that increased alcohol consumption may account for a substantial portion of the difference in mortality patterns between the countries of the former Soviet Union and Western countries [L37, L38, W11].

239. Mortality data are used in epidemiological studies as endpoints for individual follow-up of exposed populations or in aggregated form as mortality rates in geographically defined populations. Although changes in mortality patterns in the countries of the former Soviet Union are not related to radiation exposure, they must be taken into account when interpreting epidemiological studies using these data. In these countries, individual mortality data are available only on paper at the district level. The absence of centralized, computerized mortality registries poses considerable difficulty, particularly in tracing subjects who have moved from one area to another [O1].

240. ***Cancer incidence.*** A survey of cancer registration techniques in the countries of the former Soviet Union [W10] showed a number of important differences compared to Western countries. First, cancer registries in Western countries were created for research purposes, whereas in the Soviet Union they were created for health-planning purposes. The system in operation in the countries of the former Soviet Union functions as a public health surveillance system with fast reporting of statistics (three months after the end of a reporting year). The impact of the fast reporting on the quality of the information is unknown. Second, many data items are coded independently of the internationally recommended and accepted classification schemes. This is particularly relevant for one of the most important data items in cancer registration: tumour pathology. This may have important implications for the quality of the data recorded. Third, standard concepts for verifying the quality and completeness of registries, widely used for Western cancer registries, are virtually unknown in the countries of the former Soviet Union. Finally, personal identification is based on names. Differences in spelling, the increasing use of national languages rather than the Russian language, and the increasing mobility of the population raise questions about the correctness of the identifications. Whereas probabilistic record-linkage procedures are used for this purpose in Western cancer registries, these procedures remain unknown in the countries of the former Soviet Union.

241. Of the countries most contaminated by the Chernobyl accident, only Belarus had a centralized cancer registry in operation before the accident. In the 1990s, the Russian Federation and Ukraine began developing computerized cancer registration software and regional registration networks, and Belarus worked to modernize the system in operation there. This work of gradually adjusting the cancer registration techniques in these countries to satisfy international standards is being conducted within a framework of international collaboration to ensure adequate training [S6].

242. A computerized central cancer registry was established in Belarus as early as 1973, and computerized cancer incidence data have been available since 1978 [O4]. However, owing to the lack of resources, the data were computerized anonymously during the early years of operation. In 1985 personal-computer-based cancer registration was developed, including appropriate information on the individuals. Since 1991 a computerized network has provided the basis for cancer registration in Belarus.

243. Efforts to computerize cancer registration in Ukraine started at the beginning of the 1990s [W10]. By the end of 1997, computerized cancer registration had been implemented in many regions. Approximately 82% of the population of Ukraine was covered at that time, and nationwide coverage is expected by the year 2000. In recent years, the Russian Federation has also started to develop a computerized cancer registration system [W10]. Full coverage of the population of the Russian Federation with computerized cancer registration technology has to be seen as a long-term goal. In any case, priority will be given to computerizing the Chernobyl-contaminated regions and a number of control regions.

244. Probably the main source of international cancer incidence statistics is the series Cancer Incidence in Five Continents, published by the International Agency for Research on Cancer (IARC) at five-year intervals since the late 1960s. Although cancer registries all over the world are invited to contribute data, only data sets satisfying the defined quality standards are accepted for publication. No data from the USSR were included in any of the early volumes, although a supplement to Volume III, “Cancer incidence in the USSR”, was published jointly by IARC and the USSR Ministry of Health in 1983 [N6]. The two most recent volumes, presenting data for 1983–1987 and 1988–1992, include data from Belarus, Estonia and Latvia, and data from St. Petersburg and Kyrgyzstan were published in the earlier of the two volumes. However, the editors warned that all data from the countries of the former Soviet Union (except data from Estonia) may under-ascertain the number of cases, may lack validity, or may be inaccurate with respect to the denominators of the rates [P17, P23].

D. INTERNATIONAL COLLABORATIVE SCREENING PROJECTS

245. For more than three years after the Chernobyl accident, efforts to mitigate its consequences were considered by the Soviet Union to be exclusively an internal matter. International collaborations started to develop in 1990 and have since played a substantial role in the assessment of the health consequences of the Chernobyl accident.

246. Soviet health authorities initiated screening activities in June 1986 throughout the areas most affected by the accident. Initially, these activities were locally organized; large-scale screening was not started until the early 1990s. A description of the organization, completeness, and results of these efforts has not yet been published.

1. The International Chernobyl Project

247. In 1990–1991, IAEA organized the International Chernobyl Project [I1] at the request of the Government of the USSR. International experts were asked to assess the concept the USSR had developed that would enable the population to live safely in areas affected by radioactive contamination following the Chernobyl accident; they were also asked to evaluate the effectiveness of the steps taken in these areas to safeguard the health of the population. The International Chernobyl Project investigated the general health of the population of seven rural settlements in Belarus, the Russian Federation and Ukraine and of six control settlements using an age-matched study design [M10]. Psychological health, cardiovascular, thyroid and haematological disorders, cancer, radiation-induced cataracts and fetal anomalies were also investigated, and cytogenetic studies were carried out.

2. The IPHECA project

248. In 1992–1995, WHO conducted an International Programme on the Health Effects of the Chernobyl Accident (IPHECA). A number of pilot projects surveying registration activities, radiation- dose reconstruction, haematological disorders, thyroid disorders, brain damage, and oral health were carried out. The IPHECA Dosimetry Project reconstructed radiation doses from measurement surveys of the populations of contaminated and evacuated areas [W1, W13].

3. The Chernobyl Sasakawa Health and Medical Cooperation Project

249. Between 1991 and 1996, the Sasakawa Memorial Health Foundation sponsored the largest international programme of screening of children following the Chernobyl accident. The project aimed at assessing the anxiety and health effects in the people affected by the Chernobyl accident through large-scale population screening. Children were selected as the target population for the screening. Regional diagnostic centres were set up in Gomel and Mogilev in Belarus, in Klincy (Bryansk region) in the Russian Federation, and in Kiev and Korosten (Zhitomir region) in Ukraine to screen children by means of mobile examination units [S38].

250. Standard examination protocols and questionnaires focussing on thyroid disorders, haematological disturbances and radiation dose were used. The examination included collection of disease history and anthropometric data, dosimetric measurements using whole-body counters, ultrasonography of the thyroid, general blood count, determination of thyroid hormones in the serum, determination of iodine and creatinine in the urine, and examination by a paediatrician. When abnormalities were found, the child was referred to the regional diagnostic

centre for comprehensive examination and appropriate treatment. During the course of the project (May 1991-April 1996), approximately 120,000 children were examined. The results are given in Chapter V [H2, I16, I21, I26, S7, Y1].

251. International collaborative efforts are continuing, and several studies of the effects of the accident are underway. An example is a project to establish a tissue bank of thyroid carcinomas from all of the three most affected countries, which has as participating organizations the European Union, National Cancer Institute of the United States, the Sasakawa Memorial Health Foundation, the World Health Organization, and the health ministries of Belarus, the Russian Federation and Ukraine..

E. SUMMARY

252. Following the Chernobyl accident, compulsory registration and continuous health monitoring of recovery operation workers and residents of the most contaminated areas, including their offspring, were initiated throughout the Soviet Union. Until the end of 1991, the All-Union Distributed Clinico-Dosimetric Registry recorded information on 659,292 persons. After the dissolution of the Soviet Union into independent states, national Chernobyl registries have continued to operate, but independently. Changes in national registration criteria, compensation laws, dose-reconstruction methods, and follow-up mechanisms increasingly limit the comparability of data from the different national sources. More detailed registries of exposed populations exist in the Russian Federation (Registry of Professional Radiation Workers, Registry of Military Workers and the cohort of Helicopter Pilots and Crew). The quality and completeness of these registries remain largely unknown, however.

253. The number of people registered in the national Chernobyl registries continues to increase, even in recent years, which raises questions about the completeness and accuracy of registration. Information on mortality and cancer incidence is collected from many different sources and is coded independently of international guidelines. Evidence from recent cohort studies suggests that the Chernobyl health outcome data cannot be successfully compared with health data obtained from official statistical sources.

254. Systematic linkage of the Chernobyl registry population data with existing mortality and/or cancer incidence registries and the subsequent comparison of the health outcome experience in the cohort with the corresponding national reference statistics could be a valuable tool for epidemiological research. Internal comparisons, e.g. using a low-dose comparison group, are likely to provide information on risks associated with ionizing radiation in the future. However, complete information on, e.g. previous exposure to ionizing radiation in an occupational setting, will most probably only be available for small sub-cohorts.

255. Health outcome registries are an important source of information for assessing the consequences of the Chernobyl accident. Their primary advantage is that the information was collected in a systematic way before and after the accident and that the criteria for data collection are the same in all countries of the former Soviet Union. However, most of these registries, whether related to mortality, cancer incidence, or special diseases, continue to be largely operated manually, which seriously limits their use for epidemiological research purposes. The Chernobyl accident led to major international efforts to computerize cancer incidence and special disease registries and to improve their registration methods so as to comply with international standards. However, mortality registration systems have received little attention so far. Information on the quality and completeness of these systems remains scarce.

256. Compulsory cancer registration was introduced throughout the former Soviet Union in 1953. The system relies 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, there have been efforts to computerize the existing systems and to gradually improve their quality to satisfy international standards. Belarus has been covered with a network of computerized cancer registries since 1991. Computerization is well advanced in Ukraine, and full population coverage is expected soon. In the Russian Federation, efforts to develop computerized cancer registration started only recently and will be concentrated in contaminated areas and control areas.

257. Specialized population-based registries for haematological malignancies and thyroid cancer were set up in the wake of the Chernobyl accident and in response to the unknown quality and lack of detail for these sites in the general registries. Childhood cancer registries were recently developed for the same reasons. Quality assessments of these registries are underway. Other registries for hereditary disorders and malformations exist, but their quality and completeness have not so far been independently assessed.

258. Shortly after the Chernobyl accident, efforts were devoted mainly to developing adequate registration systems for future follow-up of those population groups most affected by the radionuclide deposition. More recently, international collaborations have helped to modernize the existing disease registration infrastructure. However, information on the quality and completeness of all these registries is still very scarce. The usefulness of the vast amount of data collected will become clearer in the coming decades as the long-term consequences of the accident are studied. In particular, matching the health outcomes with the dosimetric data described in Chapter II, will be of great importance.

V. LATE HEALTH EFFECTS OF THE CHERNOBYL ACCIDENT

259. The studies of late health consequences of the Chernobyl accident have focussed on, but not been restricted to, thyroid cancer in children and leukaemia and other cancer in recovery operation workers and residents of contaminated areas. Many studies have been descriptive in nature, but until individual dosimetry is completed, proper controls established, and methodological requirements satisfied, the results will be difficult to interpret. Quantitative estimates and projections will certainly be very unreliable without individual and reliable dose estimates.

260. The late health effects of the Chernobyl accident are described in this Chapter. These effects include malignancies, especially thyroid cancer and leukemia, non-malignant somatic disorders, pregnancy outcome and psychological effects. The focus will be on health effects in the most contaminated areas, but possible effects in other parts of the world will also be considered.

A. CANCER

1. Thyroid cancer

(a) Epidemiological aspects

261. Thyroid carcinomas are heterogeneous in terms of histology, clinical presentation, treatment response and prognosis. Although rare, they are nevertheless one of the most common cancers in children and adolescents. Thyroid cancer is known to be more aggressive in children than in adults, but paradoxically, the prognosis is supposed to be better in children [V8]. Several risk factors have been suggested for thyroid cancer, but only ionizing radiation has been found to have a causative effect, although a history of benign nodules, miscarriages, iodine deficiency or excess, and an elevated level of thyroid-stimulating hormones have been discussed as causative factors [F9, R18]. Risk factors for thyroid cancer are discussed in Annex I, "*Epidemiological evaluation of radiation-induced cancer*".

262. The childhood thyroid gland is, besides red bone marrow, premenopausal female breast, and lung, one of the most radiosensitive organs in the body [U2]. Age at exposure is the strongest modifier of risk; a decreasing risk with increasing age has been found in several studies [R7, T20]. Among survivors of the atomic bombings, the most pronounced risk of thyroid cancer was found among those exposed before the age of 10 years, and the highest risk was seen 15–29 years after exposure and was still increased 40 years after exposure [T20]. The carcinogenic effect of ^{131}I is less understood, and the effects of radioiodine in children have never been studied to any extent, since medical examinations or treatments rarely include children [H6]. Similar to the studies of atomic bomb survivors, there is little evidence of an increasing risk for exposures occurring after age 20 years [H6, T20].

263. As seen in Tables 56–58 an increasing number of thyroid cancers among children and adolescents living in areas most contaminated by the accident have been diagnosed in the last 12 years. Among those less than 18 years of age at exposure, 1,791 thyroid cancers were diagnosed during 1990–1998 (complete information is not available for the Russian Federation). The increase in all three countries for 1990–1998 was approximately fourfold, with the highest increase seen in the Russian Federation. The increase in absolute numbers seems to have leveled off, particularly for the older age-at-exposure cohorts. It should be emphasized that the source population in Belarus is approximately 1.3 million, in the Russian Federation 300,000 (only one region) and in Ukraine 9 million children.

264. As previously discussed in this Annex, there are considerable uncertainties in the estimates of individual thyroid doses to the population in the contaminated areas. More than 80% of the dose from internal exposure was estimated to be from ^{131}I [Z1]; external exposure contributed only a small proportion of the thyroid dose [M4] (see Section II.C.2.a).

265. Two recent studies [F13, R17] found an elevated risk of thyroid cancer mortality following adult ^{131}I treatment for hyperthyroidism, which is in contrast to previous studies of hyperthyroid patients [H14] or patients examined with ^{131}I [H6]. The reason for referral, i.e. the underlying thyroid disorder, could have influenced the risk, since the highest risk was seen less than five years after exposure. The thyroid dose (60–100 Gy) received by most hyperthyroid patients had previously been considered as having a cell-killing rather than a carcinogenic effect.

266. In a recent paper by Gilbert et al. [G23], thyroid cancer rates in the United States were related to ^{131}I doses from the Nevada atmospheric nuclear weapons tests. The analysis involved 4,602 thyroid cancer deaths and 12,657 incident cases of thyroid cancer. An elevated risk was found for those exposed before the age of one year and born during the 1950s, but no association with radiation exposure was seen in older children in the age range 1–15 years. It could be that migration complicated the dose assessment and case identification. The authors concluded that the increase was most likely due to the ^{131}I exposure, but the geographical correlation approach, i.e. lack of individual doses and information on residency, precluded them from making quantitative estimates of risk related to exposure. Further, ^{131}I exposures from nuclear weapon tests in other countries were not taken into account, nor were other releases such as those that occurred from the Hanford site [R22].

267. Between 1944 and 1957, the Hanford site in the United States released large quantities of ^{131}I into the atmosphere during fuel processing. In the Hanford Thyroid Disease Study, thyroid doses were estimated for 3,193 individuals, and the mean thyroid dose was 186 mGy [R22]. Initial results of the study indicated that a diagnosis of thyroid cancer could be made for 19 participants, but no dose-response relationship was apparent. The final report is yet to be published.

268. Prisyazhiuk [P8] described in 1991 three cases of childhood thyroid cancer in Ukraine that were diagnosed in 1990, in contrast to no diagnosed cases during the preceding eight years. A screening effect was discussed, and it was postulated that “these thyroid cancers might represent the beginning of an epidemic”. In the following year, Kazakov et al. [K11] reported 131 cases of childhood thyroid cancer in Belarus. The geographical distribution suggested a relationship with the ionizing radiation caused by radionuclides released from the Chernobyl accident, but unexplained differences existed. Most cases had been confirmed by a panel of international pathologists [B18]. Increased risks of childhood thyroid cancer were later reported in Ukraine [L6, T2] and, more recently, in the part of the Russian Federation most contaminated by the Chernobyl accident [S19, T1].

269. The large number of cases appearing within five years of the accident was surprising, since it had been believed that thyroid cancer needed an induction and latency period of at least 10 years after exposure to ionizing radiation [U2]. The findings were challenged, the major concerns being the influence of an increased awareness and of thyroid cancer screening [B23, R8, S5].

270. The numbers of thyroid cancers in children born before 26 April 1986 and who were less than 15 years of age at that time by country/region and year of diagnosis are given in Table 56 and illustrated in Figure XXIV. The corresponding incidence rates are given in Table 57 and Figure XXV Childhood thyroid cancers in heavily contaminated areas show 5-10-fold increases in incidence in 1991-1994 compared to the preceding five-year period. The number of childhood thyroid cancers occurring from 1990 to 1998 in a wider age range of children (0-17 years old at time of the accident) is presented in Table 58. It should be noted that many of the cases were diagnosed in adolescents and young adults and that only few of them have undergone histopathological review. The numbers given in Tables 56-58 are not entirely consistent, since various sources of information have been used (see Section IV.B.3.b).

271. Kofler et al. [K41] recently described thyroid cancer in children 0-14 years old at the time of the accident in Belarus. Through the Belarus cancer registry, 805 thyroid cancers were found by the end of 1997. The distribution with time and by age at exposure is presented in Figure XXVI. It can be seen that children 0-4 years old at the time of the accident still have an increase in absolute numbers of thyroid cancers, while the number of thyroid cancers diagnosed among those who were 5-9 years old seems to decrease after 1995. In those 10-14 years of age at exposure, the number of thyroid cancers seems to be stable for the period 1991-1997.

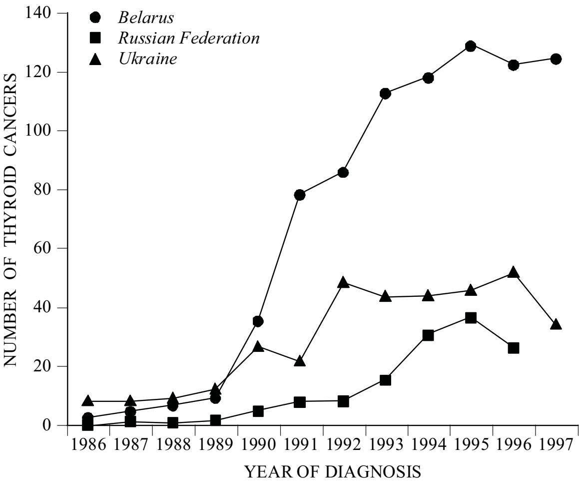


Figure XXIV. Number of thyroid cancers in children exposed before the age of 14 years as a result of the Chernobyl accident [I23, K41, T2, T16].

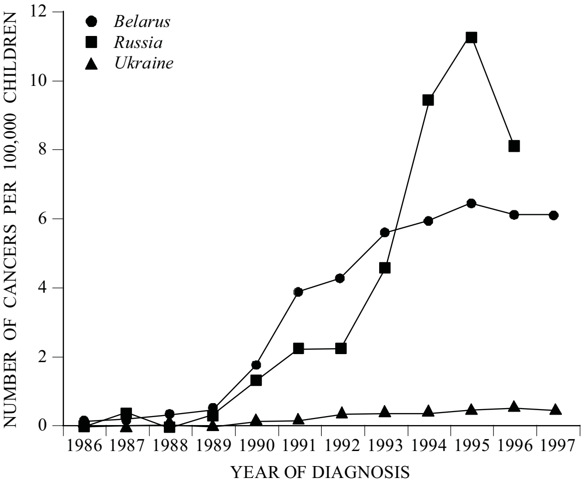


Figure XXV. Thyroid cancer incidence rate in children exposed before the age of 14 years as a result of the Chernobyl accident [I23, K41, T2, T16].

272. In a recent report on the childhood thyroid cancer cases in the Russian Federation, Ivanov et al. [I27] described findings similar to those revealed above. In total, 3,082 thyroid cancer cases in persons less than 60 years of age at diagnosis were recorded between 1982 and 1996 in the four most heavily contaminated regions of the Russian Federation (Bryansk, Kaluga, Orel and Tula). Among those 0-17 years of age at the time of the accident, 178 cases were found. A significantly lower incidence of thyroid cancer in women in these four areas compared to women in the Russian Federation as a whole was found for the period 1982-1986 (Figure XXVII). In the next five years, described as an induction period, the risk was, on

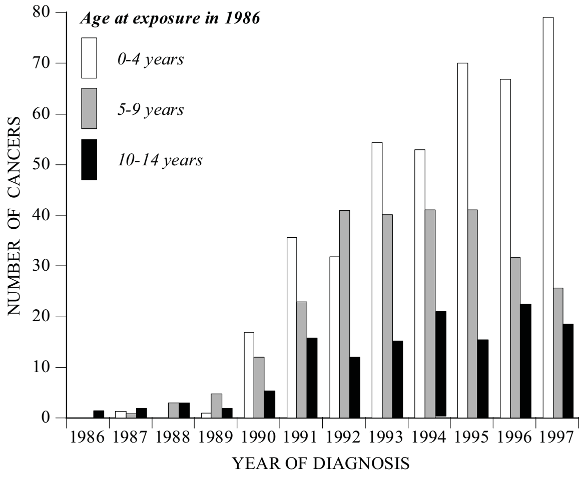


Figure XXVI. Number of diagnosed thyroid cancer cases in Belarus as a result of the Chernobyl accident [K41].

average, 1.6 times the Russian Federation baseline risk, probably reflecting increased surveillance and screening. Separate figures for those less than 14 years of age were not given, but the elevated risk seen for the period 1992–1996 was said to reflect the high rates found in those less than 14 years old at the time of the Chernobyl accident. A nearly 14-fold increased risk was found among girls 0–4 years of age at exposure compared to adult rates.

273. Jacob et al. [J2] reported a correlation between collective dose and incidence of thyroid cancer in 5,821 settlements in Belarus, the Russian Federation and Ukraine in 1991–1995. Using the southern half of Ukraine as a reference, the excess thyroid cancer risk was found to be linear in the dose interval 0.07–1.2 Gy. The study was extended in an attempt to take thyroid surveillance, background incidence, age, gender and appropriate methods into consideration [J5]. Thyroid doses in two cities and 2,122 settlements in Belarus and one city and 607 settlements in the Russian Federation were reconstructed. Thyroid cancers diagnosed during 1991–1995 in individuals between the age of 0–18 years at the time of the accident were included in the study. Information on residency at the time of the accident was collected for all cases, and 243 thyroid cancers were found, giving an excess absolute risk of 2.1 (95% CI: 1.0–4.5) per 10^4 person-year Gy (Table 59).

274. In a pooled analysis of children exposed to external photon radiation [R7], the excess absolute risk of thyroid cancer was 4.4 cases per 10^4 person-year Gy (95% CI: 1.9–10.1). The excess relative risk found by Jacob et al. [J5] was 23 Gy^{-1} (95% CI: 8.6–82), which is non-significantly higher than the excess relative risk of 7.7 Gy^{-1} (95% CI: 2.1–28.7) found by Ron et al. [R7]. It could be that indolent thyroid cancers detected only at screening were included. The possible shortening of the latency period by screening, which served to "harvest" thyroid cancers, could partly explain the differences. Another explanation for the differences could be the dosimetry, since collective thyroid doses were used, and individual dose measurements in Belarus were available for only a minority of the study population. Dose calculations were based on environmental measurements and radio-ecological models.

275. A recent case-control study by Astakhova et al. [A6] included the initial 131 Belarus thyroid cancers presented by Kazakov et al. in 1992 [K11] but excluded 24 cases for different reasons. Eleven cases did not have pathological confirmation, 8 cases were not in Belarus at time of the accident, 2 cases had no information on pathology, 2 cases were diagnosed before 1987 and 1 patient was deceased. For the remaining 107 thyroid cancers included in the study, the male:female ratio was 1:1.1, and 105 cancers (98%) were of papillary origin. Two sets of controls were chosen, both matched on age, sex, rural/urban residency, taking reason for diagnosis and area of residency into consideration. A strong relationship between estimated thyroid dose and thyroid cancer was found, even when reason for diagnosis, gender, age, year of diagnosis, and ^{131}I level in soil were taken into consideration [A6]. The mean doses were different for the cases and for the controls selected to represent the general population of children exposed to fallout from the accident (Table 60), and the odds ratio was 3.1 (95% CI: 1.7–5.8) when comparing the lowest and the two highest dose groups. The highest odds ratio, based on 19 cases and controls, was seen for those diagnosed incidentally (Table 60) when using the other set of controls, i.e. those having the same opportunity for diagnosis as the cases. The odds ratio for those thyroid cancers found at routine screening (OR = 2.1, 95% CI: 1.0–4.3) indicated that screening was conducted in high fallout areas, since no large difference in dose was noted.

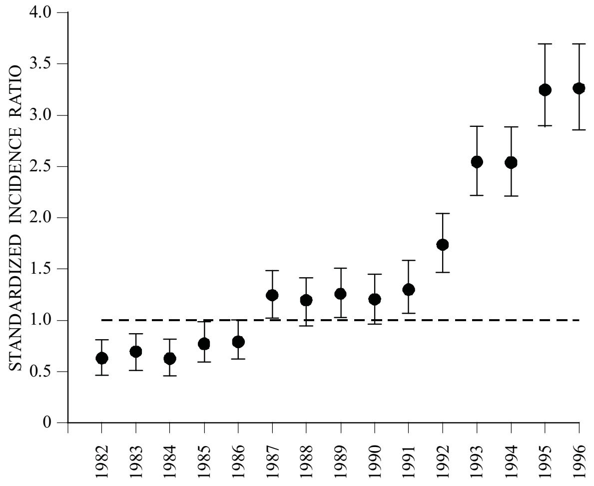


Figure XXVII. Standardized incidence ratios (SIR) of thyroid cancers among women less than 60 years of age at diagnosis in the four most contaminated areas (Bryansk, Kaluga, Orel, Tula) of Russia to Russia as a whole [I27].

276. The Astakhova case-control study [A6] is one of the more reliable published to date. Individual thyroid doses received by the children were inferred from established

relationships between adult thyroid doses and ^{137}Cs deposition on a village basis and then modified according to age-adjusted intake rates and dose coefficients. Location of the children before and after the accident was established on the basis of interviews. Although the questionnaire was designed to acquire individual information on milk-consumption rates and the administration of thyroid-blocking agents, such information was incomplete in many cases and could not be used. Age-dependent default values of milk-consumption rates were therefore used for all children in order not to introduce bias into the study; the use of blocking agents was assumed either not to have occurred at all or to have occurred too late to have been effective. Uncertainty in the individual estimates of thyroid dose is difficult to quantify, but is estimated to be at least a factor of three.

277. In a study of Ukrainian thyroid cancer patients less than 15 years old at diagnosis, registered at the Institute of Endocrinology and Metabolism, Kiev, the thyroid cancer rate for 1986–1997 exceeded the pre-accident level by a factor of ten [T18]. A total of 343 thyroid cancers occurred in patients born between 1971 and 1986, and the thyroid cancer rate for this age cohort was 0.45 per 100,000 compared with 0.04–0.06 per 100,000 before the accident. For the slightly older group of patients 15–18 years old at diagnosis in 1986–1997, 219 cases of thyroid cancers were found, and the average incidence was three times higher than that in the group diagnosed before the accident.

278. Descriptions of the dosimetric methods or dose-response models are unavailable, but it was stated that 22% of the patients aged 0–14 years at the time of the accident received a thyroid dose of >0.3 Gy [T18]. Thyroid cancer rates were analysed for different areas, and a rate of 27 per 100,000 was found in children evacuated from the villages closest to the accident (including Pripyat and Chernobyl). The authors concluded that the highest risk was found in those less than 5 years of age at the time of the accident, but it is questionable whether the methods used allow such a statement. Only cases below the age of 19 years at diagnosis are registered, thus excluding those older than 7 years of age in 1986 to be registered in 1997.

279. In a recent paper, Shirahige et al. [S34] compared 26 children diagnosed with thyroid cancer in Belarus within the framework of the Sasakawa project with 37 children diagnosed with thyroid cancer in Japan between 1962 and 1993. A peculiar finding was the peak incidence at 10 years of age at time of diagnosis and a drop thereafter among the Belarus cancer cases compared with a steady increase between the ages of 8 and 14 among the Japanese cases. This could reflect a difference in age distribution, since those exposed very early in life seemed to have an increased risk many years after exposure [G23, K41]. The differences could also indicate a different growth pattern caused by an alternative process of carcinogenesis, differences in screening routines, or the manner in which the children were selected for screening, since some registries only follow children until the age of 15.

280. In a study of male recovery operation workers from Belarus, the Russian Federation and Ukraine who worked within the 30-km zone, an increased incidence of thyroid cancer was noted, based on a total number of 28 cases [C2]. Significant thyroid doses may have been received from short-lived iodines during the first days after the accident, but information on the period workers spent within the 30-km zone was not taken into consideration. Histopathology and mode of confirmation were not available for the 28 thyroid cancers. These results must therefore be interpreted with caution, especially since the follow-up of recovery operation workers is much more active than that of the general population in the three countries (see Section IV.A.1 and IV.C.2). In a study of approximately 34,000 patients receiving ^{131}I for diagnostic purposes, 94% being older than 20 years at exposure, no increased risk of thyroid cancer related to radioiodine exposure could be found [H6]. As previously discussed, the intensity of screening may greatly influence the observed incidence of thyroid cancer in adults [S4].

281. Ivanov et al. [I8, I14, I33] extensively studied the late effects in Russian recovery operation workers. The Russian National Medical and Dosimetric Registry (the former Chernobyl registry) was used, and a significantly increased risk of thyroid cancer was found when the number of observed cases was compared to the number expected from national incidence figures. With the exception of the recent papers by Ron [R17] and Franklyn [F13], this is the first time an increased risk of thyroid cancer has been reported in adults after exposure to ionizing radiation. The study has been criticized for not using individual doses and internal comparisons [B30, B31]. The increased medical surveillance and active follow-up of the emergency workers most likely influenced the results, particularly when observed numbers are contrasted to national background rates.

282. In a descriptive study of cancer incidence in the six most contaminated regions of the Russian Federation [R2], the thyroid cancer incidence increased over time in adults, and the increase was larger than that observed in the whole of the Russian Federation. The highest values were found in the Bryansk region in 1994; the thyroid cancer incidence for women there was 11 per 100,000 compared with 4.0 per 100,000 for the Russian Federation as a whole. The corresponding figures for males were 1.7 and 1.1 per 100,000, respectively. It was concluded that no correlation was found between adult thyroid cancer and the levels of radioactive contamination [R2]. A pronounced difference was observed in children based on 14 cases; the incidence was 2.5 in the Bryansk region compared with 0.2 per 100,000 for the whole of the Russian Federation. Before the accident, the incidence of thyroid cancer in children in Bryansk and in the Russian Federation was the same. The registration and follow-up of the Russian population as a whole are probably not comparable to that in the highly contaminated regions surrounding Chernobyl (see Section IV.A.1 and IV.C.2), and this influences the results.

283. Thyroid examinations, including ultrasound and fine needle aspiration, were conducted in 1,984 Estonian recovery

operation workers nine years after the accident [I19]. The average age on arrival at Chernobyl was 32 years and at thyroid examination, 40 years. The mean documented dose from external irradiation of the thyroid was 108 mGy, but a poor correlation was found with biological indicators of exposures such as loss of expression of the glycophorin A gene in erythrocytes. Doses from incorporated iodine were not taken into consideration. Two cases of papillary carcinoma were identified and referred for treatment. Both men with thyroid cancer had worked at Chernobyl in May 1986, when the potential of exposure to radioactive iodine was highest.

284. In a study of 3,208 Lithuanian recovery operation workers in 1991–1995, three thyroid cancers (two papillary carcinomas and one mixed papillary-follicular carcinoma) were detected [K9]. There was no significant difference compared with the Lithuanian male population and no association with level of radiation dose or duration of stay in the area of Chernobyl.

285. Three years after the Chernobyl accident, Jewish residents of the former USSR began to emigrate in large numbers to Israel. Between 1989 and 1996, about 140,000 persons from contaminated regions of Belarus, the Russian Federation and Ukraine moved to Israel. The thyroid status of 300 immigrant children brought to the clinic voluntarily by parents was evaluated [Q1], and enlarged thyroid glands were found in about 40% of subjects. One 12-year-old girl from Gomel was found to have a malignant papillary carcinoma of the thyroid.

286. Several studies on the late health effects of the Chernobyl accident were carried out in Europe and have been critically reviewed and summarized [S12]. No increase in thyroid cancer among children was observed, although no study focussed specifically on childhood thyroid cancer, since the disease is so rare and a small increase could have gone undetected in these studies.

287. Screening programmes have increased the ascertainment of occult thyroid tumours through the use of ultrasound examination [B23, S5], a possibility discussed in one of the original reports [B18]. Thyroid screening was locally organized in the most contaminated areas after the accident, but large-scale screening with ultrasound examination, supported by the Sasakawa and IPHECA programmes, did not start until 1991 and 1992. Soviet health authorities initiated a national screening programme shortly after the accident, and each country later continued the thyroid screening [S19]. It is anticipated that 40%–70% of the diagnosed childhood thyroid cancer cases have been found through these programmes. In the case-control study of 107 childhood thyroid cancers [A6], 63 cases were found through endocrinological screening (Table 60). In a survey of 50 thyroid childhood cancers in Belarus [A5, C1], 12 cases were detected by targeted screening and another 23 cases were found incidentally in other examinations (Table 61). A study by Ron et al. [R8] supports these findings of a screening effect. Increased screening of a cohort given external photon radiation for benign head and neck diseases in the United States resulted in a roughly sevenfold increase in thyroid cancers.

288. Although rarely fatal, the aggressiveness of the thyroid cancers found in the Chernobyl area, which is frequently present with periglandular growth and distant metastases [E1, K11, W8], argues against the findings being entirely a result of screening. Although thyroid tumours in adults are usually tumours of relatively low malignancy, they tend to be more aggressive in children [S3], so it could be argued that the growth pattern would have led to the diagnosis of a thyroid cancer sooner or later.

289. Although ultrasound screening is not sufficiently widespread to explain the majority of the thyroid cancer cases observed until now, it is clear that increased awareness and medical attention to thyroid disorders during routine medical examinations in the contaminated territories influence the findings. Enhanced examinations in schools may have advanced the time at which some tumours were recognized [A5]. However, the continuing increase in the number of cases [C4, I27, K41] and the observation that the increase appears to be confined to children who were born before the accident support the conclusion that ascertainment bias could not fully explain the increased rates. Rates among those conceived after the accident appear to be similar to pre-accident rates in the affected countries.

290. Factors other than screening and lack of individual dosimetry may modify the risk of radiation-induced thyroid cancer, one of them being iodine saturation. The iodine deficiency in some of the affected areas will affect not only the level of dose received by the thyroid gland at the moment of exposure but also, if continued, thyroid function in the years after exposure [Y1]. The risk of thyroid cancer may be enhanced when the excretion of radioactive iodine is limited owing to reduced thyroid hormone synthesis and blocked thyroid hormone secretion [R6]. Iodide dietary supplementation had been terminated in the former USSR approximately 10 years before the accident. The relationship between iodine deficiency and goiter is discussed in paragraph 345.

291. Another risk-modifying influence might be a genetic predisposition to radiation-induced thyroid cancer, perhaps related to ethnicity. A recent survey indicated that cases occurred in siblings in at least three families in Belarus [A5, C1], a finding unlikely to be explained by chance alone. In a study of children exposed in the Michael Reese hospital in the United States, the risk of radiation-induced thyroid cancer appeared to vary by ethnic origin of the children [S4]. The genetic susceptibility to thyroid cancer and its familial aggregation were studied in relatives of 177 patients with thyroid cancer [V8]. No significantly increased rate of thyroid cancer was seen compared with controls. In a recent study, 7 of 119 patients with papillary thyroid microcarcinoma had a family history of thyroid carcinoma, and they experienced less favourable tumour behaviour than patients without a family history of thyroid carcinoma [L39]. The possible existence of a genetic predisposition to radiation-induced thyroid cancer might be important.

(b) Clinical and biological aspects

292. A large proportion of the childhood thyroid cancers in Belarus and Ukraine were reported to be locally aggressive; extrathyroidal growth was seen in 48%–61% of the cases, lymph node metastases in 59%–74% and distant metastases (mainly lung) in 7%–24% [F5, P2, P6, T4, T18]. Comparisons with characteristics of tumours from other countries (France, Italy, Japan, the United Kingdom and the United States) indicate a higher percentage of extrathyroidal extension for tumours from Belarus and the Russian Federation but similar percentages of cases with metastases [N5, P2, P6, V8, Z3].

293. In a recent pooled analysis of 540 thyroid cancers diagnosed before the age of 20 years (mean age at diagnosis, 14 years) that included nine Western centres, the average male:female ratio was 1:3.2 and the mean follow-up was 20 years [F7]. Eighty-six percent were papillary thyroid carcinomas, 79% showed evidence of lymph node metastases, 20%–60% had extracapsular invasion and 23% were diagnosed with distant metastases. In nearly all cases the presenting sign was a neck mass. Thirteen of the patients died as a consequence of the disease.

294. Two of the above-mentioned centres participated in a study in which 369 Italian and French thyroid cancers were compared to 472 Belarusian cancers [P2]. The Belarusian cases were diagnosed between May 1986 and end of 1995 and included approximately 98% of the cases in the country diagnosed in that period. The Belarusian patients were younger at diagnosis, and 95% of the cancers were of papillary origin compared to 85% in Italy/France. Extrathyroidal extension and lymph node metastases were more frequent in Belarus, 49% and 65%, compared to Italy/France, where the corresponding figures were 25% and 54%, respectively. Thyroid lymphocytic infiltration and circulating antithyroidperoxidase were more frequent in the Belarusian patients, possibly indicating a higher rate of autoimmune thyroid disorders. The male:female ratio was 1:2.5 in Italy/France, in contrast to 1:1.6 in Belarus. The low male:female ratio could be a screening effect, since no difference in sex ratio of occult thyroid cancer was found at autopsy in young individuals [F10]. The age distribution could probably also explain some of the difference in stage, the histopathological distribution and gender ratio.

295. A number of thyroid cancer cases in Belarus were treated with radioiodine at the university clinics of Essen and Würzburg [R23]. All 145 patients had undergone operations at the Centre for Thyroid Tumors in Minsk; lymph node metastases were found in 140 patients and distant metastases in 74 of them. The mean age at diagnosis was 12 years. Among 125 children subsequently followed, 90 were classified as in complete remission and the others had partial remissions.

296. In a study of 577 Ukrainian thyroid cancer cases diagnosed in patients less than 19 years of age [T18], histopathology was evaluated in 296 cases (123 were analysed by non-Ukrainian pathologists, who confirmed the initial diagnosis in all cases). Ninety-three percent were papillary carcinomas, and 65% were found to be of the more aggressive solid/follicular type. In 55% of cases, lymph node metastases were found, and in 17% lung metastases were found either at initial diagnosis or in later follow-up. Difference in TNM classification [H17] over time did not show a significant trend towards more advanced stages (Table 62), as could have been anticipated if radiation-associated cancers are indeed more aggressive. Cancers diagnosed in 1996 and 1997 were more likely to be locally aggressive, stage T4, but they revealed the same pattern of lymph node metastases and distant spread. The male:female ratio was found to be influenced by age at the time of diagnosis (Table 63): the ratio was 1.1:1 for those less than 5 years of age at time of diagnosis and 1:2.7 for those 15–18 years. However, age at time of the accident did not seem to influence the male:female ratio (Table 63). A possible sex difference in the susceptibility of the thyroid tissue to ionizing radiation did not seem to influence the gender ratio, since age at diagnosis and not age at exposure influenced the distribution.

297. In a study in the United States of 4,296 patients previously irradiated for benign disorders, 41 childhood (mean age at diagnosis, 16 years) and 77 adult (mean age at diagnosis, 27 years) thyroid cancers were found [S4]. The childhood cancers more often presented themselves with lymph node metastases and vessel invasion but were significantly smaller in adults and found incidentally when benign nodules were operated. Of the childhood cancers, 95% were papillary carcinomas compared with 84% of the adult cancers. Thirty-nine percent of the childhood cancers relapsed compared with 16% of the adult cancers. After a mean follow-up of 19 years, there was only one death due to thyroid cancer, and this was in the adult group.

298. The histopathology of over 400 post-Chernobyl thyroid cancers diagnosed in children under the age of 15 years was reviewed by pathologists from the United Kingdom and from the countries where the children were diagnosed [E2]. Virtually all cases were papillary carcinomas, in contrast to thyroid cancers in British children of similar age who were not exposed to ionizing radiation, where 68% of the carcinomas were of papillary origin [H3]. The solid variant of papillary carcinoma, indicating a low level of differentiation, was particularly prevalent in those cases believed to have resulted from radiation exposure following the Chernobyl accident [E2]. This finding is not in agreement with a study of 19 cases in the Gomel area carried out by the Chernobyl Sasakawa Health and Medical Cooperation Project, where no specific morphological evidence of radiation-induced thyroid cancer was observed [I26].

299. Shirahige et al. [S34] examined 26 Belarusian and 37 Japanese children diagnosed with thyroid cancer and found the mean tumour diameter to be smaller in Belarus (1.4 cm) than in Japan (4.1 cm). The solid growth pattern was seen in 62% of the Belarusian papillary carcinomas

compared to 18% of the Japanese carcinomas. All cancers from Belarus showed a papillary growth pattern, compared to 92% of the cancers found in Japan.

300. Recent advances in the field of molecular biology have improved the understanding of the mechanisms underlying the thyroid carcinomas. Cellular signalling has become a major research area, and signalling via protein tyrosine kinases has been identified as one of the most important events in cellular regulation. Protein tyrosine kinases are thus important in the development of cancer, and the *RET* proto-oncogene is one of the genes coding for a receptor tyrosine kinase. Rearrangements of the tyrosine kinase domain of the *RET* proto-oncogene have been found in some thyroid cancers and at a higher rate among those supposed to be associated with ionizing radiation [F2, I21, K14]. Other mutations are those seen in the *RAS* gene, which probably represent an early event in the carcinogenic process; the mutations of the *RAS* gene therefore possess an early gate-keeper function, as reflected by the fact that they are found in similar frequencies in both thyroid carcinomas and adenomas. Point mutations in the *TP53* gene are rare in differentiated thyroid carcinomas but are found in anaplastic thyroid cancer [F8].

301. A number of studies have been carried out to determine whether any specific molecular biological alterations characterize the childhood papillary cancers in the Chernobyl area. A high frequency of *RET/PTC3*-type rearrangement in post-Chernobyl papillary carcinoma was suggested in two early studies [F2, K14]. However, a study including more cases showed that a *RET/PTC1* rearrangement was more frequent than *PTC3* [E2] and that there was no significant increase in the proportion of papillary carcinomas showing RET rearrangement, when compared with a non-irradiated population of a similar age [W3]. In a French study, a higher frequency of *RET/PTC* rearrangements (84%) was found among 19 thyroid cancer patients who had received previous external radiotherapy for a benign or malignant condition than among 20 "sporadic" thyroid cancers (15%) [B12]. The most frequently observed chimeric gene was *RET/PTC1*, and for the first time *RET/PTC* rearrangements were found in follicular adenomas.

302. Recent findings indicate a strong dependence of age at exposure and latency period in the distribution of *RET/PTC* rearrangements [S35]. When comparing 51 Belarusian childhood papillary thyroid carcinomas (mean age at exposure: three years) with 16 Belarusian and 16 German adult thyroid cancers patients, only *RET/PTC1* mutations were found in adults (Table 64), while similar frequencies of *RET/PTC1* and *RET/PTC3* were found in children. The authors suggested that thyroid cancers expressing *RET/PTC3* may be a feature of cancers detected soon after exposure, while *RET/PTC1* may be a marker of later-occurring, radiation-associated papillary thyroid carcinoma in both children and adults. It also seems like *RET/PTC3* rearrangements are more common in younger individuals. These findings are supported by a study comparing *RET/PTC* rearrangements in Belarusian radiation-associated thyroid cancers diagnosed in 1991–1992 and in 1996 [P27]. A switch occurred from *RET/PTC3* rearrangements in patients diagnosed in the early 1990s to *RET/PTC1* alterations in patients diagnosed later on.

303. The morphological subtype may also influence the pattern of *RET* rearrangements in papillary thyroid carcinomas, as shown by Thomas et al. [T19]. Among 116 Chernobyl-related childhood papillary thyroid cancers, *RET/PTC1* and *RET/PTC3* mutations were found in 9% and 19%, respectively, of the solid follicular subtype. The corresponding figures for the non-solid follicular subtype (classic papillary carcinoma and diffuse sclerosing carcinoma) were 46% and 0%, respectively. It could be that the solid, less differentiated, follicular subtype associated with *RET/PTC3* rearrangements have a shorter induction period.

304. Despite the large amount of information accumulated on *RET* activations in radiation-associated thyroid cancers, little is known about the clinical significance of the deletions. No significant differences were found, e.g. in tumour size, multicentricity, extrathyroidal growth, vascular invasion, lymphocytic invasion, or lymph node invasion, when eight *RET* positive thyroid cancers were compared with 25 carcinomas not displaying the activation [S39]. A lower proliferation rate was, however, seen in the *RET*-activated tumours.

305. Karyotype abnormalities were studied in 56 childhood thyroid tumours from Belarus, and clonal structural aberrations were seen in 13 cases [Z2]. In particular, aberrations in 1q, 7q, 9q and 10q were found. It is interesting to note that the 10q chromosomal band harbours the *RET* proto-oncogene.

306. Two new rearrangements have been described in three post-Chernobyl thyroid carcinomas. One is the *RET/PTC4*, which involves a different breakpoint in the *RET* gene [F6] and *PTC5*, which involves fusion of *RET* with another ubiquitously expressed gene, *rgf5* [K31]. However, *PTC4* and *PTC5* appear to be present in only a small number of post-Chernobyl papillary cancers. Just recently, two novel types *RET* rearrangements have been described, *RET/PTC6* and *PTC7* in childhood papillary thyroid carcinomas [K27].

307. No association has previously been shown between mutations of other types of genes, e.g. *RAS*, *bcl-2*, and *TP53,* and thyroid carcinogenesis [E2, S9]. However, in a study of 22 papillary thyroid cancers associated with ionizing radiation, four mutations of *TP53* were found compared to none in the 18 thyroid cancers not known to have been exposed to ionizing radiation [F8]. In three of the four mutation carriers, invasion beyond the thyroid capsule was found compared with 2 out of 17 in the rest of the radiation-associated thyroid cancer patients. In a study of thyroid adenomas and of well and poorly differentiated thyroid cancers, the rates of *TP53* mutations were 0%, 11% and 63%, respectively [P1]. However, no correlation with age, sex, stage, or survival was seen.

(c) Summary

308. There can be no doubt about the relationship between the radioactive materials released from the Chernobyl accident and the unusually high number of thyroid cancers observed in the contaminated areas during the past 14 years. While several uncertainties must be taken into consideration, the main ones being the baseline rates used in the calculations, the influence of screening, and the short follow-up, the number of cases is still higher than anticipated based on previous data. This is probably partly a result of age at exposure, iodine deficiency, genetic predisposition, and uncertainty that surrounds the role of ^{131}I compared with that of short-lived radioiodines. The exposure to short-lived radioiodines is entirely dependent on the distance from the release and the mode of exposure, i.e. inhalation or ingestion. It was only in the Gomel region, the area closest to the Chernobyl reactor, that Astakhova et al. [A6] found a significantly increased risk of thyroid cancer. It has been suggested that the geographical distribution of thyroid cancer cases correlates better to the distribution of shorter-lived radioisotopes (e.g. ^{132}I, ^{133}I and ^{135}I) than to that of ^{131}I [A7].

309. The identification of a genomic fingerprint that shows the interaction of a specific target cell with a defined carcinogen is a highly desirable tool in molecular epidemiology. However, a specific molecular lesion is almost always missing, probably because of the large number of factors acting on tumour induction and progression. Signalling via protein tyrosine kinases has been identified as one of the most important events in cellular regulation, and rearrangements of the tyrosine kinase domain of the *RET* proto-oncogene have been found in thyroid cancers thought to be associated with ionizing radiation [F2, I21, K14]. However, the biological and clinical significance of *RET* activation remains controversial, and further studies of the molecular biology of radiation-induced thyroid cancers are needed before the carcinogenic pathway can be fully understood.

2. Leukaemia

310. As discussed in Annex I, "*Epidemiological evaluation of radiation-induced cancer*", the risk of leukaemia has been found to be elevated after irradiation for benign and malignant conditions, after occupational exposure (radiologists), as well as among the survivors of the atomic bombings. Leukaemia, although a rare disease, is the most frequently reported malignancy following radiation exposure. However, not all subtypes of leukaemia are known to be associated with ionizing radiation, e.g. chronic lymphatic leukaemia and adult T-cell leukaemia. The naturally occurring subtypes of leukaemia have an age dependency, with acute lymphatic leukaemia most common in childhood and acute myeloid leukaemia predominating in adulthood.

311. The incidence of leukaemia was increasing in countries of the former USSR even before the accident. Prisyazhiuk et al. [P7] found an increase starting already in 1981, which was most pronounced in the elderly. The increase may simply be the result of improved registration and diagnosis, but this cannot yet be exactly quantified. The underlying trend must, however, be taken into account when interpreting the results of studies focussing on the period after the accident. Most existing studies have not addressed this problem and suffer from a number of other limitations and methodological weaknesses, making it premature to attempt a quantitative risk assessment based on the results.

312. A number of publications have presented details of the medical and dosimetric follow-up of the large number of workers who took part in recovery operations following the Chernobyl accident [K6, O2, T3, T7, T8, T9, T10]. Cardis et al. [C2] analysed cancer incidence in 1993 and 1994 among male recovery operation workers who worked within the 30-km zone of the reactor during 1986 and 1987. The observed numbers of cancers were obtained from the national cancer registry in Belarus and from the Chernobyl registries in the Russian Federation and Ukraine. In total, 46 leukaemia cases were reported in the three countries in the two-year period (Table 65), and non-significant increases were observed in Belarus and in the Russian Federation. In Ukraine, a significant increase was reported (28 cases observed, 8 cases expected) [C2]. It is most likely that the increase reflects the effect of increased surveillance of the recovery operation workers and under-registration of cases in the general population, since no systematic centralized cancer registration existed in the three countries at the time of the accident (see Section IV.A.1 and IV.C.2). It could also be that different registries define haematological malignancies differently, including, for example, myelodysplastic syndrome, which could result in a leukaemia.

313. Ivanov et al. [I8, I9, I14] studied the late effects in 142,000 Russian recovery operation workers. The Russian National Medical and Dosimetric Registry (formerly the Chernobyl registry) was used, and a significantly increased risk of leukaemia was found when the observed cases were compared with those expected from national incidence rates. The studies have been criticized for not using individual doses and internal comparisons and for including chronic lymphatic leukaemia, a malignancy not linked to radiation exposure [B30, B31]. The increased medical surveillance and active follow-up of the emergency workers, coupled with under-reporting in the general population, most likely influenced the results.

314. In contrast to their findings for the above-mentioned cohort of recovery operation workers, the same investigators [I29] did not find an increased risk of leukaemia related to ionizing radiation in a case-control setting. From 1986 to 1993, 48 cases of leukaemia were identified through the Russian National Registry and 34 of these patients (10 cases were diagnosed as chronic lymphatic leukaemia) were selected for the case-control study. The same registry was used when four controls were chosen for each case, matched on age and region of residence at diagnosis. For cases occurring among those

who were working in 1986 and 1987, controls had to have worked during the same period, which is a questionable approach, since dose is highly dependent on the period of work in the Chernobyl area. The mean dose for the cases was 115 mGy compared with 142 mGy for controls. No association was found between leukaemia risk and radiation.

315. These studies [I8, I9, I14, I29] suggest that, at least in the case of the Russian Federation, cancer incidence ascertainment in the exposed populations differs from that in the general population. Future epidemiological investigations might be more informative if they are based on appropriate Chernobyl registry-internal comparison populations, although care must be taken if recent additions to the register have been made because of disease diagnosis and compensation (see Section IV.C.1).

316. In discussing the discrepancy between the findings of the case-control and cohort studies, Boice and Holm [B31] claimed that the increased incidence in the cohort analyses reflected a difference in case ascertainment between recovery operation workers and the general population and not an effect of radiation exposure. Boice [B30] further argued that the results of the case-control study and of a study of Estonian recovery operation workers [R13] indicate that leukaemia risk among recovery operation workers is not consistent with predictions from atomic bomb survivors. He postulated that this may be due to an overestimation of official doses received by recovery operation workers and/or to the effect of protracted exposure. In response, Ivanov [I18] questioned the interpretation of the case-control analyses because of the considerable uncertainty surrounding the accuracy and quality of the official estimates of radiation doses available in the Chernobyl registry of the Russian Federation. Cardis et al. [C2] estimated that 150 cases of leukaemia should occur within 10 years of the accident among 100,000 recovery operation workers exposed to an average dose of 100 mSv. Such numbers have not been apparent in any studies or reports.

317. Shantyr et al. [S31] examined 8,745 Russian recovery operation workers involved in operations from 1986 to 1990. Dosimetry records were available for 75% of the workers, and the doses generally fell in the range 0–250 mSv. Although cancer incidence increased, particularly 4–10 years after the accident, no evidence of a systematic dose-response relationship was found, and it was suggested that the aging of the cohort influenced the findings. Tukov and Dzagoeva [T11] observed no increased risk of haematological diseases, including acute forms of leukaemia, in a careful study of Russian recovery operation workers and workers from the nuclear industry.

318. Osechinsky et al. [O6] studied the standardized incidence rates of leukaemia and lymphoma in the general population of the Bryansk region of the Russian Federation for the period 1979–1993 on the basis of an *ad hoc* registry of haematological diseases established after the Chernobyl accident. The results were not adjusted for age, and the rates in the six most contaminated districts (more than 37 kBq m^{-2} of ^{137}Cs deposition density) did not exceed the rates in the rest of the region or in Bryansk city, where the highest rates were observed. Comparisons of crude incidence rates before and after the accident (1979–1985 and 1986–1993) showed a significant increase in the incidence of all leukaemia and non-Hodgkin's lymphoma, but this was mainly due to increases in the older age groups in rural areas. The incidence of childhood leukaemia and non-Hodgkin's lymphoma was not significantly different in the six most contaminated areas from the incidence in the rest of the region.

319. The health status of 174,812 Ukrainian recovery operation workers (96% males) was examined by Buzunov et al. [B21]. Information on diagnosis was obtained from the State register of Ukraine and on leukaemia from an *ad hoc* registry for haematological disorders. The majority (77%) of the recovery operation workers were exposed in 1986–1987, and information on radiation exposure was available for approximately 50% of the workers. A total of 86 cases of leukaemia were reported in the period 1987–1992, and the highest number of cases was found among those employed in April-June 1986. The average rate of leukaemia among male recovery operation workers was 13.4 per 100,000 among those employed in 1986 and 7.0 per 100,000 among those employed in 1987. No apparent trend over time was seen among those employed in 1986. Eighteen cases of acute leukaemia among recovery operation workers exposed to 120–680 mGy were recorded as occurring 2.5–3 years after exposure in 1986–1987. No difference in histopathology or response to treatment was found compared with cases that occurred before the accident [B20].

320. Leukaemia and lymphoma incidence among adults and children in the regions of Kiev and Zhitomir, Ukraine, during 1980–1996 was examined by Bebeshko et al. [B32]. Total incidence in adults increased from 5.1 per 100,000 during 1980–1985 to 11 per 100,000 during 1992–1996, but there were no excess cases in contaminated areas of the regions. Likewise, no excess cases among children who resided in contaminated districts were found.

321. The incidence of leukaemia and lymphoma in the three most contaminated regions of Ukraine increased from 1980 to 1994 [P12]. This result should be viewed cautiously, since the findings were based on only a few cases, and lymphomas have not previously been known to be induced by radiation. Increased awareness and better health-care facilities and diagnosis most likely influenced the findings.

322. Childhood leukaemia in Belarus during 1982–1994 was investigated with regard to area of residency [I20]. Approximately 75% of the leukaemia cases were of the acute lymphatic subtype. No evidence of an increasing number of childhood leukaemia cases over time was noted. When the two most heavily contaminated areas, Gomel and Mogilev, were compared with the rest of the country, no difference was seen.

323. The incidence of leukaemia and lymphoma in the general population of Belarus was studied for 1979–1985 and 1986–1992 [I11]. Among children, no difference was observed either over time or in relation to ^{137}Cs ground contamination. In adults, significant increases were noted in the post-accident period for most subtypes of leukaemia and for lymphoma, but no relationship with the level of radioactive contamination was found.

324. An analysis of the mortality and cancer incidence experience of Estonian Chernobyl recovery operation workers took a different approach. First, a cohort consisting of 4,833 recovery operation workers was constructed using multiple data sources not based solely on Chernobyl registry data [R13, T6]. Second, mortality data were ascertained from vital registration sources, and death certificates in the cohort were coded following the same coding rules used by the Statistical Office of Estonia and compared to the official national mortality statistics [T6]. Furthermore, cancer incidence data in the cohort, along with the corresponding national cancer incidence rates, were obtained from the Estonian cancer registry. During 1986–1993, 144 deaths were identified compared with 148 expected [R13, T6]. A non-significant excess of non-Hodgkin's lymphoma was observed, based on three cases, while no case of leukaemia was found.

325. Fujimura et al. [F1] reported the results of haematological screening organized in the framework of the Sasakawa project. By the end of 1994, 86,798 children who were less than 10 years of age at the time of the accident were examined, and four cases of haematological malignancies were found. No correlation was observed between the prevalence of any haematological disorder and either the level of environmental contamination or ^{137}Cs measured by whole-body counting.

326. The European Childhood Leukaemia–Lymphoma Incidence Study (ECLIS), coordinated by IARC, was set up to monitor trends in childhood leukaemia and lymphoma [P5, P11]. Incidence rates from European cancer registries were related to the calculated radiation dose in the large geographical regions for which environmental dose estimates were provided in the UNSCEAR 1988 Report [U4]. Thirty-six cancer registries in 23 countries are collaborating in ECLIS by supplying an annual listing of cases in children less than 15 years of age. Data for 1980–1991 indicated a slight increase in the incidence of childhood leukaemia in Europe. This increase was, however, not related to the estimated radiation dose from the accident [P11, P21]. No indication of an increased incidence among those exposed *in utero* was noticed.

327. A study of infant leukaemia incidence in Greece after *in utero* exposure to radiation from the Chernobyl accident was based on *ad hoc* registration of childhood leukaemia cases diagnosed throughout Greece since 1980 by a national network of pediatric oncologists [P3]. Based on 12 cases, a statistically significant 2.6-fold increase in the incidence of infant leukaemia (from 0 to 11 months after birth) was observed among the 163,337 live births exposed *in utero* (i.e. born between 1 January 1986 and 31 December 1987) compared with 31 cases among non-exposed children. Those born to mothers residing in areas of high radioactive fallout were at significantly higher risk of developing leukaemia. The reported association, which is not consistent with risk estimates from other studies of prenatal exposures, is based on the selective grouping of data. It is unclear how the authors chose the group <1 year to represent "infant leukaemia", as there is little *a priori* aetiologic reason for limiting to this age group. No significant difference in the incidence of leukaemia among children aged 12–47 months born to presumably exposed mothers was found.

328. Michaelis et al. [M6] conducted a study of childhood leukaemia using the population-based cancer registry in Germany. Cohorts were defined as exposed and non-exposed, based on dates of birth using the same criteria as Petridou et al. [P3] in the Greek study. The cohorts were subdivided into three categories based on level of ^{137}Cs ground deposition (<6, 6–10 and >10 kBq m^{-2}). These categories corresponded to the estimated *in utero* doses of 0.55 mSv for the lowest exposure category and 0.75 mSv for the highest exposure category. Overall, a significantly elevated risk was seen (1.48, 95% CI: 1.02–2.15) for the "exposed cohort" compared with the "non-exposed", based on 35 cases observed in a cohort of 900,000 births. However, the incidence was higher for those born in April to December 1987 than for those born between July 1986 and March 1987, although *in utero* exposure levels in the latter group would have been much higher than in the former group. The authors concluded that the observed increase was not related to radiation exposure from the Chernobyl accident.

329. A cluster effect described several decades ago could explain the Greek findings. A total of 13,351 cases of childhood leukaemia diagnosed between 1980–1989 in 17 countries was included in a study aimed at relating childhood leukaemia to epidemic patterns of common infectious agents [A2]. A general elevation of the incidence was found in densely (but not the most densely) populated areas, and weak, but significant, evidence of clustering was found. When seasonal variation in the onset of childhood leukaemia was studied in the Manchester tumour registry catchment area, the onset of acute lymphatic leukaemia (n = 1,070) demonstrated a significant seasonal variation, with the highest peak found in November and December [W6]. Both studies provide supportive evidence for an infectious aetiology for childhood leukaemia.

330. In a Swedish study of cancer incidence among children [T21] in areas supposed to have been contaminated as a consequence of the Chernobyl accident, 151 cases of acute lymphatic leukaemia were found during 1978–1992 in those 0–19 years at diagnosis. The areas were divided into three exposure categories, and the lowest risk was found in the supposedly highest exposure group. A non-significant decreasing trend with calendar year was also noted. A Finnish study covering nearly the same

period analysed leukaemia risks among those 0–14 years of age for the whole country [A13]. The estimated population-weighted mean effective dose was 0.4 mSv. No increased incidence of childhood leukaemia could be seen for 1976–1992, and no risk could be related to exposure to ionizing radiation. These results are consistent with the magnitude of effects expected.

331. ***Summary***. Although leukaemia has been found to be one of the early carcinogenic effects of ionizing radiation with a latency period of not more than 2–3 years [U4], no increased risk of leukaemia related to ionizing radiation has been found among recovery operation workers or in residents of contaminated areas. Numerous reports have compared incidence and mortality data from the registers described in Chapter IV with national rates not taking the differences in reporting into consideration. A case-control study would diminish this bias, and a recent paper by Ivanov et al. [I29] failed to show an increased risk of leukaemia related to ionizing radiation in 48 cases of leukaemia in recovery operation workers identified through the Russian National Registry.

3. Other solid tumours

332. Given the doses received by the recovery workers, described in Chapter II, and the previous data on radiation-associated cancer in exposed populations, reviewed in Annex I, "*Epidemiological evaluation of radiation-induced cancer*", an increased number of solid tumours could be anticipated in the years to come. The induction and latency period of 10 years [U4] and the protracted nature of the exposure probably explain why no radiation-associated cancers have been noticed so far.

333. The numbers of observed and expected cases of cancer in 1993–1994 among residents of the territories with ^{137}Cs contamination in excess of 185 kBq m^{-2} included in the Chernobyl registries of Belarus, the Russian Federation and Ukraine are presented in Table 65 [C2]. The observed numbers of cancer cases were obtained from the national cancer registry in Belarus and from the Chernobyl registries in the Russian Federation and Ukraine. Age- and sex-standardized expected numbers were based on rates for the general national population. Fewer solid tumours than anticipated were seen in workers in Belarus, while the workers in the Russian Federation and Ukraine revealed higher risks. The different registries used in the three countries could probably explain these differences. No increased risk was seen among those residing in contaminated areas [C2].

334. The crude incidence of malignant diseases per 100,000 persons among Russian recovery operation workers, excluding leukaemia, was estimated by Tukov and Shafransky [T13]. It rose from 152 in 1989, 193 in 1991 and 177 in 1993, to 390 in 1995. This increase was interpreted as an effect of age, but no attempt was made to adjust for age. The cause of death has changed over time. Accidents and trauma were the main cause of death in 1989–1990, while cardiovascular diseases were responsible for 43% of all deaths in 1996, followed by cancers (20%) and accident and trauma (15%) [T14]. The increase found in the report is similar to and consistent with that reported for the population of the Russian Federation as a whole [L26].

335. In a recent paper covering 114,504 of the approximately 250,000 Russian recovery operation workers, 983 cases of solid tumours were found during the years 1986–1996 [I32]. The observed number of cases was compared with the Russian national rates, and the overall standardized incidence ratio was 1.23 (95% CI: 1.15–1.31), with a significant excess relative risk per gray of 1.13. The only individually elevated site was the digestive tract (n = 301), and the corresponding figures were 1.11 (95% CI: 1.01–1.24) and 2.41, respectively. No increased risk of respiratory tract tumours was noticed. Increased ascertainment could influence the data but probably not explain the dose-response relationship. The excess relative risk is higher than what has been reported for survivors of the atomic bombings [T20], which might indicate uncertainty in the individual dose estimates.

336. When the same investigators presented data on individuals living in contaminated areas, somewhat contradictory results were seen [I12]. Cancer risks in three of the most contaminated districts of the Kaluga region were compared with the region as a whole. The population of the three regions contained approximately 40,000 individuals, and incidence rates before and after the accident were compared. The increase over time was similar for almost all sites regardless of exposure status. No increased risk of gastrointestinal cancer was seen for men, but an increased risk for respiratory tract cancers was suggested for women, based on 31 cases. However, the overall cancer risk among women in the contaminated areas was only one third of the incidence for the region in 1981–1985, a sign of previous under-reporting.

337. A descriptive study of cancer incidence in 1981–1994 was performed for the six most contaminated regions of the Russian Federation (Bryansk, Kaluga, Orel, Tula, Ryazan and Kursk) [R2]. Information on cancer incidence was gathered from the local oncological dispensaries and compared with Russian national statistics. It is unclear whether the analyses were adjusted for age, and the absolute number of cases was not reported. An increased incidence of all cancers was observed over the study period, both in the contaminated regions and for the Russian Federation as a whole. However, from 1987 onwards, the increase was more pronounced in the six study regions than in the rest of the country. The incidence rate of solid cancer among men in 1994 in Bryansk and Ryazan was 305 per 100,000 compared with 272 per 100,000 for the Russian Federation as a whole. The corresponding figures for women were 180 per 100,000 and 169 per 100,000, respectively.

338. An increase in dysplasia and urinary bladder cancer was seen in 45 Ukrainian males living in contaminated

areas and compared to 10 males living in uncontaminated areas of the country [R16]. Forty-two of the exposed individuals had signs of irradiation cystitis. It was reported that the incidence of bladder cancer in the Ukrainian population gradually increased, from 26 to 36 per 100,000, between 1986 and 1996. Among other histopathological features, increased levels of p53 were noted in the nucleus of the urothelium in the exposed individuals, indicating either an early transformation event or an enhancement of repair activities. Further analyses of the exposed patients, including urine sediments collected 4–27 months after the first biopsy, indicated a novel type of *p53* mutation not seen in the first analyses and showed that the mutation carriers could be identified [Y2]. The authors concluded that screening would be required.

339. The health status of the 45,674 recovery operation workers from Belarus registered in the Chernobyl registry was studied by Okeanov et al. [O2]. Eighty-five percent of them were men, and 31,201 (90%) had worked in the 30-km zone. For 1993 and 1994, the overall cancer incidence was lower than anticipated for both male (standardized incidence ratio (SIR) = 77; 95% CI: 65–90) and female (SIR = 90; 95% CI: 59–131) workers compared with the general population. Among men, a significant excess of urinary bladder cancer was seen (SIR = 219; 95% CI: 123–361), and non-significant increases were seen for cancers of the stomach, colon, and thyroid and for leukaemia. The numbers of cases on which these comparisons are based were small, particularly for thyroid cancer (n = 4). Recovery operation workers who worked in the 30-km zone more than 30 days had a slightly higher incidence of all cancers than other recovery operation workers.

340. Breast cancer incidence data in different time periods for the Mogilev region of Belarus were recently presented [O5]. A steadily increasing incidence was noted for the whole follow-up period, 1978–1996, and when the period 1989–1992 was compared with 1993–1996, a difference was found, but only for those 45–49 years at diagnosis, i.e. 35–42 years at the time of the accident. The findings could be due to increased awareness, documentation, or accessibility to screening, since the rates are lower in all age categories compared with the ages found in Western data. It is peculiar that younger age groups were not affected, and continued follow-up is warranted. However, as in all studies of radiation-associated cancer, individual dosimetry is essential, and individual doses were not used in this study.

341. Several studies of the effects of the Chernobyl accident outside the former Soviet Union have been carried out [E5, P5, P11]. The evaluations have mainly been done on a local or national level. Most studies have focussed on various possible health consequences of the accident, ranging from changes in birth rates to adult cancer. Studies related to cancer have been critically reviewed and summarized [S12]. Overall, no increase in cancer incidence or mortality that could be attributed to the accident has been observed in countries of Europe outside the former USSR.

342. ***Summary***. The occurrence of solid tumours other than thyroid cancers in workers or in residents of contaminated areas have not so far been observed. The weaknesses in the scientific studies, the uncertainties in the dose estimates, the latency period of around 10 years and the protracted nature of the exposures probably explain why no radiation-associated cancers have been noticed so far. Some increase in incidence of solid tumours might have been anticipated in the more highly exposed recovery operation workers.

B. OTHER SOMATIC DISORDERS

1. Thyroid abnormalities

343. The first report of non-malignant thyroid disorders in the Chernobyl area was published in 1992 [M10]. The prevalence of thyroid nodules among individuals in seven contaminated villages in Belarus, the Russian Federation and Ukraine was compared with the prevalence in six uncontaminated villages, and 1,060 individuals, in total, were examined. Ultrasound examinations revealed an overall rate of discrete nodules of 15% in adults and 0.5% in children, with a higher prevalence in women. No difference related to exposure status was found, but it was suggested that it might be helpful to screen selected groups such as recovery operation workers and individuals living in contaminated areas.

344. The Chernobyl Sasakawa Health and Medical Cooperation Project started in May 1991 as a five-year programme, and through April 1996, approximately 160,000 children had been examined [S2, S7, Y1]. The examined children were all born in Belarus, the Russian Federation and Ukraine between 26 April 1976 and 26 April 1986. The thyroid examinations included ultrasound, serum free thyroxine, thyroid-stimulating hormone (TSH), antithyroperoxidase, antithyroglobulin and urine iodine concentration. A total of 45,905 thyroid abnormalities were found in 119,178 examined children (Table 66) [Y1]. Ninety-one percent of the abnormalities were diagnosed as goiter, and 62 thyroid cancers were found. The incidence rates in Gomel, the area of Belarus with the highest contamination, had the lowest incidence of goiter but the highest incidence of abnormal echogenity, cystic lesions, nodular lesions, and cancer, the latter two known to be related to radiation (Table 67). No association between thyroid antibodies, hypo- or hyperthyroidism, and ^{137}Cs activity in the body or soil contamination was seen in 114,870 children examined [Y1].

345. The contaminated areas around Chernobyl have been recognized as iodine-deficient areas, but the influence on the goiter prevalence has not been clear. In an extended study of the 119,178 children included in the Chernobyl Sasakawa Health and Medical Cooperation Project [A8], urinary iodine excretion levels were measured in 5,710 selected cases. The study did not reveal any correlation between goiter and whole-body ^{137}Cs content or ^{137}Cs

contamination level at the place of residence either at the time of examination or the time of the accident. However, a significant negative correlation was indicated between prevalence of goiter and urinary iodine excretion levels. The highest prevalence of goiter (54%) was found in Kiev, where the incidence of childhood cancer was relatively low. However, the Kiev area was also identified as an endemic iodine-deficient zone. The opposite was found in Gomel, i.e. no profound iodine deficiency and a lower rate of thyroid nodules (18%) in an area with a higher rate of childhood thyroid cancer.

346. For inhabitants of the Bryansk region in the Russian Federation who were born before the accident and examined with ultrasound, the overall prevalence of thyroid abnormalities did not differ when contaminated and uncontaminated areas were compared [K10]. A difference was revealed when age was taken into consideration. For those 0–9 years of age at the time of the accident, the prevalence of thyroid abnormalities was 8.1% in the exposed cohort compared with 1.6% in the non-exposed. The corresponding figures for individuals 10–27 years in 1986 were 18.8% and 17.7%, respectively. Approximately half of the pathological findings identified through ultrasound were also noticed at palpation.

347. The prevalence of thyroid antibodies (antithyroglobulin and antithyroperoxidase) in children and adolescents in Belarus was measured in 287 individuals residing in contaminated areas (average ^{137}Cs contamination, 200 kBq m^{-2}) and compared to the findings in 208 individuals living in uncontaminated areas (average ^{137}Cs contamination, <3.7 kBq m^{-2}) [P20]. All individuals were younger than 12 years at time of the accident. Significantly elevated concentrations of thyroid antibodies were found among the exposed individuals with most pronounced concentrations in girls of puberty age. No indication of thyroid dysfunction was found, but the future development of clinically relevant thyroid disorders was thought to be a possibility.

348. Blood samples from 12,803 children living in the Kaluga region were studied for antibodies to thyroid antigen with a modifying reaction of passive haemoagglutination [S15]. In the sixth year after the accident, the reaction showed positive results in only a small percentage of samples (1.2%–4.8%). However, in children from contaminated areas, the percentage of positive results was consistently higher than in children from uncontaminated areas.

349. Similar results were found in a Russian study in which 89 exposed and 116 non-exposed children were examined [K28]. There was no apparent alteration in thyroid function, but a higher rate of thyroid antibodies was found in the exposed group. This group also had a lower percentage of individuals with iodine deficiency, as defined by urinary iodine excretion (76%), than groups living in uncontaminated areas (92%), but at the same time a fivefold greater rate of thyroid enlargement was identified by ultrasound. No sex difference was seen for goiters in the exposed group compared with a 1:2 male to female ratio in the non-exposed group.

350. Fifty-three Ukrainian children (0–7 years of age at the time of the accident) living in contaminated areas were compared with 45 children living in supposedly uncontaminated regions [V1]. The level of antithyroglobulin, thyroid-stimulating hormone and abnormal findings at ultrasound were higher in the exposed individuals, and it was concluded that there was a dose-response relationship. In contrast, no difference in thyroid function was noticed when 888 Belarusian schoolchildren living in contaminated areas were compared with 521 age-matched, non-exposed controls [S10]. Both groups lived in iodine- deficient areas, and the prevalence of diffuse goiter was significantly higher in the exposed group. Thyroid antibodies were not measured.

351. When 143 children 5 to 15 years old at examination living in a contaminated area were compared with 40 age- and sex-matched controls living in clean areas of the Tula region of the Russian Federation, a higher prevalence of thyroid autoimmunity was found in the exposed group [V10]. The difference was only noticed in those less than 5 years of age at the time of the accident, and no difference in thyroid function was noticed.

352. A total of 700,000 persons from the former Soviet Union have immigrated to Israel, approximately 140,000 of whom come from territories affected by the Chernobyl accident [Q1, Q2]. The thyroid status of 300 immigrant children voluntarily brought for thyroid examination by their parents was evaluated. Enlarged thyroid glands were found in about 40% of subjects, irrespective of whether they came from the contaminated or uncontaminated areas, i.e. ^{137}Cs greater or less than 37 kBq m^{-2} [Q1, Q2]. Thyroid-stimulating hormone levels, although within normal limits, were significantly higher ($p < 0.02$) for girls from the more contaminated regions.

353. Thyroid screening was performed in 1,984 Estonian recovery operation workers through palpation of the neck by a thyroid specialist and high-resolution ultrasonography by a radiologist [I19]. Fine- needle biopsy was carried out for palpable nodules and for nodules larger than 1 cm found by ultrasound; enlarged nodules were observed in 201 individuals. The prevalence of nodules increased with age at examination but was not related to recorded dose, date of first duty at Chernobyl, duration of service at Chernobyl, or the activities carried out by the recovery operation workers. Two cases of papillary carcinoma and three benign follicular neoplasms were identified and referred for treatment [I19].

354. Thyroid examinations by ultrasound were performed on 3,208 Lithuanian recovery operation workers in 1991–1995, and thyroid nodularity (nodules > 5 mm) was detected in 117 individuals [K9]. There was, however, no significant difference in the prevalence of thyroid nodularity compared with the Lithuanian male population as a whole and no association with level of radiation dose or duration of stay in the Chernobyl area.

355. The development of hypothyroidism following high-level external or internal exposures to ionizing radiation is well known. A change in hypothyroid rates in newborns has been shown in some areas of the United States and was supposed to be related to fallout from the Chernobyl accident [M9]. These findings were challenged [W4] on the grounds that the received doses were far too low to induce hypothyroidism. Doses received in the northwestern part of the United States were approximately 1/10,000 of that received in the Chernobyl area, and extensive examinations of children in Belarus, the Russian Federation and Ukraine have not shown a relationship between dose and either hyper- or hypothyroidism [Y1].

356. ***Summary.*** Other than the occurrence of thyroid nodules in workers and in children, which is unrelated to radiation exposure, there has been no evidence of thyroid abnormalities in affected populations following the Chernobyl accident. Even the large screening programme conducted by the Chernobyl Sasakawa Health and Medical Cooperation Project in 1991–1996, involving 160,000 children, less than 10 years of age at time of the accident, there was no increased risk of hypothyroidism, hyperthyroidism or goiter that could be related to ionizing radiation. Neither was an increase in thyroid antibodies noticed, which is in contradiction with some other minor studies.

2. Somatic disorders other than thyroid

357. The first study of health effects other than cancer and thyroid disorders on a representative sample of the populations from contaminated and control districts was carried out in the framework of the International Chernobyl Project [I1]. The conclusion of this project was that, although there were significant health disorders in the populations of both contaminated and control settlements, no health disorder could be attributed to radiation exposure.

358. As discussed previously, between 1991 and 1996, the Sasakawa Memorial Health Foundation of Japan funded the largest international screening programme of children in five medical centres in Belarus, the Russian Federation and Ukraine [Y1]. In all, haematological investigations were carried out for 118,773 children. White blood cells, red blood cells, haemoglobin concentration, haematocrit, mean corpuscular volume and concentration, and platelets were measured. The prevalence of anaemia was higher in girls than in boys and ranged from 0.2% to 0.5 %. An extended examination of 322 children suggested that iron deficiency was the cause of one third of these cases. The prevalence of leukopenia was somewhat lower in girls than boys (overall range, 0.2%–1.1%), while no sex difference was seen for leukocytosis (range, 2.8%–4.9%). No differences between sexes or centres were seen for trombocytopenia (range, 0.06%–0.12%), trombocytosis (range, 1.0%–1.3%), or eosinophilia (range, 12.2%–18.9%). The prevalence of eosinophilia changed dramatically during the five years of follow-up, from 25% in 1991 to 11% in 1996. There are probably several reasons for this decline, among them better socioeconomic conditions, a greater awareness of health, and improved medical conditions. The frequency of haematological disorders showed no difference by level of ^{137}Cs contamination at the place of residency at the time of the accident, current residency, or ^{137}Cs concentration in the body [Y1].

359. A number of studies have addressed the general morbidity of populations living in contaminated areas [I8, O2, W1]. When individuals in the contaminated areas were compared with the general population in these countries, increased morbidity due to diseases of the endocrine, haematopoietic, circulatory and digestive systems was found. A higher rate of mental disorders and disability has also been noted. It is difficult to interpret these results, since the observations may be at least partly explained by the active follow-up of the exposed populations and by the fact that age and sex are not taken into account in these studies. On the other hand, they may reflect a real increase in morbidity following the Chernobyl accident, which would mainly be an effect of psycho-social trauma, since existing epidemiological studies of radiation-exposed populations are not consistent with these findings. Stress and economic difficulties following the accident are most likely influencing the results.

360. The demographic situation in Belarus has changed since the accident. People have moved to the cities to a larger extent, and the population is, on average, older as a result of the low birth rate. Mortality due to accidents and cardiovascular diseases has increased, particularly among evacuated populations and people living in zones recommended for relocation [W1]. Mortality rates in the Russian Federation regions of Kaluga and Bryansk are close to those in the rest of the country and are relatively stable over time; however, infant mortality is steadily decreasing. Except for an increase in accidental deaths in the contaminated areas, no significant difference in cause of death was found [W1]. Population growth in Ukraine, as in other parts of the former Soviet Union, has become negative. General mortality in contaminated areas is higher (14–18 per 1,000) than in the whole of Ukraine (11–12 per 1,000). The pattern in causes of death in Ukraine is stable, with some decrease in cardiovascular mortality [W1].

361. Since 1990, 4,506 children (3,121 from Ukraine, 1,018 from the Russian Federation and 367 from Belarus) from the Chernobyl area have received medical care at the Centre of Hygiene and Radiation Protection, in Cuba [G18]. Measured body burdens of ^{137}Cs were in the range 1.5–565 Bq kg^{-1} (90% of children had levels below 20 Bq kg^{-1}). Doses from external irradiation were estimated to range from 0.04 to 30 mSv (90% < 2 mSv), 2 to 5.4 mSv from internal irradiation and thyroid doses from 0 to 2 Gy (44% < 40 mGy). Assessment of overall health condition, including haematological and endocrinological indicators, did not differ when the children were divided into five groups on the basis of ^{137}Cs contamination (<37, 37–185, >185 kBq m^{-2}, evacuated, unknown).

362. The incidence of non-malignant disorders in children was evaluated using the Belarus Chernobyl registry [L19]. The children were divided into three groups: evacuated from the 30-km zone, residing (or previously residing) in areas with contamination >555 kBq m^{-2}, and born to exposed parents. Increased rates of gastritis, anaemia and chronic tonsillitis were found among all exposure categories compared to Belarus as a whole, and the highest rates were for children in the Gomel region. The authors concluded that the increases were most probably due to psycho-social factors, lifestyle, diet and increased medical surveillance and suggested that further analyses would be needed to establish aetiological factors.

363. When hormonal levels, biologically active metabolites and immunoglobulins in 132 Russian recovery operation workers were stratified by absorbed doses, no differences related to ionizing radiation were seen except for so-called biomarkers of oxidative stress, e.g. conjugated dienes [S8]. These biomarkers are, however, not specific for radiation damage and can be seen in several pathological conditions.

364. In an Estonian cohort of 4,833 recovery operation workers, 144 deaths were identified in the period 1986–1993, compared with 148 expected [R13, T6]. A relatively high number of deaths were due to accidents, violence and poisoning. In nearly 20%, the cause of death was suicide, and the relative risk of 1.52 (n = 28) was statistically significant [R13, T6].

365. A Lithuanian cohort of 5,446 recovery operation workers was followed regularly at the Chernobyl Medical Centre during the years 1987–1995, and 251 deaths were observed [K3]. The major causes of death were injuries and accidents, and the overall mortality rate of the recovery operation workers was not higher than that of the total population.

3. Immunological effects

366. Acute as well as fractionated exposures to low doses of ionizing radiation have been reported to alter several immunological parameters in experimental animals. It is, however, not clear what effects are found in humans. Many papers have been published in the last decade on the immunological effects of exposure to radiation from the Chernobyl accident. Since it is unclear, however, if possible confounding factors have been taken into account, including, in particular, infections and diet, it is difficult to interpret the results.

367. The immunological status of 1,593 recovery operation workers was studied by Kosianov and Morozov [K24]. A moderate decrease in the number of leukocytes was observed, as well as a decrease in T-lymphocytes and periodic decreases in the number of B-lymphocytes and in immunoglobulin level. These disturbances lasted for 4–6 months in individuals with a dose <2.5 mGy and about a year in those with doses from 2.5 to 7 mGy.

368. The immune status of 85 recovery operation workers who were professional radiation workers from the Mayak plant was studied carefully between 9 and 156 days after they finished work in the Chernobyl area [T17]. The radiation doses were between 1 and 330 mGy. Only some decreases in T-lymphocytes and increases in null-lymphocytes showed causal relations to the radiation dose.

369. A three-year study of 90 recovery operation workers living in the town of Chelyabinsk [A1] showed that the average numbers of leukocytes, neutrophyls and lymphocytes in the whole period were the same as in the control group, consisting of the general population of Chelyabinsk with the same age and sex distribution. During the first and second years, a moderate increase of IgM level in blood was found, while a slight decrease was seen in the first month; complete recovery was seen in the third year [A1].

370. A five-year study of the immunological status of 62 helicopter pilots exposed to radiation doses from 180 to 260 mGy did not reveal significant quantitative changes in functional characteristics of T- and B-lymphocytes [U15]. Among persons with the highest doses and with some chronic diseases, however, an increase in the functional activity of B-lymphocytes and other non-specific changes in immune status were observed.

371. A careful immunological study of 500 healthy children evacuated from Pripyat with doses from 0.05 to 0.12 Gy did not show significant differences in comparison with Kiev-resident children of the same age [B8]. This study considered the T-lymphocyte subpopulation, natural killer activity, levels of immune complexes, and of interleukin-1 and -2. Some changes in immunoglobulin-A with hypoglobulineaemia and other functional changes were found in children who suffered from respiratory allergy and chronic infections.

372. No differences in absolute and relative levels of T-lymphocytes were found in more than 1,000 examined children living in contaminated areas of the Gomel and Mogilev regions [G20]. A slight increase in serum Ig-G level and B-lymphocytes was observed in children 3–7 years old at the time of examination. The study was conducted in the second year after the accident.

373. Immune status was studied in 84 children 7–14 years old (at the time of the accident) and living in contaminated areas of Belarus and in a control group of 60 children (with the same age and sex distribution) living in uncontaminated areas [K25]. The study was conducted four and half years after the accident. A direct association was observed between the T-lymphocyte levels in children from contaminated areas and the average reconstructed dose from radioiodine to the thyroid in the settlements where the children resided.

374. While evaluating the significance of these various findings, it must be borne in mind that the doses received by the subjects were unlikely to directly affect constituents of the immune system. The long period over which disturbances of

immune function were observed are not consistent with the understanding of recovery of immune functions following acute exposure of experimental animals. It is quite likely, therefore, that psychological stress mediated by neuro-endocrine factors, cytokines, respiratory allergies, chronic infections, and autoimmunity related imbalances could have caused the fluctuations in some immunological parameters in different groups of subjects.

375. ***Summary***. With the exception of the increased risk of thyroid cancer in those exposed at young ages, no somatic disorder or immunological defect could be associated with ionizing radiation caused by the Chernobyl accident.

C. PREGNANCY OUTCOME

376. In a group of Belarusian children born to exposed mothers with *in utero* doses ranging from 8 to 21 mSv, no relationship between birth defects and residency in contaminated areas was seen [L5]. The observations that the defects were largely of multifactorial origin and varied according to the residency of the mother appeared to reflect the influence of complex and multiple non-radiation factors. No consistent relationship was seen between the detected rate of chromosome and chromatid aberrations in children and the level of radioactive ground contamination.

377. Later studies of birth defects and malformations in Belarus yielded conflicting results [L8]. The studies conducted on all legal medical abortions from 1982 to 1994 revealed increased rates of polydactyly, limb reduction, and multiple malformations in highly contaminated areas (>555 kBq m^{-2}) when pre- and post-accidental rates were compared [L8]. In the less contaminated areas (<37 kBq m^{-2}), increased rates of anenchephaly, spina bifida, cleft lip/palate, polydactyly, limb reduction and multiple malformations were noted. The city of Minsk was used as a control, and spina bifida, polydactyly, multiple malformations, and Down's syndrome were found to have increased. No changes in birth defects over time could be related to exposure to ionizing radiation.

378. One explanation to the findings of Lazjuk [L8] could be that classification of birth disorders has not been consistent over time, probably reflecting the lack of clarity of diagnostic criteria and the significant improvement in diagnostic procedures. Only a few reliable clinical studies have been undertaken in representative groups and regions [K5], and these studies suggest that the observed shifts in the health status of children are unlikely to have been caused by radiation exposure only.

379. Somewhat conflicting results have also been reported when reproductive outcomes in contaminated areas of the Russian Federation were examined [B19, L27, L28, L29]. The outcomes before and after the accident were compared in regions of different contamination levels. The results are summarized in Table 68. Birth rates decreased in all three regions and were related to severity of contamination, while spontaneous abortions increased in two of the three regions. Congenital malformations, stillbirths, premature births and perinatal mortality were studied, but no consistency or apparent relationship to ionizing radiation was noticed.

380. The frequency of unfavourable pregnancy outcomes for 1986–1992 was studied through interviews of 2,233 randomly selected women from 226 contaminated settlements of Belarus and the Russian Federation [G11]. In the contaminated areas of Gomel and Mogilev (Belarus) and of Bryansk (the Russian Federation), a decrease in the birth rate in both urban and rural populations was reported. This corresponds to an increase in the number of medical abortions in both populations.

381. Studies of chromosomal aberrations in distant populations have been critically reviewed [L32, V5]. Increased numbers of cases of Down's syndrome were reported in West Berlin in January 1987 [S23], in the region of Lothian, in Scotland [R14] and in the most contaminated areas of Sweden [E4]. All studies were based on a small number of cases and were later challenged [B13]. The doses in Berlin and Scotland reached 10% of the natural background irradiation, and it is not likely that this contribution was enough to cause the non-disjunction in oocytes during meiosis that is needed for the specific aneuploidy of Down's syndrome. The findings have not been confirmed in larger and more representative series in Europe [D9, L32]. In particular, no peak in Down's syndrome among children exposed at time of conception was observed in equally contaminated zones of Europe (e.g. Finland) or even in Belarus [B34, V5]. In a careful study of birth defects in Belarus, no increased rate of Down's syndrome was found when pre- and post-accident figures were compared in contaminated areas [L8].

382. According to a recent paper [K4], perinatal mortality in Germany showed a statistically significant increase in 1987, and it was concluded that this was an effect of the Chernobyl accident fallout. The findings were later questioned, since whole-body doses from incorporated caesium were found to be 0.05 mSv [R19]. No effect of the Chernobyl accident could be found when temporal patterns of perinatal mortality in Bavaria were correlated to different fallout levels and subsequent exposures [G24].

383. ***Summary***. Several studies on adverse pregnancy outcomes related to the Chernobyl accident have been performed in the areas closest to the accident and in more distant regions. So far, no increase in birth defects, congenital malformations, stillbirths, or premature births could be linked to radiation exposures caused by the accident.

D. PSYCHOLOGICAL AND OTHER ACCIDENT-RELATED EFFECTS

384. Many aspects of the Chernobyl accident have been suggested to cause psychological disorders, stress and anxiety in the population. The accident caused long-term changes in the lives of people living in the contaminated districts, since measures intended to limit radiation doses included resettlement, changes in food supplies and restrictions on the activities of individuals and families. These changes were accompanied by important economic, social and political changes in the affected countries, brought about by the disintegration of the former Soviet Union. These psychological reactions are not caused by ionizing radiation but are probably wholly related to the social factors surrounding the accident.

385. The decisions of individuals and families to relocate were often highly complex and difficult. The people felt insecure, and their lack of trust in the scientific, medical and political authorities made them think they had lost control [H9]. Experts who tried to explain the risks and mollify people were perceived as denying the risk, thus reinforcing mistrust and anxiety.

386. The environmental contamination created widespread anxiety that should be referred to not as radiophobia, as it initially was, but as a real, invisible threat, difficult to measure and localize. The key to how people perceive risk is the degree of control they exert over it. Once measures are taken to improve the quality of life for those still living in contaminated areas, the climate of social trust improves, probably because of the better cooperation between inhabitants and local authorities [H9].

387. Psychological effects related to the Chernobyl accident have been studied extensively [I1, L3, L4]. Symptoms such as headache, depression, sleep disturbance, inability to concentrate, and emotional imbalance have been reported and seem to be related to the difficult conditions and stressful events that followed the accident.

388. The psychological development of 138 Belarusian children who were exposed to radiation from the Chernobyl accident *in utero* was compared with that of 122 age-matched children from uncontaminated areas [K46]. The children were followed for 6–12 years and the study included neurological, psychiatric and intellectual assessments of children and parents. The exposed group was found to have a slightly lower intellectual capability and more emotional disorders. A correlation was found between anxiety among parents and emotional stress in children. It was concluded that unfavourable psychosocial factors, such as broken social contacts, adaptation difficulties, and relocation, explained the differences between the exposed and non-exposed groups. No differences could be related to ionizing radiation.

389. Many individuals affected by the Chernobyl accident are convinced that radiation is the most likely cause of their poor health [H7]. This belief may cause or amplify psychosomatic distress in these individuals. When studying the impact of the accident in exposed areas of Belarus, Havenaar et al. [H11, H12] found that depression, general anxiety and adjustment disorders were more prevalent among those evacuated and in mothers with children under 18 years of age. It was concluded that the Chernobyl accident had had a significant long-term impact on psychological well-being, health-related quality of life, and illness in the exposed populations [H10]. However, none of the findings could be directly attributed to ionizing radiation.

390. Post-traumatic stress is an established psychiatric diagnostic category involving severe nightmares and obsessive reliving of the traumatic event. Although it is widely perceived by victims of disasters, such stress is supposed to occur only in those persons who were directly and immediately involved. The uncertainty, threat and social disruption felt by the wider public has been termed chronic environmental stress disorder by Lee [L3], who compared the consequences of the Chernobyl accident with the consequences of other destructive events and accidents.

391. Among recovery operation workers, those without occupational radiation experience suffered a higher rate of neurotic disturbances than the general population [R5, S13]. Clinically expressed disturbances with significant psychosomatic symptoms were predominant in this group, but the increased medical attention, which leads to the diagnosis of chronic somatic diseases and subclinical changes that persistently attract the attention of the patient, complicates the situation. The possibility of rehabilitation decreased correspondingly, while unsatisfactory and unclear legislation exacerbated the conflicts and tended to prolong the psychoneurotic reactions of the patients [G4, S13]. The health status of recovery operation workers who were nuclear industry professionals did not seem to be different from that of the rest of the cohort [N3].

392. Social and economic suffering among individuals living in contaminated areas has exacerbated the reactions to stressful factors. Although the incidence of psychosomatic symptoms in the population of highly contaminated areas is higher than that in populations of less contaminated areas, no direct correlation with radiation dose levels has been observed. The self-appraisal of this group is low, as is their general physical health, as observed in systematic screening programmes, including the International Chernobyl Project [I1]. This makes the individuals functionally unable to solve complicated social and economic problems and aggravates their psychological maladaptation. The tendency to attribute all problems to the accident leads to escapism, “learned helplessness”, unwillingness to cooperate, overdependence, and a belief that the welfare system and government authorities should solve all problems. It also contributes to alcohol and drug abuse. There is evidence of an increased incidence of accidents (trauma, traffic incidents, suicides, alcohol intoxication and sudden death with unidentified cause) in this population, as well as in recovery operation workers, compared with the populations of unaffected regions.

393. A follow-up study of the psychological status of 708 emigrants to Israel from the former Soviet Union was carried out over a two-year period [C3]. A total of 374 adults who had lived in contaminated areas and for whom body-burden measurements had been carried out and 334 non-exposed emigrants matched by age, sex and year of emigration were compared. The subjects from exposed areas were categorized into two exposure groups: high and low (^{137}Cs greater or less than 37 kBq m^{-2}) on the basis of the map of ground caesium contamination [I1]. The prevalence of post-traumatic stress disorders, depression, anxiety and psychosomatic effects, such as high blood pressure and chronic illness, were measured. Interviews were carried out during the initial contact and approximately one year later with 520 of the original respondents. The results obtained in the first interview showed that psychological symptoms were much more prevalent in the exposed groups than in the non-exposed group; in the second interview, a decline in the prevalence of disorders was noted. The proportion of those who reported three or more chronic health problems was 48% among the high-exposure group, 49% in the low-exposure group, and 31% in the non-exposed group ($p < 0.0003$). Based on these results, the authors concluded that the Chernobyl accident had had a strong impact on both the mental and physical health of the immigrants from contaminated areas of the former Soviet Union.

394. ***Summary***. The Chernobyl accident caused long-term changes in the lives of people living in the contaminated areas, since measures intended to limit radiation dose included resettlement, changes in food supplies, and restrictions on the activities of individuals and families. These changes were accompanied by important economic, social, and political changes in the affected countries, brought about by the disintegration of the former Soviet Union. The anxiety and emotional stress among parents most likely influenced the children, and unfavourable psychosocial factors probably explain the differences between the exposed and non-exposed groups.

E. SUMMARY

395. A majority of the studies completed to date on the health effects of the Chernobyl accident are of the geographic correlation type that compare average population exposure with the average rate of health effects or cancer incidence in time periods before and after the accident. As long as individual dosimetry is not performed no reliable quantitative estimates can be made. The reconstruction of valid individual doses will have to be a key element in future research on health effects related to the Chernobyl accident.

396. The number of thyroid cancers in individuals exposed in childhood, particularly in the severely contaminated areas of the three affected countries, is considerably greater than expected based on previous knowledge. The high incidence and the short induction period have not been experienced in other exposed populations, and factors other than ionizing radiation are almost certainly influencing the risk. Some such factors include age at exposure, iodine intake and metabolic status, endemic goitre, screening, short-lived isotopes other than ^{131}I, higher doses than estimated, and, possibly, genetic predisposition. Approximately 1,800 thyroid cancer cases have been reported in Belarus, the Russian Federation and Ukraine in children and adolescents for the period 1990–1998. Age seems to be an important modifier of risk. The influence of screening is difficult to estimate. Approximately 40%–70% of the cases were found through screening programmes, and it is unclear how many of these cancers would otherwise have gone undetected. Taking the advanced stage of the tumours at time of diagnosis into consideration, it is likely that most of the tumours would have been detected sooner or later.

397. The present results from several studies indicate that the majority of the post-Chernobyl childhood thyroid carcinomas show the intrachromosomal rearrangements characterized as *RET/PTC1* and *3*. There are, however, several questions left unanswered, e.g. the influence of age at exposure and time since exposure on the rate of chromosome rearrangements.

398. The risk of leukaemia has been shown in epidemiological studies to be clearly increased by radiation exposure. However, no increased risk of leukaemia linked to ionizing radiation has so far been confirmed in children, in recovery operation workers, or in the general population of the former Soviet Union or other areas with measurable amounts of contamination from the Chernobyl accident.

399. Increases in a number of non-specific detrimental health effects other than cancer in recovery operation workers and in residents of contaminated areas have been reported. It is 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, are often passively recorded and are not always complete, it is not appropriate to compare them with data for the exposed populations, who undergo much more intensive and active health follow-up than the general population.

400. Some investigators have interpreted a temporary loss of ability to work among individuals living in cotaminated areas as an increase in general morbidity. High levels of chronic diseases of the digestive, neurological, skeletal, muscular and circulatory systems have been reported. However, most investigators relate these observations to changes in the age structure, the worsening quality of life, and post-accident countermeasures such as relocation.

401. Many papers have been published in the last decade on the immunological effects of exposure to radiation from the Chernobyl accident. Since it is unclear, however, if possible confounding factors have been taken into account, including, in particular, infections and diet, it is difficult to interpret these results.

CONCLUSIONS

402. The accident of 26 April 1986 at the Chernobyl nuclear power plant, located in Ukraine about 20 km south of the border with Belarus, was the most serious ever to have occurred in the nuclear industry. It caused the deaths, within a few days or weeks, of 30 power plant employees and firemen (including 28 with acute radiation syndrome) and brought about the evacuation, in 1986, of about 116,000 people from areas surrounding the reactor and the relocation, after 1986, of about 220,000 people from Belarus, the Russian Federation and Ukraine. Vast territories of those three countries (at that time republics of the Soviet Union) were contaminated, and trace deposition of released radionuclides was measurable in all countries of the northern hemisphere. In this Annex, the radiation exposures of the population groups most closely involved in the accident have been reviewed in detail and the health consequences that are or could be associated with these radiation exposures have been considered.

403. The populations considered in this Annex are (a) the workers involved in the mitigation of the accident, either during the accident itself (emergency workers) or after the accident (recovery operation workers) and (b) members of the general public who either were evacuated to avert excessive radiation exposures or who still reside in contaminated areas. The contaminated areas, which are defined in this Annex as being those where the average ^{137}Cs ground deposition density exceeded 37 kBq m^{-2} (1 Ci km^{-2}), are found mainly in Belarus, in the Russian Federation and in Ukraine. A large number of radiation measurements (film badges, TLDs, whole-body counts, thyroid counts, etc.) were made to evaluate the exposures of the population groups that are considered.

404. The approximately 600 emergency workers who were on the site of the Chernobyl power plant during the night of the accident received the highest doses. The most important exposures were due to external irradiation (relatively uniform whole-body gamma irradiation and beta irradiation of extensive body surfaces), as the intake of radionuclides through inhalation was relatively small (except in two cases). Acute radiation sickness was confirmed in 134 of those emergency workers. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy. Ninety-three patients received higher doses and had more severe acute radiation sickness: 50 persons with 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 from beta exposures, evaluated for eight patients with acute radiation sickness, were in the range of 400–500 Gy.

405. About 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators (recovery operation workers), 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 and of a town for reactor personnel. These tasks were completed by 1990.

406. A registry of recovery operation workers was established in 1986. This registry includes estimates of effective doses from external irradiation, which was the predominant pathway of exposure for the recovery operation workers. The registry data show that the average recorded doses decreased from year to year, being about 170 mSv in 1986, 130 mSv in 1987, 30 mSv in 1988, and 15 mSv in 1989. It is, however, difficult to assess the validity of the results that have been reported because (a) different dosimeters were used by different organizations without any intercalibration; (b) a large number of recorded doses were very close to the dose limit; and (c) there were a large number of rounded values such as 0.1, 0.2, or 0.5 Sv. Nevertheless, it seems reasonable to assume that the average effective dose from external gamma irradiation to recovery operation workers in the years 1986–1987 was about 100 mSv.

407. Doses received by the general public came from the radionuclide releases from the damaged reactor, which led to the ground contamination of large areas. The radionuclide releases occurred mainly over a 10-day period, with varying release rates. From the radiological point of view, the releases of ^{131}I and ^{137}Cs, estimated to have been 1,760 and 85 PBq, respectively, are the most important. Iodine-131 was the main contributor to the thyroid doses, received mainly via internal irradiation within a few weeks after the accident, while ^{137}Cs was, and is, the main contributor to the doses to organs and tissues other than the thyroid, from either internal or external irradiation, which will continue to be received, at low dose rates, during several decades.

408. The three main contaminated areas, defined as those with ^{137}Cs deposition density 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. The Central area is within about 100 km of the reactor, predominantly to the west and northwest. The Gomel-Mogilev-Bryansk contaminated area is centred 200 km north-northeast of the reactor at the boundary of the Gomel and Mogilev regions of Belarus and of the Bryansk region of the Russian Federation. The Kaluga-Tula-Orel area is in the Russian Federation, about 500 km to the northeast of the reactor. All together, territories from the former Soviet Union with an area of about 150,000 km^2 were contaminated with ^{137}Cs deposition density greater than 37 kBq m^{-2}. About five million people reside in those territories.

409. Within a few weeks after the accident, more than 100,000 persons were evacuated from the most contaminated areas of Ukraine and of Belarus. The thyroid doses received by the evacuees varied according to their age, place of residence, dietary habits and date of evacuation. For example, for the residents of Pripyat, who were evacuated essentially within 48 hours after the accident, the population-weighted average thyroid dose is 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 is estimated to be 0.47 Gy. Doses to organs and tissues other than the thyroid were, on average, much smaller.

410. Thyroid doses also have been estimated for the residents of the contaminated areas who were not evacuated. In each of the three republics, thyroid doses are estimated to have exceeded 1 Gy 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 was approximately 0.2 Gy; the variability of the thyroid dose was two orders of magnitude, both above and below the average.

411. Following the first few weeks after the accident, when ^{131}I was 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 came essentially from external exposure from ^{134}Cs and ^{137}Cs deposited on the ground and internal exposure due to the contamination of foodstuffs by ^{134}Cs and ^{137}Cs. Other, usually minor, contributions to the long-term radiation exposures include the consumption of foodstuffs contaminated with ^{90}Sr and the inhalation of aerosols containing plutonium isotopes. Both external irradiation and internal irradiation due to ^{134}Cs and ^{137}Cs result in relatively uniform doses in all organs and tissues of the body. The average effective doses from ^{134}Cs and ^{137}Cs that were received during the first 10 years after the accident by the residents of contaminated areas are estimated to be about 10 mSv.

412. The papers available for review by the Committee to date regarding the evaluation of health effects of the Chernobyl accident have in many instances suffered from methodological weaknesses that make them difficult to interpret. The weaknesses include inadequate diagnoses and classification of diseases, selection of inadequate control or reference groups (in particular, control groups with a different level of disease ascertainment than the exposed groups), inadequate estimation of radiation doses or lack of individual data and failure to take screening and increased medical surveillance into consideration. The interpretation of the studies is complicated, and particular attention must be paid to the design and performance of epidemiological studies. These issues are discussed in more detail in Annex I, "*Epidemiological evaluation of radiation-induced cancer*".

413. Apart from the substantial increase in thyroid cancer after childhood exposure observed in Belarus, in the Russian Federation and in Ukraine, there is no evidence of a major public health impact related to ionizing radiation 14 years after the Chernobyl accident. No increases in overall cancer incidence or mortality that could be associated with radiation exposure have been observed. For some cancers no increase would have been anticipated as yet, given the latency period of around 10 years for solid tumours. The risk of leukaemia, one of the most sensitive indicators of radiation exposure, has not been found to be elevated even in the accident recovery operation workers or in children. There is no scientific proof of an increase in other non-malignant disorders related to ionizing radiation.

414. The large number of thyroid cancers in individuals exposed in childhood, particularly in the severely contaminated areas of the three affected countries, and the short induction period are considerably different from previous experience in other accidents or exposure situations. Other factors, e.g. iodine deficiency and screening, are almost certainly influencing the risk. Few studies have addressed these problems, but those that have still find a significant influence of radiation after taking confounding influences into consideration. The most recent findings indicate that the thyroid cancer risk for those older than 10 years at the time of the accident is leveling off, the risk seems to decrease since 1995 for those 5–9 years old at the time of the accident, while the increase continues for those younger than 5 years in 1986.

415. There is a tendency to attribute increases in cancer rates (other than thyroid) over time to the Chernobyl accident, but it should be noted that increases were also observed before the accident in the affected areas. Moreover, a general increase in mortality has been reported in recent years in most areas of the former USSR, and this must also be taken into account in interpreting the results of the Chernobyl-related studies. Because of these and other uncertainties, there is a need for well designed, sound analytical studies, especially of recovery operation workers from Belarus, the Russian Federation, Ukraine and the Baltic countries, in which particular attention is given to individual dose reconstruction and the effect of screening and other possible confounding factors.

416. Increases of a number of non-specific detrimental health effects other than cancer in accident recovery workers have been reported, e.g. increased suicide rates and deaths due to violent causes. It is difficult to interpret these findings without reference to a known baseline or background incidence. The exposed populations undergo much more intensive and active health follow-up than the general population. As a result, using the general population as a comparison group, as has been done so far in most studies, is inadequate.

417. Adding iodine to the diet of populations living in iodine-deficient areas and screening the high-risk groups could limit the radiological consequences. Most data suggest that the youngest age group, i.e. those who were less than five years old at the time of the accident, continues to have an increased risk of developing thyroid cancer and should be closely monitored. In spite of the fact that many thyroid cancers in childhood are presented at a

more advanced stage in terms of local aggressiveness and distant metastases than in adulthood, they have a good prognosis. Continued follow-up is necessary to allow planning of public health actions, to gain a better understanding of influencing factors, to predict the outcomes of any future accidents, and to ensure adequate radiation protection measures.

418. Present knowledge of the late effects of protracted exposure to ionizing radiation is limited, since the dose-response assessments rely heavily on high-dose exposure studies and animal experiments. The Chernobyl accident could, however, shed light on the late effects of protracted exposure, but given the low doses received by the majority of exposed individuals, albeit with uncertainties in the dose estimates, any increase in cancer incidence or mortality will most certainly be difficult to detect in epidemiological studies. The main goal is to differentiate the effects of the ionizing radiation and effects that arise from many other causes in exposed populations.

419. Apart from the radiation-associated thyroid cancers among those exposed in childhood, the only group that received doses high enough to possibly incur statistically detectable increased risks is the recovery operation workers. Studies of these populations have the potential to contribute to the scientific knowledge of the late effects of ionizing radiation. Many of these individuals receive annual medical examinations, providing a sound basis for future studies of the cohort. It is, however, notable that no increased risk of leukaemia, an entity known to appear within 2–3 years after exposure, has been identified more than 10 years after the accident.

420. The future challenge is to provide reliable individual dose estimates for the subjects enrolled in epidemiological studies and to evaluate the effects of doses accumulated over protracted time (days to weeks for thyroid exposures of children, minutes to months for bone-marrow exposures of emergency and recovery operation workers, and months to years for whole-body exposures of those living in contaminated areas). In doing this, many difficulties must be taken into consideration, such as (a) the role played by different radionuclides, especially the short-lived radioiodines; (b) the accuracy of direct thyroid measurements; (c) the relationship between ground contamination and thyroid doses; and (d) the reliability of the recorded or reconstructed doses for the emergency and recovery operation workers.

421. Finally, it should be emphasized that although those exposed as children and the emergency and recovery operation workers 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. For the most part, they were exposed to radiation levels comparable to or a few times higher than the natural background levels, and future exposures are diminishing as the deposited radionuclides decay. Lives have been disrupted by the Chernobyl accident, but from the radiological point of view and based on the assessments of this Annex, generally positive prospects for the future health of most individuals should prevail.

Table 1
Radionuclide inventory in Unit 4 reactor core at time of the accident on 26 April 1986

Radionuclide	*Half-life*	*Activity (PBq)*			
		1986 estimates [a] *[I2]*	*Estimates by [B1, I2]*	*Estimates by [S1]*	*Estimates by [B2, B3, B4]* [b]
^{3}H	12.3 a			1.4 [d]	
^{14}C	5 730 a			0.1 [d]	
^{85}Kr	10.72 a	33	33	28	
^{89}Sr	50.5 d	2 000	2 330	3 960	
^{90}Sr	29.12 a	200	200	230	220
^{95}Zr	64.0 d	4 400	4 810	5 850	
^{95}Nb	35 d			5 660	
^{99}Mo	2.75 d	4 800	5 550	6 110	
^{103}Ru	39.3 d	4 100	4 810	3 770	
^{106}Ru	368 d	2 100	2 070	860	850
^{110m}Ag	250 d			1.3	
^{125}Sb	2.77 a			15	
^{129m}Te	33.6 d			1 040	
^{132}Te	3.26 d	320	2 700	4 480	4 200 [f]
^{129}I	15 700 000 a			0.000081 [d]	
^{131}I	8.04 d	1 300	3 180	3 080	3 200 [f]
^{132}I	2.3 h			4 480	4 200 [f]
^{133}I	20.8 h			6 700	4 800 [f]
^{134}I	52.6 min				2 050 [f]
^{135}I	6.61 h				2 900 [f]
^{133}Xe	5.25 d	1 700	6 290	6 510	
^{134}Cs	2.06 a	190	190	170	150
^{136}Cs	13.1 d			110 [e]	
^{137}Cs	30.0 a	290	280	260	260
^{138}Cs	32.2 min			6 550	
^{140}Ba	12.7 d	2 900	4 810	6 070	
^{140}La	40.3 h			6 070	
^{141}Ce	32.5 d	4 400	5 550	5 550	
^{144}Ce	284 d	3 200	3 260	3 920	3 920
^{147}Nd	11.0 d			2 160	
^{154}Eu	8.6 a			14	
^{235}U	704 000 000 a			0.000096 [d]	
^{236}U	23 400 000 a			0.0085 [d]	
^{238}U	4 470 000 000 a			0.0023 [d]	
^{237}Np	2 140 000 a			0.00026	
^{239}Np	2.36 d	140	49 600 [c]	58,100	58 100
^{236}Pu	2.86 a			0.0001	
^{238}Pu	87.74 a	1	1.0	1.3	0.93
^{239}Pu	24065 a	0.8	0.85	0.95	0.96
^{240}Pu	6537 a	1	1.2	1.5	1.5
^{241}Pu	14.4 a	170	170	180	190
^{242}Pu	376 000 a		0.0025	0.0029	0.0021
^{241}Am	432 a			0.17	0.14
^{243}Am	7 380 a			0.0097	0.0056
^{242}Cm	163 d	26	15 [c]	43	31
^{244}Cm	18.1 a			0.43	0.18

a Decay-corrected to 6 May 1986.
b Values used in this Annex.
c Corrected to account for burnup of individual fuel assemblies.
d Reference [K1].
e Corrected value.
f Reference [K16].

Table 2
Estimates of the principal radionuclides released in the accident

Radionuclide	*Activities released (PBq)*			
	1986 estimates [a] *[I2]*	*1996 estimates* [b] *[B4, B27, D8]*	*1996 estimates* *[K37]*	*1996 estimates* [c d] *[D5, D8, N4]*
Noble gases				
^{85}Kr	33	33	33	
^{133}Xe	1 700	6 500	6 500	6 500
Volatile elements				
^{129m}Te		240		
^{132}Te	48	1 000		~1 150
^{131}I	260	1 200–1 700	1 800	~1 760
^{133}I		2 500		
^{134}Cs	19	4 4–48	50	~54
^{136}Cs		36		
^{137}Cs	38	74–85	86	~85
Intermediate				
^{89}Sr	80	81	80	~115
^{90}Sr	8	8	8	~10
^{103}Ru	120	170	120	>168
^{106}Ru	63	30	25	>73
^{140}Ba	170	170	160	240
Refractory (including fuel particles)				
^{95}Zr	130	170	140	196
^{99}Mo	96	210		>168
^{141}Ce	88	200	120	196
^{144}Ce	96	140	90	~116
^{239}Np	4.2	1 700		945
^{238}Pu	0.03	0.03	0.033	0.035
^{239}Pu	0.024	0.03	0.0334	0.03
^{240}Pu	0.03	0.044	0.053	0.042
^{241}Pu	5.1	5.9	6.3	~6
^{242}Pu	0.00007	0.00009		
^{242}Cm	0.78	0.93	1.1	~0.9
Total (excluding noble gases)	1 000–2 000	8 000 [e]-	–	5 300

a Decay-corrected to 6 May 1986.

b Estimate of release, decay-corrected to 26 April 1986.

c Estimate of total release during the course of the accident.

d Values used in this Annex.

e Decay correction to beginning of accident allows more short-lived radionuclides to be included, giving a higher estimate of total release, which, however, is a probable overestimate since many of these radionuclides would have decayed inside the damaged core before any release to the atmosphere could occur.

Table 3
Estimated daily releases of iodine-131 during the accident

Day of release	*Percentage (based on [A4, I6])*	*Daily releases (PBq)*
26 April	40.0	704
27 April	11.6	204
28 April	8.5	150
29 April	5.8	102
30 April	3.9	69
1 May	3.5	62
2 May	5.8	102
3 May	6.1	107
4 May	7.4	130
5 May	7.4	130
Total	100	1 760

Table 4
Estimated amounts of radioiodines [a] and tellurium-132
[K16]

Radionuclide	*Half-life*	*Amount in the reactor core at the time of the accident (PBq)*	*Activity released [b] (PBq)*
^{132}Te	78.2 h	4 200	1 040
^{132}I [c]	2.3 h	4 200	1 040
^{133}I	20.8 h	4 800	910
^{134}I	52.6 min	2 050	25
^{135}I	6.61 h	2 900	250

a The activity of iodine-131 in the reactor core at the time of the accident is taken to be 3,200 PBq. The release of iodine-131 is assumed to be 1,760 PBq.
b With decay correction.
c Iodine-132 is assumed to be in radioactive equilibrium with tellurium-132.

Table 5
Contaminated areas in European countries following the accident
[I24]

Country	*Area in deposition density ranges (km^2)* [a]			
	37–185 kBq m^{-2}	185–555 kBq m^{-2}	555–1 480 kBq m^{-2}	>1 480 kBq m^{-2}
Russian Federation	49 800	5 700	2 100	300
Belarus	29 900	10 200	4 200	2 200
Ukraine	37 200	3 200	900	600
Sweden	12 000	–	–	–
Finland	11 500	–	–	–
Austria	8 600	–	–	–
Norway	5 200	–	–	–
Bulgaria	4 800	–	–	–
Switzerland	1 300	–	–	–
Greece	1 200	–	–	–
Slovenia	300	–	–	–
Italy	300	–	–	–
Republic of Moldova	60	–	–	–

a The ^{137}Cs levels include a small contribution (2-4 kBq m^{-2}) from fallout from the atmospheric weapons tests carried out mainly in 1961 and 1962.

Table 6
Composition of radionuclide deposition in the near and far zones around the reactor
[B5, I6]

Radionuclide	*Ratio to ^{137}Cs release*	*Ratio to ^{137}Cs deposition* [a]					
		Near zone (<100 km)			*Far zone*		
	[B4]	*North*	*South*	*West*	*Northeast* [b]	*South* [c]	*Southeast* [d]
^{89}Sr	1.0	0.7	12	4	0.14	0.3	1.0
^{90}Sr	0.1	0.13	1.5	0.5	0.014	0.03	0.1
^{91}Y		2.7	8	5	0.06	0.17	0.6
^{95}Zr	2.0	3	10	5	0.06	0.3	1.0
^{99}Mo		3	25	8	(0.11)	(0.5)	(1.5)
^{103}Ru	2.0	2.7	12	4	1.9	2.7	6
^{106}Ru	0.4	1.0	5	1.5	0.7	1.0	2.3
^{110m}Ag		0.01	0.01	0.005	0.008	(0.01)	(0.01)
^{125}Sb		0.02	0.1	0.05	0.05	0.1	0.1
^{131}I	20	17	30	15	10	(1)	(3)
^{132}Te	5	17	13	18	(13)	(1)	(3)
^{134}Cs	0.5	0.5	0.5	0.5	0.5	0.5	0.5
^{137}Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{140}Ba	2.0	3	20	7	0.7	(0.5)	(1.5)
^{141}Ce	2.3	4	10	5	0.11	0.5	1.8
^{144}Ce	1.6	2.3	6	3	0.07	0.3	1.2
^{239}Np	20	7	140	25	(0.6)	(3)	(10)

a Decay-corrected to 26 April 1986; values from indirect data in parentheses.
b Areas of higher ^{137}Cs deposition in Belarus and Russian Federation.
c District south of Kiev.
d Northern Caucasus.

Table 7
Areal extent of ^{137}Cs contamination from the accident in the European part of the former USSR
[G16, I3]

Country / Region	*Area in deposition density ranges (km^2)*				
	37–185 kBq m^{-2}	*185–555 kBq m^{-2}*	*555–1 480 kBq m^{-2}*	*>1 480 kBq m^{-2}*	*Total*
Belarus					
Gomel	16 900	6 700	2 800	1 625	
Mogilev	5 500	2 900	1 400	525	
Brest	3 800	500			
Grodno	1 700	12			
Minsk	2 000	48			
Vitebsk	35				
Total	29 900	10 200	4 200	2 200	46 500
Russian Federation					
Bryansk	6 750	2 630	2 130	310	
Kaluga	3 500	1 420			
Tula	10 320	1 270			
Orel	8 840	130			
Other	20 350				
Total	49 760	5 450	2 130	310	57 650
Ukraine	37 200	3 200	900	600	41 900
Other republics	60				60
Total area	116 920	18 850	7 230	3 110	146 110

Table 8
Estimated ^{137}Cs deposit from the accident

^{137}Cs deposition density (kBq m^{-2})		*Area [I3] (km^2)*	*^{137}Cs deposit (PBq)*		
Range	*Mean* [a]		*Total*	*From fallout* [b]	*From Chernobyl accident*
7.4–19	12	654 200	7.8	1.3–2.6	5.2–6.5
19–37	26	211 850	5.6	0.4–0.8	4.8–5.2
37–185	83	116 920	9.7	0.2–0.4	9.3–9.5
185–555	320	18 850	6.0	0.05–0.1	5.9
555–1 480	910	7 230	6.6	0.02–0.04	6.6
>1 480	2 200	3 110	6.8	0.008–0.02	6.8
Total			42.5	2.0–4.0	38.5–40.5

a Assumed to be geometric mean of range.

b The estimated residual range in 1986 of ^{137}Cs deposition density from atmospheric nuclear weapons fallout is 2–4 kBq m^{-2}.

Table 9
Measured transfer coefficients for ^{137}Cs in natural meadows of the Polissya region in Ukraine, 1988–1989
[S40]

Type of soil	*Type of meadow*	*Transfer coefficient* [a]
Black soil loam	Floodplain humid	0.6
Loamy sand	Dry valley normal	2–3
	Floodplain humid	8–11
Soddic-podzolic loam	Dry valley normal	1–4
	Dry valley normal	5–9
Soddic-podzolic sand	Dry valley, water-saturated	13–22
	Floodplain humid	25–39
Peaty-gley	Peaty drained	30–45
	Peaty flooded	58–82
	Peaty callows	135–190

a Bq kg^{-1} of dry grass per kBq m^{-2} deposited on the ground.

Table 10
Staff on site and emergency workers in initial hours of the accident
[K23]

Professional group	*Accident witnesses*	*Emergency workers (at 8 a.m. on 26 April 1986)*
Staff of the power plant (Units 1, 2, 3 and 4)	176	374 [c]
Construction workers at Units 5 and 6	268	–
Firemen	14 [a], 10 [b]	69
Guards	23	113
Staff of the local medical facility	–	10

a Arrived on the site of the accident at 1.27 a.m.

b Arrived on the site of the accident at 1.35 a.m.

c Excluding the accident victims, the numbers of whom are given in Table 11.

Table 11
Emergency workers with acute radiation sickness following the accident
[I5]

Degree of acute radiation sickness	*Range of dose (Gy)*	*Number of patients treated* [a]		*Number of deaths* [b]	*Number of survivors*
		Moscow	*Kiev*		
Mild (I)	0.8–2.1	23	18	0 (0%)	41
Moderate (II)	2.2–4.1	44	6	1 (2%)	49
Severe (III)	4.2–6.4	21	1	7 (32%)	15
Very severe (IV)	6.5–16	20	1	20 (95%)	1
Total	0.8–16	108	26	28	106

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

Table 12
Error range of estimated external doses evaluated by cytogenetic analysis to patients admitted to Hospital 6 in Moscow
[P14]

Dose range (Gy)	*Number of persons sampled*	*Number of counted cells per sample*	*Statistical error range (%)*
10.1–13.7	7	19–100	11–18
6.1–9.5	12	19–101	11–16
4.0–5.8	16	65–630	8.6–36
2.1–3.8	33	30–300	22–56
1.0–1.9	19	30–300	33–100
0.5–0.9	17	65–900	–100; +100
0.1–0.4	25	50–350	–100; +300

Table 13
Estimated internal and external doses to victims of the accident

Personal code	*Internal absorbed dose until time of death [a] (Gy) [K17, K18]*		*External dose [b] (Gy) [G25]*
	Thyroid	*Lungs*	
25	0.021	0.00026	8.2
18	0.024	0.0028	6.4
22	0.054	0.00047	4.3
5	0.062	0.00057	6.2
9	0.071	0.00077	5.6
21	0.077	0.00068	6.4
8	0.13	0.0015	3.8
2	0.13	0.0022	2.9
19	0.21	0.0035	4.5
23	0.31	0.0023	7.5
1	0.34	0.0087	11.1
15	0.32	0.0027	6.4
16	0.47	0.0041	4.2
3	0.54	0.0068	7.2
17	0.60	0.12	5.5
4	0.64	0.034	6.5
7	0.78	0.0047	10.2
10	0.89	0.0094	8.6
11	0.74	0.029	9.1
14	0.95	0.02	7.2
20	1.9	0.019	5.6
24	2.2	0.021	3.5
13	4.1	0.04	4.2

a The relative errors in the organ doses are estimated to be less than 30%.
b Evaluated by chromosome analysis of peripheral blood lymphocytes.

Table 14
Estimates of internal doses received by surviving emergency workers [a]
[K17, K18]

Tissue	*Absorbed dose (Gy)*	
	Average [b]	*Maximum*
Bone surface	0.28	3.6
Lungs	0.25	2.4
Wall of lower large intestine	0.22	2.9
Thyroid gland	0.096	1.8
Wall of upper large intestine	0.090	1.2
Liver	0.056	0.73
Red bone marrow	0.036	0.46

a Doses estimated from measurements with whole-body counters; the relative error does not exceed 45%.
b The doses were averaged over 375 individuals.

Table 15
Distribution of thyroid doses in workers treated at Hospital 6 in Moscow during April and May 1986
[G12]

Thyroid dose range [a] (Gy)	*Number of workers*
0–1.2	173
1.2–3.7	18
3.7–6.1	4
6.1–8.6	4
8.6–11	2
11–13	2
13–16	0
16–18	2
18–21	0
21–23	1
>23	2

[a] Doses assessed by repeated *in vivo* thyroid counting, except for the two workers with estimated doses greater than 23 Gy; for those two workers, the doses were assessed by repeated gamma spectrometry of bioassay samples (blood and urine). The relative error in the estimated individual thyroid doses does not exceed 30%.

Table 16
Estimated effective doses from external irradiation received by recovery operation workers in the 30-km zone during 1986–1987
[I25]

Group	*Number of workers*		*Average dose (mSv)*		*Collective dose (man Sv)*	
	1986	*1987*	*1986*	*1987*	*1986*	*1987*
Staff of nuclear power plant	2 358	4 498	87	15	210	70
Construction workers	21 500	5 376	82	25	1 760	130
Transport, security workers	31 021	32 518	6.5	27	200	870
Military servicemen	61 762	63 751	110	63	6 800	4 000
Workers from other power plants		3 458		9.3		30
Annual total or average	116 641	109 601	77	47	8 970	5 100
Total or average	226 242		62		14 070	

Table 17
Distribution of the external doses received by emergency and recovery operation workers
[K44]

Group	*Number of persons*	*Percentage in the dose interval (mSv)*						
		0–10	*10–50*	*50–100*	*100–200*	*200–250*	*250–500*	*>500*
Emergency workers and accident witnesses	820 [a]	–	–	2	4	–	7	87
Staff of nuclear power plant 1986	2 358	13	45	24	14	2	2	–
Staff of nuclear power plant 1987	4 498	66	42	1	1	–	–	–
Construction workers 1986	21 500	23	24	11	18	11	13	–
Construction workers 1987	5 376	47	23	24	4	1	1	–
Military servicemen 1986	61 762	13	22	16	23	19	19	–
Military servicemen 1987	63 751	15	15	49	15	6	6	–
Workers from other power plants 1987	3 458	78	21	1	–	–	–	–

[a] Number of persons included in the registry of the Institute of Biophysics in Moscow.

Table 18
Distribution of doses to recovery operation workers [a] as recorded in national registries
[C2, M13]

Area and period	*Number of recovery operation workers*	*Percentage for whom dose is known*	*Effective dose (mSv)*			
			Mean	*Median*	*75th percentile*	*95th percentile*
Belarus						
1986–1987	31 000	28	39	20	67	111
1986–1989	63 000	14	43	24	67	119
Russian Federation						
1986	69 000	51	169	194	220	250
1987	53 000	71	92	92	100	208
1988	20 500	83	34	26	45	94
1989	6 000	73	32	30	48	52
1986–1989	148 000	63	107	92	180	240
Ukraine						
1986	98 000	41	185	190	237	326
1987	43 000	72	112	105	142	236
1988	18 000	79	47	33	50	134
1989	11 000	86	35	28	42	107
1986–1989	170 000	56	126	112	192	293
Total						
1986	187 000	45	170			
1987	107 000	65	130			
1988	45 500	80	30			
1989	42 500	80	15			
1986–1989	381 000	52	113			

[a] Including those who worked outside the 30-km zone, but excluding those for whom the year of service is not recorded.

Table 19
Stable iodine prophylaxis among a sample of workers involved in early phases of the accident
[K44]

Time of iodine prophylaxis [a] (h)	*Number of workers*	*Percentage of sample*
Before arrival at the plant	19	11
Upon arrival at the plant	22	12.5
0–1	22	12.5
1–3	16	9
3–10	27	15
10–30	22	12.5
30–100	23	13
100–300	3	2
Did not accept prophylaxis	22	12.5
Total	176	100

[a] Counted from the time of arrival of the worker at the plant.

Table 20
Population groups evacuated in 1986 from contaminated areas

Country	*Area*	*Date*	*Number of evacuees*
Belarus [M4, S24]	51 villages within the 30-km zone	2–7 May	11 358
	28 villages outside the 30-km zone	3–10 June	6 017
	29 villages outside the 30-km zone	August/September	7 350
	Total of 108 villages		24 725
Russian Federation [S20]	4 villages of Krasnaya Gora district, Bryansk region	August	186
Ukraine [U14]	Pripyat town	27 April	49 360
	Railway station Yanov	27 April	254
	Burakovka village	30 April	226
	15 villages within the 10-km zone	3 May	9 864
	Chernobyl town	5 May	13 591
	43 villages within the 30-km zone	3–7 May	14 542
	8 villages outside the 30-km zone	14–31 May	2 424
	4 villages outside the 30-km zone	10 June–16 August	434
	Bober village	September	711
	Total of 75 settlements		91 406
Former USSR	Total of 187 settlements		116 317

Table 21
Estimates of thyroid doses from intake of ^{131}I received by the Ukrainian evacuees of towns and villages within the 30-km zone
[G8, R12]

Age at time of accident (years)	*Pripyat town [G8]*			*Chernobyl town* [a]			*Evacuated villages* [a]			*Total collective dose (man Gy)*
	Number of persons	*Arithmetic mean dose (Gy)*	*Collective dose (man Gy)*	*Number of persons*	*Arithmetic mean dose (Gy)*	*Collective dose (man Gy)*	*Number of persons*	*Arithmetic mean dose (Gy)*	*Collective dose (man Gy)*	
<1	340	2.18	741	219	1.5	329	369	3.9	1 439	2 509
1–3	2 030	1.28	2 698	653	1	653	1 115	3.6	4 014	7 265
4–7	2 710	0.54	1 463	894	0.48	429	1 428	1.7	2 428	4 320
8–11	2 710	0.23	623	841	0.15	126	1 360	0.62	843	1 592
12–15	2 710	0.12	325	846	0.11	93	1 448	0.46	666	1 084
16–18	2 120	0.066	140	650	0.09	59	941	0.39	367	566
>18	36 740	0.066	2 425	9 488	0.16	1 518	21 794	0.40	8 718	12 661
Total	49 360		8 315	13 591		3 206	28 455		18 475	29 996

a Assumes same age distribution of population as Pripyat.

Table 22
Estimates of thyroid doses from intake of ^{131}I received by the evacuees of Belarusian villages
[G15]

Age at time of accident [a] (years)	*Number of measured persons*	*Arithmetic mean thyroid dose (Gy)*	*Median thyroid dose (Gy)*	*Estimated number of residents [b]*	*Collective thyroid dose (man Gy)*
<1	145	4.3	2.3	586	2 519
1-3	290	3.7	1.7	966	3 573
4-7	432	2.1	1.2	1 199	2 517
8-11	460	1.4	0.86	1 105	1 548
12-15	595	1.1	0.61	1 392	1 531
16-17	221	1.0	0.59	704	704
>17	7 332	0.68	0.38	18 773	12 766
Total	9 475			24 725	25 158

a Derived from information on year of birth; e.g. age <1 includes children born in 1986 and 1985.
b Based on the age distribution available for 17,513 evacuees.

Table 23
Summary of estimated collective effective and thyroid doses to populations of areas evacuated in 1986

Country	*Number of persons evacuated*	*Collective dose (man Sv)*		
		Thyroid [a]	*External effective dose*	*Internal effective dose*
Belarus	24 725	25 000	770	150
Russian Federation	186	<1 000	< 10	< 10
Ukraine	91 406	30 000	1 500	1 300
Total	116 317	55 000	2 300	1 500

a Units: man Gy.

Table 24
Distribution of the estimated first-year doses from external irradiation to inhabitants of Belarus evacuated from the exclusion zone
[S24]

Dose interval (mSv)	*Number of persons in the dose interval*	
	In the absence of evacuation (calculated)	*In the evacuated population (actual)*
0-10	1 956	7 357
10-20	4 710	7 652
20-30	3 726	3 480
30-40	2 552	1 764
40-50	1 795	1 094
50-60	1 226	761
60-70	961	556
70-80	726	416
80-90	565	314
90-100	453	239
100-150	1 513	605
150-200	1 015	195
200-250	814	109
250-300	646	67
300-350	494	42
350-400	371	26
>400	1 204	28

Table 25
Inhabitants in 1986 and 1987 of the areas of strict control
[I3, I4]

Country	*Region*	*Population*	*Total population*
Belarus	Gomel Mogilev	85 700 23 300	109 000
Russian Federation	Bryansk	111 800	111 800
Ukraine	Kiev Zhitomir	20 800 31 200	52 000
Total			272 800

Table 26
Distribution of the inhabitants in 1995 of areas contaminated by the Chernobyl accident
[K23, R11, V3]

^{137}Cs deposition density (kBq m^{-2})	*Population [a]*			
	Belarus	*Russian Federation*	*Ukraine*	*Total*
37–185	1 543 514	1 654 175	1 188 800	4 386 389
185–555	239 505	233 626	106 700	579 831
555–1 480	97 593	95 474	300	193 367
Total	1 880 612	1 983 275	1 295 600	5 159 487

[a] For social and economic reasons, some of the populations living in areas contaminated below 37 kBq m^{-2} are also included.

Table 27
Values of occupancy/shielding factors used in evaluation of external exposure 0–1 year and >1 year after the accident
[B14]

Population group	*Occupancy/shielding factor*			
	Rural areas		*Urban areas*	
	0–1 year after accident	*>1 year after accident*	*0–1 year after accident*	*>1 year after accident*
Wooden houses				
Indoor workers	0.32	0.26	0.23	0.29
Outdoor workers	0.41	0.36	0.29	0.25
Schoolchildren	0.39	0.34		
Brick houses				
Indoor workers	0.24	0.22	0.15	0.13
Outdoor workers	0.34	0.31	0.23	0.20
Schoolchildren	0.31	0.29		
Both types of houses				
Representative value	0.36	0.31	0.22	0.20
UNSCEAR assessment [U4]	0.36 [a]	0.36	0.18 [a]	0.18

[a] Estimated for time period from one month to one year after the accident.

Table 28
Values of occupancy factor in the summer for rural populations of Belarus, Russian Federation, and Ukraine
[E7]

Location	*Occupancy factor*								
	Indoors			*Outdoors in same village*			*Outdoors elsewhere*		
	Belarus	*Russia*	*Ukraine*	*Belarus*	*Russia*	*Ukraine*	*Belarus*	*Russia*	*Ukraine*
Indoor workers	0.77	0.65	0.56	0.19	0.32	0.40	0.04	0.03	0.04
Outdoor workers	0.40	0.50	0.46	0.25	0.27	0.29	0.35	0.23	0.25
Retired people	0.44	0.56	0.54	0.42	0.40	0.41	0.14	0.04	0.05
Schoolchildren	0.44	0.57	0.75	0.45	0.39	0.21	0.11	0.04	0.04
Preschool children		0.64	0.81		0.36	0.19		0	0

Table 29
Ratio of external effective dose of specific population groups to that of the representative group
[B14]

Population living in	*Dose ratio to representative group*			
	Indoor workers	*Outdoor workers*	*Herders, foresters*	*Schoolchildren*
Wooden dwellings	0.8	1.2	1.7	0.8
One- or two-storey brick houses	0.7	1.0	1.5	0.9
Multi-storey buildings	0.6	0.8	1.3	0.7

Table 30
Estimated values of the overall coefficient used to calculate external effective dose on the basis of the absorbed dose in air

Country	*Type of settlement*	*Dose coefficient (mSv mGy^{-1})*	
		1986 [a]	*1987–1995*
Former USSR [M11]	Rural Small town Large town	0.28 0.19 –	0.28 0.19 0.14
Belarus [K38]	Rural Urban	0.19 0.12	0.12 0.12
Russian Federation [R9]	Rural Small town Large town	0.24 0.15 0.13	0.19 0.12 0.10
Ukraine [M16]	Rural Small town Large town	0.23 0.16 0.10	0.23 0.16 0.10

[a] Covers the time span from 26 April 1986 to 25 April 1987.

Table 31
Estimates of external effective doses per unit deposition density of ^{137}Cs for the residents of contaminated areas

Country	*Type of settlement*	*Normalized effective dose (µSv per kBq m^{-2})*				
		1986 [a]	*1987–1995*	*1986–1995*	*1996–2056*	*1986–2056*
Former USSR [b] [A12, G3, M11]	Rural Urban	13–28 7–15	34 23	47–62 30–38	48 33	95–108 63–71
Belarus [K38]	Rural Urban	19 12	36 36	55 48		
Russian Federation [M17]	Rural Urban	15 11	22 14	37 25	28 17	65 42
Ukraine [M16]	Rural Urban	24 17	36 25	60 42	28 19	88 61

[a] Covers the time span from 26 April 1986 to 25 April 1987.

[b] The estimates were obtained mainly in the empirical manner by relating the results derived from monitoring the residents of settlements in Belarus, Russian Federation, and Ukraine by means of TLD devices to the ^{137}Cs deposition density in those settlements (37–2,200 kBq m^{-2}).

Table 32
Reference values of absorbed dose rate in air per unit deposition density of ^{137}Cs

Country	*Normalized absorbed dose rate in air* [a] *(nGy h^{-1} per kBq m^{-2})*								
	1987	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*
Belarus [K38] [b]	4.5	3.1	2.3	1.9	1.6	1.4	1.3	1.2	1.0
Russian Federation [B26, M17]	3.4	2.4	1.9	1.5	1.3	1.1	1.0	0.93	0.85
Ukraine [L36]	2.1	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5
[M16]	4.5	3.0	2.3	1.9	1.6	1.4	1.3	1.2	1.1
Former USSR [A12, G3] [b]	3.0	2.4	1.9	1.6	1.3	1.1	1.0	0.89	0.79

[a] Estimated for May of the corresponding year.

[b] In publications [A12, G3, K38], the normalized absorbed dose rate in air is expressed in µR h^{-1} per Ci km^{-2}. The conversion from exposure to absorbed dose in air was made using the relationship 8.7 nGy per µR.

Table 33
Selected values of external effective dose normalized to the deposition density of ^{137}Cs for the residents of contaminated areas

Country	*Type of settlement*	*Normalized effective dose (µSv per kBq m^{-2})*				
		1986	*1987–1995*	*1986–1995*	*1996–2056*	*1986–2056*
Belarus	Rural Urban	19 12	22 14	41 26	28 17	69 43
Russian Federation	Rural Urban	15 11	22 14	37 25	28 17	65 42
Ukraine	Rural Urban	24 17	36 25	60 42	28 19	88 61

Table 34
Estimated collective effective doses to the populations of contaminated areas 1986–1995, (excluding thyroid dose)

Region	*^{137}Cs deposition density (kBq m^{-2})*	*Population*	*Collective effective dose (man Sv)*		
			External	*Internal*	*Total*
Belarus [S46]					
Brest	37–185	151 312	404	311	715
	185–555	16 183	159	118	277
	Total	167 495	563	429	992
Gomel	37–185	1 246 613	2 792	1 676	4 468
	185–555	140 732	1 556	1 237	2 793
	≥ 555	77 571	2 315	822	3 137
	Total	1 464 916	6 663	3 735	10 398
Grodno	37–185	28 060	71	57	128
	185–555	282	2.6	2.2	4.8
	Total	28 342	74	59	133
Minsk	37–185	23 809	68	61	129
	185–555	880	7	6	13
	Total	24 689	75	67	142
Mogilev	37–185	93 658	347	302	649
	185–555	81 428	796	584	1 380
	≥ 555	20 022	1 118	328	1 446
	Total	195 108	2 261	1 214	3 475
Vitebsk	37–185	62	0.12	0.11	0.23
Total	≥ 37	1 880 612	9 636	5 504	15 140
Russian Federation [B37, M17]					
Belgorod	37–185	73 350	114	48	162
Bryansk	37–185	205 625	472	1 414	1 886
	185–555	150 002	1 440	1 023	2 463
	≥ 555	95 462	2 611	799	3 410
	Total	451 089	4 523	3 236	7 759
Kaluga	37–185	91 801	201	74	275
	185–555	12 654	108	45	153
	Total	104 455	309	119	428
Kursk	37–185	133 720	278	118	396
Leningrad	37–185	8 434	18	43	61
Lipetsk	37–185	50 732	58	47	105
Mordovia	37–185	10 909	20	20	40
Orel	37–185	151 008	328	183	511
	185–555	14 435	64	34	98
	Total	165 443	392	217	609
Penza	37–185	9 910	16	16	32
Pyazan	37–185	199 687	275	313	588
Tambov	37–185	16 832	23	23	46
Tula	37–185	667 168	1 916	649	2 565
	185–555	56 535	453	115	568
	≥ 555	12	0.25	0.03	0.28
	Total	723 715	2 369	764	3 133
Ulyanovsk	37–185	2 805	4	4	8
Voronezh	37–185	32 194	55	23	78
Total	≥ 37	1 983 275	8 454	4 991	13 445

Table 34 (continued)

Region	*^{137}Cs deposition density (kBq m^{-2})*	*Number of population*		*Collective effective dose (man Sv)*					
				External		*Internal*		*Total*	
		Rural	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*
Ukraine									
Vinnyts'ka	37–185	66 000	17 100	261	34.5	73.6	36.0	335	70.5
Volyns'ka	37–185	15 400		49.7		214.3		264	
Zhytomyrs'ka	37–185	207 200	18 300	1 012	81.2	1 785	38.7	2 797	120
	185–555	21 300	66 300	332	769	264	140	596	909
	≥555	300		10.8		13.7		24.6	
Ivano-Frankivs'ka	37–185	8 500		45.1		15.4		60.5	
Kyivs'ka	37–185	243 500	142 400	941	483	570	288	1 510	771
	185–555	11 500		176		56.4		233	
Rivnens'ka	37–185	221 700	49 600	903	121	3 710	188	4 613	309
	185–555	1 400		18.1		30.8		48.9	
Sums'ka	37–185	4 500		22.7		21.2		44.0	
Ternopils'ka	37–185	7 400		29.6		11.7		41.2	
Khmel'nyts'ka	37–185	2 000		10.0		3.0		13.0	
	185–555	100		0.6		0.2		0.8	
Cherkas'ka	37–185	61 700	69 600	252	255	70.7	147	323	401
	185–555	2 900		43.2		10.7		53.9	
Chernivets'ka	37–185	18 500		87.2		31.3		119	
	185–555	3 000		35.5		10.2		45.6	
Chernihivs'ka	37–185	25 400	9 900	101	24.9	105	20.8	206	45.7
	185–555	300		4.7		3.3		7.9	
Total		922 600	373 200	4 336	1 768	7 000	858	11 340	2 626

Table 35
Distribution of estimated total effective doses received by the populations of contaminated areas, 1986–1995 (excluding thyroid dose)

Dose interval (mSv)	*Number of persons in dose interval*	*Percentage of persons in dose interval*	*Cumulative percentage of persons in dose interval*
Belarus [S46]			
<1	133 053	7.07	7.07
1–2	444 709	23.65	30.72
2–3	362 510	19.28	50
3–4	221 068	11.75	61.75
4–5	135 203	7.19	68.94
5–10	276 605	14.71	83.65
10–20	163 015	8.67	92.32
20–30	63 997	3.40	95.72
30–40	32 271	1.71	97.43
40–50	17 521	0.93	98.36
50–100	25 065	1.33	99.69
100–200	5 105	0.27	99.96
>200	790	0.04	100
Total	1 880 912	100	
Russian Federation [B37, M17, S46]			
<1	155 301	7.83	7.83
1–2	445 326	22.45	30.28
2–3	383 334	19.32	49.60
3–4	258 933	13.06	62.66
4–5	165 537	8.35	71.01
5–10	317 251	16	87.01
10–20	156 925	7.91	94.92
20–30	50 010	2.52	97.44
30–40	21 818	1.10	98.54
40–50	11 048	0.55	99.09
50–100	14 580	0.74	99.83
100–200	2 979	0.15	99.98
>200	333	0.02	100
Total	1 983 375	100	

Ukraine [L44]

Dose interval (mSv)	*Number of persons in dose interval*		*Percentage of persons in dose interval*		*Cumulative percentage of persons in dose interval*
	Rural	*Urban*	*Rural*	*Urban*	
1–2					0
2–3	26 100		2.0		2.0
3–4	57 100	38 800	4.4	3.0	9.4
4–5	97 200	111 700	7.5	8.6	25.6
5–10	294 700	145 700	22.7	11.2	59.5
10–20	290 500	77 000	22.4	6.0	87.9
20–30	99 100		7.7		95.6
30–40	31 400		2.4		98.0
40–50	18 200		1.4		99.4
50–100	7 700		0.59		99.97
100–200	400		0.03		100
Total	922 400	373 200	71.2	28.8	100

Table 36
Summary of estimated collective effective doses to the populations of contaminated areas, 1986–1995 (excluding thyroid dose)

^{137}Cs deposition density (kBq m^{-2})	*Population*	*Collective effective dose (man Sv)*		
		External	*Internal*	*Total*
Belarus [S46]				
37–185 185–555 ≥555	1 543 514 239 505 97 593	3 682 2 521 3 433	2 409 1 945 1 150	6 091 4 466 4 583
Total	1 880 612	9 636	5 504	15 140
Russian Federation [B37, M17, S46]				
37–185 185–555 ≥555	1 654 175 233 626 95 474	3 778 2 065 2 611	3 009 1 183 799	6 787 3 248 3 410
Total	1 983 275	8 454	4 991	13 445

Ukraine [L44]

^{137}Cs deposition density (kBq m^{-2})	*Population*		*Collective effective dose (man Sv)*					
			External		*Internal*		*Total*	
	Rural	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*
37–185 185–555 >555	881 800 40 400 300	306 800 66 300	3 715 610 11.0	999 769	6 610 375 13.8	717 140	10 330 986 24.8	1 717 909
Total	922 500	373 100	4 336	1 768	7 000	857	11 340	2 626

Table 37
Distribution of external dose rates before and after decontamination measures in Kirov, Belarus, in 1989 [S25]

Population group	*Measured mean dose rate (μGy d^{-1})*		*External dose ratio after/before*
	Before decontamination	*After decontamination*	
Cattle breeders	12.3	11.9	0.97
Field workers	17.5	13.2	0.75
Office workers	12.1	11.8	0.98
Housewives and retired persons	12.9	12.8	0.99
Schoolchildren	15.0	9.7	0.65
Tractor drivers	12.8	12.7	0.99
Average	13.7	12.1	0.89

Table 38
Distribution of estimated individual doses in the thyroid of children in contaminated districts of Belarus
[G13]

Absorbed dose in thyroid (Gy)	*Number of children in age range* [a]						
	<1 year	*1–3 years*	*4–7 years*	*8–11 years*	*12–15 years*	*16–18 years*	*All children*
Gomel district							
<0.05	134 (6.7)	198 (6.1)	452 (7.4)	518 (8.4)	540 (8.8)	596 (16)	2 438 (8.9)
0.05–0.1	58 (2.9)	107 (3.3)	362 (5.9)	399 (6.5)	485 (7.9)	354 (9.4)	1 765 (6.4)
0.1–0.3	224 (11)	449 (14)	1 089 (18)	1 385 (22)	1 613 (26)	1 086 (29)	5 846 (21)
0.3–1	587 (30)	963 (29)	2 023 (33)	2 365 (38)	2 364 (38)	1 119 (30)	9 421 (34)
1–2	318 (16)	590 (18)	1 075 (18)	868 (14)	695 (11)	383 (10)	3 929 (14)
>2	3 667 (34)	965 (29)	1 095 (18)	643 (10)	464 (7.5)	230 (6.1)	4 064 (15)
Total	1 988 (100)	3 272 (100)	6 096 (100)	6 178 (100)	6 161 (100)	3 768 (100)	27 463 (100)
Mogilev district							
<0.05	33 (13)	43 (9.1)	210 (19)	273 (28)	326 (29)	227 (37)	1 112 (24)
0.05–0.1	31 (12)	93 (20)	215 (19)	157 (16)	207 (19)	103 (17)	806 (18)
0.1–0.3	65 (26)	170 (36)	351 (31)	324 (33)	372 (33)	169 (28)	1 451 (32)
0.3–1	74 (29)	127 (27)	275 (25)	190 (20)	195 (17)	99 (16)	960 (21)
1–2	36 (14)	28 (5.9)	55 (4.9)	24 (2.5)	15 (1.3)	14 (2.3)	172 (3.8)
>2	14 (5.5)	14 (3.0)	16 (1.4)	1 (0.1)	1 (0.09)	1 (0.2)	47 (1.0)
Total	253 (100)	475 (100)	1 122 (100)	969 (100)	1 116 (100)	613 (100)	4 548 (100)

[a] Percent of total in parentheses.

Table 39
Thyroid doses to 0–7-year-old children and to the total population in contaminated areas of Belarus
[I28]

Region	*Number of persons*		*Average absorbed dose (Gy)*		*Collective dose (man Gy)*	
	Children	*Total*	*Children*	*Total*	*Children*	*Total*
Gomel						
Rural	23 900	238 600	1.1	0.4	25 000	98 000
Urban	8 600	85 600	0.4	0.2	3 800	15 000
Mogilev						
Rural	9 300	93 700	0.4	0.2	4 100	17 000
Urban	4 900	48 700	0.2	0.08	1 100	4 000
Total	46 700	466 600	0.7	0.3	34 000	134 000

Table 40

Estimates of collective thyroid doses to populations of Belarus, the Russian Federation, and Ukraine

Country/region	*Population*	*Collective thyroid dose (man Gy)*
Belarus [D1, G7]		
Brest	1 400 000	101 000
Gomel	1 700 000	301 000
Grodno	1 200 000	49 000
Minsk	3 200 000	68 000
Mogilev	1 300 000	32 000
Vitebsk	1 400 000	2 000
Entire country	10 000 000	553 000
Russian Federation [Z1]		
Bryansk	1 500 000	55 000
Orel	900 000	15 000
Tula	1 900 000	50 000
Bryansk, Kaluga, Kursk, Leningrad, Orel, Ryaza, and Tula [a] [S21]	3 700 000	234 000
Entire country [B14]	150 000 000	200 000–300 000
Ukraine		
Kiev [L15]	3	110 000
Eight districts [b] plus Pripyat [L12]	0.5	190 000
Entire country [L6]	55	740 000 [c]

a Only the territories with ^{137}Cs deposition densities greater than 37 kBq m^{-2} were considered.

b Situated around the Chernobyl nuclear power plant.

c Derived from an estimated collective thyroid dose of 400,000 man Gy for children aged 0–18 years in the entire Ukraine.

Table 41

Ratios of the average thyroid doses in children and teenagers to those in adults for the populations of contaminated areas in the Russian Federation

[Z6, Z7]

Age group (years)	*Urban population*	*Rural population*
<1	15±5	7±2
1–2	10±3	6±2
3–7	5±2	3±1
8–12	2.0±0.5	1.0±0.5
13–17	1.5±0.5	2.0±0.5
>17	1	1

Table 42

Input data for internal thyroid dose reconstruction in the Russian Federation

[B39]

Region	*Number of measurements*					*Personal interviews*
	^{131}I in thyroid	*^{131}I in milk*	*^{137}Cs in soil*	*^{137}Cs in food products*	*^{137}Cs in human body*	
Bryansk	12 700	2 100	2 081	217 000	300 000	17 000
Tula	644	2 157	2 308	2 000	17 000	1 800
Orel	3 600	872	1 577	17 000	10 000	–
Kaluga	28 000	256	578	18 000	28 000	6 000
Total	45 000	5 385	6 544	250 000	360 000	25 000

Table 43
Collective and average thyroid doses in population of the Russian Federation
[R3, Z1]

Region	*Population (millions)*			*Collective thyroid dose (man Gy)*			*Average thyroid dose (mGy)*		
	Urban	*Rural*	*Total*	*Urban*	*Rural*	*Total*	*Urban*	*Rural*	*Total*
Bryansk	1.0	0.5	1.5	33 000	27 000	60 000	33	54	40
Kaluga	0.8	0.3	1.1	4 000	3 000	7 000	5	10	6
Orel	0.6	0.3	0.9	8 000	5 000	13 000	13	17	15
Tula	1.5	0.4	1.9	14 000	6 000	20 000	9	15	11
Other regions [a]	-	-	16	-	-	110 000 ±30 000	-	-	7
Total	-	-	21	-	-	110 000 ±30 000	-	-	10

a Other eleven contaminated regions: Belgorod, Voronezh, Kursk, Leningrad (without city of St. Petersburg), Lipetsk, Mordovia, Penza, Ryazanj, Smolensk, Tambov, Uljanov.

Table 44
Age distribution of the collective thyroid doses to inhabitants of the Bryansk region in the Russian Federation
[Z6]

Age (years)	*Population*		*Collective thyroid dose (man Gy)*	
	Urban	*Rural*	*Urban*	*Rural*
0-2	47 000	21 000	9 000	4 000
3-5	47 000	19 000	5 000	3 000
6-9	59 000	23 000	3 000	2 000
10-15	85 000	36 000	2 000	2 000
16-19	59 000	17 000	1 000	1 000
20	694 000	368 000	13 000	15 000
Total	992 000	483 000	33 000	27 000

Table 45
Calculated mean thyroid doses for infants and adults in three districts of the Chernigov region, Ukraine
[L25]

District	*Type of settlement*	*Parameter values*			*Mean thyroid doses (Gy)*	
		K (Gy)	*a*	*b (a^{-1})*	*Infants (1 a)*	*Adults (20 a)*
Repkine	Towns	0.031	7.4	0.049	0.21	0.065
	Villages	0.082	5.0	0.094	0.35	0.11
Chernigov	City	0.030	10	0.064	0.26	0.057
	Villages	0.17	3.0	0.079	0.47	0.22
Kozelets	Towns	0.012	18	0.15	0.14	0.014
	Villages	0.047	7.4	0.062	0.30	0.085

Table 46
Estimated age-dependent thyroid dose distribution in the population of the Ukrainian regions of Cherkassy, Chernigov, Kiev, Vinnitsa, and Zhitomir [a]
[L10]

Age at the time of the accident (years)	*Percentage of age groups within dose intervals*					
	0–0.049 Gy	*0.05–0.099 Gy*	*0.1–0.29 Gy*	*0.3–0.99 Gy*	*1–1.99 Gy*	*>2 Gy*
<1	2.8	10.4	55.5	23.3	7.4	0.5
1–3	3.2	10.3	58.6	24.9	2.1	0.9
4–7	10.8	27.2	47.7	13.4	0.9	0.0
8–11	19.3	39.6	34.0	6.1	0.9	0.0
12–15	35.3	35.2	24.4	4.3	0.7	0.0
16–18	45.7	26.8	23.5	4.1	0.0	0.0
>18	54.6	21.0	21.6	2.8	0.0	0.0

[a] Excludes the 30-km zone and city of Kiev.

Table 47
Distribution of absorbed dose in the thyroid of the population of Ukraine from the Chernobyl accident
[L12]

Absorbed dose (Gy)	*Number of persons*	*Collective thyroid dose (man Gy)*
<0.01	7 325 000	36 625
0.01–0.05	3 400 000	102 000
0.05–0.1	1 312 000	98 400
0.1–0.3	228 000	45 600
0.3–0.5	131 000	52 400
0.5–1.0	26 000	19 500
1.0–1.5	28 000	35 000
Total	12 450 000	390 000 [a]

[a] Estimate is less by a factor of 2 for more realistic intake model.

Table 48
Normalized effective doses from radiocaesium via internal exposure to rural inhabitants of Ukraine in different soil zones
[K23]

Soil zone	*Transfer coefficient from soil to milk in 1991 (Bq l^{-1} per kBq m^{-2})*	*Normalized doses (μSv per kBq m^{-2})*		
		1986	*1987–1995*	*1986–1995*
I	<1	9	26	35
II	1–5	42	144	186
III	5–10	95	320	415
IV	>10	176	591	767

Table 49
Values of the transfer coefficient and of the normalized effective dose from internal exposure for sodic-podzol sand and chernozem soils in the Russian Federation

[B25, R9]

Type of soil	*Transfer coefficient (Bq kg^{-1} per kBq m^{-2})*				*Normalized effective dose (µSv per kBq m^{-2})*		
	Milk		*Potatoes*				
	1987	*1993*	*1987*	*1993*	*1986*	*1987–1994*	*1995–2056*
Sodic-podzol sand	5	0.2	0.16	0.04	90	78	16
Chernozem	0.07	0.01	0.03	0.004	28	2	1

Table 50
Rounded estimates of internal effective doses per unit of ^{137}Cs deposition density for inhabitants of contaminated areas of the Russian Federation

Region	*Normalized effective dose (µSv per kBq m^{-2})*			
	1986	*1987–1995*	*1996–2056*	*1986–2056*
Bryansk [a]	36 (10)	48 (13)	9 (9)	93 (32)
Tula	15	6	1.8	23
Orel	15	8	2.4	25

a The values within parentheses correspond to areas with a ^{137}Cs deposition density greater than 555 kBq m^{-2}.

Table 51
Average effective doses from internal exposure per unit deposition density of ^{137}Cs for population subgroups in Belarus

[D3, K22]

Location	*Age group*	*Normalized effective dose (µSv per kBq m^{-2})*			
		1986	*1987–1990*	*1991–1995*	*1986–1995*
Rural areas	0–6 years	3–17	6–32	3–7	12–56
	7–17 years	5–19	8–45	2–6	15–70
	>18 years	5–24	12–62	3–10	20–96
Towns	0–6 years	2	5	2	9
	7–17 years	2	4	2	8
	>18 years	3	7	4	14

Table 52
Populations in Europe examined in epidemiological studies
[S12]

Country	*Study region*	*Age group*	*Average absorbed dose (mGy)* [a]
Thyroid studies			
Croatia	Whole country	All ages	15 [b]
Greece	Whole country	20-60 years	5
Hungary	Whole country	All ages	3 [b]
Poland	Krakow, Nowy Sacz	All ages	4 [b]
Turkey	Five most affected areas on Black Sea coast and Edirne province	All ages	1.5 [b]
Leukaemia studies			
Bulgaria	Whole country	Adults	2
		Children 0-14 years	2
Finland	Whole country	Children 0-14 years	2
Germany	Bavaria	Children 0-14 years	4
Greece	Whole country	Children 0-14 years	1
Hungary	Six counties	All ages	0.7
Romania	Whole country	Children 0-14 years [c]	3
Sweden	Whole country	Children 0-14 years	4
Turkey	Five most affected areas on Black Sea coast and Edirne province	All ages	0.7

a To thyroid in thyroid studies and to bone marrow in leukaemia studies; assumes bone marrow dose is numerically equal to effective dose and dose in children is the same as in adults.

b Assumes population-weighted thyroid dose is three times that to adults.

c Age at death.

Table 53
Summary of estimated collective effective doses to populations of areas contaminated by the Chernobyl accident (1986-1995)

Country	*Population*	*Collective effective dose (man Sv)*			*Average effective dose (mSv)*		
		External exposure	*Internal exposure*	*Total*	*External exposure*	*Internal exposure*	*Total*
Belarus	1 880 000	9 600	5 500	15 100	5.1	2.9	8.0
Russian Federation	1 980 000	8 500	5 000	13 500	4.3	2.5	6.8
Ukraine	1 300 000	6 100	7 900	14 000	4.7	6.1	10.8
Total	5 160 000	24 200	18 400	42 600	4.7	3.5	8.2

Table 54
Distribution of the estimated total individual effective doses received by the populations of contaminated areas, 1986-1995 (excluding thyroid dose)

Dose interval (mSv)	*Number of persons in dose interval in*			
	Belarus	*Russian Federation*	*Ukraine*	*Total*
<1	133 053	155 301	0	288 804
1-2	444 709	445 326	0	890 035
2-3	362 510	383 334	26 100	771 944
3-4	221 068	258 933	95 900	575 901
4-5	135 203	165 537	208 900	509 640
5-10	276 605	317 251	440 400	1 034 056
10-20	163 015	156 925	367 500	687 440
20-30	63 997	50 010	99 100	213 107
30-40	32 271	21 818	31 400	85 489
40-50	17 521	11 048	18 200	46 769
50-100	25 065	14 580	7 700	47 345
100-200	5 105	2 979	400	8 484
>200	790	333	0	1 123
Total	1 880 912	1 983 375	1 295 600	5 159 887

Table 55
Deaths of survivors of acute radiation sickness during 1986-1998
[W5]

Year of death	*Grade of acute radiation sickness*	*Disease recorded and/or cause of death*
1987	II	Lung gangrene
1990	II	Coronary heart disease
1992	III	Coronary heart disease
1993	I	Coronary heart disease
	III	Myelodysplastic syndrome
1995	I	Lung tuberculosis
	II	Liver cirrhosis
	I	Fat embolism
	III	Myelodysplastic syndrome
1998	II	Liver cirrhosis
	II	Acute myeloid leukaemia

Table 56
Thyroid cancer cases in children under 15 years old at diagnosis

Region	*Number of cases*												
	1986	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*
Belarus [P9]													
Brest	–	–	1	–	8	7	9	28	19	20	16	17	16
Vitebsk	–	–	–	–	1	3	3	–	2	–	–	2	–
Gomel	1	2	2	2	15	38	28	34	38	41	37	33	14
Grodno	2	1	1	2	1	4	6	5	4	5	4	5	5
Minsk city	–	–	1	–	4	5	7	9	3	9	1	4	7
Minsk	–	1	1	1	–	4	8	5	7	2	6	8	3
Mogilev	–	–	–	–	2	1	1	6	4	5	3	4	3
Total	3	4	6	5	31	62	62	87	77	82	67	73	48
Russian Federation [I23]													
Bryansk region													
Novozybkovsky	–	–	–	–	–	–	–	–	4	–	–	–	
Klintsovsky	–	–	–	–	–	1	1	1	–	5	2	3	
Klimovsky	–	–	–	–	–	–	1	–	–	1	–	–	
Sturodubsky	–	–	–	–	–	–	1	–	–	–	–	–	
Unechsky	–	–	–	–	–	–	–	–	–	–	–	–	
Komarichsky	–	–	–	–	–	–	–	–	–	–	–	–	
Dyatkovsky	–	1	–	–	–	–	–	–	1	–	–	2	
Surazhsky	–	–	–	–	–	–	–	–	–	–	–	–	
Vygonechsky	–	–	–	–	–	–	–	–	1	–	–	–	
Suzemsky	–	–	–	–	1	–	–	–	–	1	–	–	
Total	–	1	–	–	1	1	3	1	6	7	2	5	
Ukraine [T2, T16]													
Zhitomir	–	–	–	–	2	1	3	3	5	7	6	5	7
Kiev	2	–	–	2	4	4	10	10	3	9	18	8	7
Kiev city	1	–	1	1	2	3	9	5	5	9	4	4	6
Rovno	–	–	–	–	–	1	5	2	–	–	3	2	2
Cherkassy	–	–	1	–	–	2	4	4	2	2	2	2	1
Chernigov	–	–	–	1	3	2	3	4	11	4	4	6	3
Other regions	5	7	6	7	15	9	15	16	18	16	19	9	18
Total	8	7	8	11	26	22	49	44	44	47	56	36	44

Table 57
Thyroid cancer incidence rates in children under 15 years old at diagnosis

Region	*Number of cases per 100 000 children*												
	1986	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*
Belarus [P9]													
Brest	–	–	0.4	–	3.3	2.9	3.7	11.6	8.1	8.8	7.3	8.2	8.0
Vitebsk	–	–	–	–	0.5	1.4	1.4	–	1.0	–	–	1.2	–
Gomel	0.4	0.7	0.7	0.7	5.6	15.0	11.2	13.9	15.9	17.9	16.9	16.0	7.1
Grodno	1.1	0.6	0.5	1.1	0.6	2.2	3.2	2.7	2.2	2.8	2.4	3.1	3.3
Minsk city	–	–	0.4	–	1.5	1.9	2.7	3.5	1.2	3.9	0.5	2.0	3.7
Minsk	–	0.4	0.4	0.4	–	1.7	3.2	2.0	3.0	0.9	2.8	3.9	1.6
Mogilev	–	–	–	–	1.0	0.5	0.5	3.2	2.2	2.9	1.8	2.6	2.0
Total	0.2	0.3	0.4	0.3	1.9	3.9	3.9	5.5	5.1	5.6	4.8	5.6	3.9
Russian Federation [I23]													
Bryansk region													
Novozybkovsky	–	–	–	–	–	–	–	–	26.6	–	–	–	
Klintsovsky	–	–	–	–	–	4.3	4.3	4.3	–	21.7	8.6	12.9	
Klimovsky	–	–	–	–	–	–	12.1	–	–	12.1	–	–	
Sturodubsky	–	–	–	–	–	–	9.9	–	–	–	–	–	
Unechsky	–	–	–	–	–	–	–	–	–	–	–	–	
Komarichsky	–	–	–	–	–	–	–	–	–	–	–	–	
Dyatkovsky	–	9.1	–	–	–	–	–	–	9.1	–	–	18.2	
Surazhsky	–	–	–	–	–	–	–	–	–	–	–	–	
Vygonechsky	–	–	–	–	–	–	–	–	20.2	–	–	–	
Suzemsky	–	–	–	–	23.2	–	–	–	–	23.2	–	–	
Krasnogorsky	–	–	–	–	–	–	–	–	–	18.8	–	–	
Navlinsky	–	–	–	–	–	–	–	–	–	–	–	14.3	
Karachevsky	–	–	–	–	–	–	–	–	10.5	–	–	10.5	
Bryansk city	–	–	–	–	–	–	–	–	10.0	–	–	–	
Total	–	0.3	–	–	0.3	0.3	0.9	0.3	2.8	2.5	0.6	2.2	
Ukraine [T2, T16]													
Zhitomir	–	–	–	–	0.6	0.3	0.9	1.0	1.6	2.3	2.0	1.7	2.5
Kiev	0.5	–	–	0.5	1.0	1.0	2.5	2.5	0.8	2.4	4.9	2.2	2.0
Kiev City	0.2	–	0.2	0.2	0.4	0.6	1.7	1.0	1.0	1.8	0.8	0.9	1.4
Rovno	–	–	–	–	–	0.3	1.7	0.7	–	–	1.1	0.7	0.7
Cherkassy	–	–	0.3	–	–	0.7	1.3	1.3	0.7	0.7	0.7	0.7	0.4
Chernigov	–	–	–	0.4	1.1	0.8	1.2	1.6	4.4	1.7	1.7	2.6	1.4
Other regions	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Total	0.2	0.1	0.1	0.1	0.2	0.2	0.5	0.4	0.4	0.5	0.6	0.4	0.5

Table 58
Thyroid cancer cases diagnosed among children 0–17 years old at the time of the Chernobyl accident

Region	*Sex*	*Number of cases in year of diagnosis*									
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*Total*
Belarus [P9]											
Brest	M	3	6	5	11	11	9	10	8	14	77
	F	4	5	5	26	18	27	23	18	20	146
Gomel	M	9	13	19	15	16	25	16	24	19	156
	F	7	35	15	31	41	37	41	42	34	283
Grodno	M	1	3	6	–	5	4	3	3	1	26
	F	–	4	6	8	5	4	7	5	8	47
Minsk city	M	1	5	5	3	2	4	5	5	9	39
	F	4	5	5	14	14	15	10	11	22	100
Minsk	M	1	2	4	2	5	3	5	9	2	33
	F	–	3	8	11	5	5	6	5	8	51
Mogilev	M	3	1	2	2	1	3	1	1	3	17
	F	–	–	–	5	8	7	4	8	12	44
Vitebsk	M	–	2	5	–	1	–	1	2	2	13
	F	2	2	5	2	5	4	4	5	6	35
Total		35	86	90	130	137	147	136	146	160	1 067
Russian Federation [I23]											
Bryansk	M	–	1	2	4	5	6	3	6		27
	F	–	2	4	5	17	11	7	15		61
Kaluga	M	–	–	1	–	2	1	2	1		7
	F	1	1	–	–	2	–	1	2		7
Orel	M	–	1	–	–	3	1	1	–		6
	F	2	–	3	6	10	9	14	2		46
Tula	M	–	3	2	1	–	5	1	–		12
	F	2	2	–	3	8	8	7	9		39
Total		5	10	12	19	47	41	36	35		205
Ukraine [T16]											
Zhitomir	M	1	2	–	1	4	4	3	4	5	24
	F	1	1	4	2	7	9	5	5	9	43
Kiev	M	2	3	5	6	2	10	13	5	2	48
	F	7	6	11	7	9	14	26	17	10	107
Kiev city	M	3	1	5	3	4	3	3	5	7	34
	F	4	5	12	13	10	25	14	16	15	114
Rovno	M	–	1	3	2	3	3	4	4	1	22
	F	–	1	2	1	1	1	2	2	5	16
Cherkassy	M	–	–	2	1	1	1	1	–	2	8
	F	1	3	3	6	5	1	4	5	2	30
Chernigov	M	2	1	2	2	7	1	1	3	3	22
	F	1	3	4	5	6	7	6	7	12	51
Total		22	27	55	49	59	79	82	73	73	519

Table 59
Thyroid cancers and risk for children 0–18 years old at the time of the Chernobyl accident for the years 1991–1995 in three cities and 2,729 settlements in Belarus and the Russian Federation

[J5]

Thyroid dose	*Person years at risk*	*Observed number of cases*	*Expected number of cases* [a]	*Excess absolute risk* [b] *(10^4 PY Gy)$^{-1}$*
0–0.1 (0.05)	1 756 000	38	16	2.6 (0.5–6.7)
0.1–0.5 (0.21)	1 398 000	65	13	1.9 (0.8–4.1)
0.5–1.0 (0.68)	386 000	52	3.6	2.0 (0.9–4.2)
1.0–2.0 (1.4)	158 000	50	1.5	2.3 (1.1–4.9)
>2.0 (3.0)	56 000	38	0.5	2.4 (1.1–5.1)

a Calculated by multiplying the age-specific incidence observed in Belarus in 1983–1987 by three.
b 95% confidence intervals in parentheses.

Table 60
Odds ratio for thyroid cancer cases in Belarusian children compared with age-, location-, and exposure-matched controls

[A6]

Pathway to diagnosis	*Number of cases or controls at estimated thyroid dose from ^{131}I*				
	<0.30 Gy	*0.30–0.99 Gy*	*>0.99 Gy*	*Total*	*Odds ratio* [a]
Routine endocrinological screening					
Cases	32	16	15	63	2.1
Control	43	16	4	63	(1.0–4.3)
Incidental findings					
Cases	13	4	2	19	8.3
Control	18	1	0	19	(1.1–58)
Enlarged or nodular thyroid					
Cases	19	6	0	25	3.6
Control	23	2	0	25	(0.7–18)
Cases	64	26	17	107	3.1
Controls	84	19	4	107	(1.7–5.8)
Total	152	41	21	214	

a Comparing lowest and two highest groups. 95% confidence interval in parentheses.

Table 61
Circumstances of diagnosis of thyroid problems

[A5]

Probable circumstance of diagnosis	*Ultrasound diagnosis*			
	Unknown	*No*	*Yes*	*Total*
Formal screening programme	2 (29%)	7 (20%)	3 (38%)	12
Incidental to other examination	2 (29%)	18 (51%)	3 (38%)	23
Consulted since unwell	1 (14%)	8 (23%)	1 (13%)	10
Consulted even though well	2 (29%)	2 (6%)	1 (13%)	5
Total	7	35	8	50

Table 62
Pathological types of thyroid cancers in Ukrainian children less than 15 years old at diagnosis
[T18]

Pathological classification [a]	Number of cancers in relation to year of diagnosis [b]			
	1986–1990	1991–1995	1996–1997	Total
T1	–	4 (2)	1 (1)	5 (1)
T2	9 (18)	49 (20)	18 (16)	76 (19)
T3	6 (12)	27 (11)	6 (5)	39 (10)
T4	14 (29)	69 (28)	38 (35)	121 (30)
N1	9 (18)	45 (18)	22 (20)	76 (19)
N2	9 (18)	45 (18)	22 (20)	76 (19)
M1	2 (4)	6 (2)	3 (3)	11 (3)
Total	49 (100)	245 (100)	110 (100)	404 (100)

a Staging system of the World Health Organization [H17].
b Percentage of total in parentheses.

Table 63
Age and sex distribution of Ukrainian children and adolescents who underwent surgery for thyroid carcinoma during 1986–1997
[T18]

Age at time of surgery (years)	Number		Ratio female : male
	Females	Males	
0–4	5	5	1.0 : 1
5–9	46	42	1.1 : 1
10–14	176	84	2.1 : 1
15–18	159	61	2.7 : 1
0–14	227	131	1.7 : 1
Age at time of exposure (years)	**Number**		**Ratio female : male**
	Females	Males	
0–4	146	88	1.7 : 1
5–9	149	58	2.6 : 1
10–14	69	30	2.3 : 1
15–18	15	7	2.1 : 1
0–14	364	176	2.1 : 1

Table 64
Frequency of *RET* rearrangements in thyroid papillary carcinomas in relation to age and radiation history
[S35]

Patient group	Number of cases	Mean age at exposure (years)	Mean age at surgery (years)	Number of cases	
				with RET/PTC1 mutations	with RET/PTC3 mutations
Children (Belarus)	51	2	12	12 (23.5%)	13 (25.5%)
Adults (Belarus)	16	22	31	11 (69%)	–
Adults (Germany) [a]	16	–	48	3 (19%)	–

a Negligible radiation exposure from Chernobyl accident.

Table 65
Incidence of leukaemia and all cancer during 1993–1994 among recovery operation workers and residents of contaminated areas
[C2]

Country	*Leukaemia cases* [a]		*All cancer cases* [a]		*Standardized incidence ratio (SIR)*	
	Observed	*Expected*	*Observed*	*Expected*	*Leukaemia*	*All cancer*
Recovery operation workers [b]						
Belarus	9	4.5	102	136	200	75
Russian Federation	9	8.4	449	405	108	111
Ukraine	28	8	399	329	339	121
Residents of contaminated areas [c]						
Belarus	281	302	9 682	9 387	93	103
Russian Federation	340	328	17 260	16 800	104	103
Ukraine	592	562	22 063	22 245	105	99

a ICD9 codes: 204-208 (leukaemia) and 140-208 (all cancer); expected cases are for age- and sex-matched members of the general population.
b Males who worked in the 30-km zone during 1986 and 1987.
c Areas with ^{137}Cs deposition density > 185 kBq m^{-2}.

Table 66
Thyroid abnormalities diagnosed by ultrasonography in children 0–10 years old at the time of the accident screened by the Chernobyl Sasakawa project during 1991–1996
[Y1]

Region	*Number of children screened*	*Number of children with diagnosis*					
		Goitre	*Abnormal echogenity*	*Cystic lesion*	*Nodular lesion*	*Cancer*	*Anomaly*
Mogilev	23 531						
Boys		2 231	91	19	5	1	16
Girls		2 391	188	25	19	1	19
Gomel	19 273						
Boys		1 355	332	59	130	12	67
Girls		2 053	604	63	212	25	73
Bryansk	19 918						
Boys		3 666	172	56	46	3	7
Girls		4 480	251	51	53	5	8
Kiev	27 498						
Boys		6 634	246	18	13	2	4
Girls		8 194	588	40	33	4	7
Zhitomir	28 958						
Boys		4 473	38	34	23	4	17
Girls		6 453	87	137	43	5	19
Total	119 178	41 930	2 597	502	577	62	237

Table 67
Incidence of thyroid abnormalities diagnosed by ultrasonography in children screened by the Sasakawa project during 1991–1996
[Y1]

Region	*Incidence rate per 1000 children examined*					
	Goitre	*Abnormal echogenity*	*Cystic lesion*	*Nodular lesion*	*Cancer*	*Anomaly*
Mogilev	219	11.9	1.9	1.0	0.08	1.5
Gomel	177	48.6	6.3	17.7	1.9	7.3
Bryansk	409	21.2	5.4	5.0	0.4	0.8
Kiev	539	30.3	2.1	1.7	0.2	0.4
Zhitomir	377	4.3	5.9	2.3	0.3	1.2
Total	352	21.8	4.2	4.8	0.5	2.0

Table 68
Comparison of reproductive effects in population groups in the Russian Federation during 1980–1993
[B19, L27, L28, L29]

Parameter / effect	*Ratio of effect before and after accident* [a]							
	Bryansk region			*Tula region*			*Ryazan region*	
	<37 kBq m^{-2}	*37–185 kBq* m^{-2}	*185–555 kBq* m^{-2}	*<37 kBq* m^{-2}	*37–185 kBq* m^{-2}	*185–555 kBq* m^{-2}	*<37 kBq* m^{-2}	*37–185 kBq* m^{-2}
Birth rate	0.81	0.83	0.75	0.87	0.73	0.69	1.0	0.90
Spontaneous abortions	1.27	1.34	1.34	0.90	1.03	1.18	1.22	0.91
Congenital anomalies	0.66	1.41	1.67	1.32	1.28	0.91	1.43	0.91
Stillbirths	0.66	1.39	1.29	1.50	0.93	1.41	0.90	0.97
Perinatal mortality	1.18	1.13	0.91	0.77	1.57	1.21	1.13	1.00
Premature births	1.07	0.95	1.39	0.88	0.86	0.71	0.83	1.23
Overall diseases in newborns	1.02	1.03	1.42	1.06	1.32	1.29	1.00	1.38
Overall unfavourable pregnancy outcome	1.07	1.16	1.35	0.95	0.97	0.92	1.07	1.00

a Number of women examined before and after accident: Byransk region: 3,500–4,100 in each area; Tula region, 2,400 (<37 kBq m^{-2}), 2,100 (37-185 kBq m^{-2}) and 810–860 (185–555 kBq m^{-2}); Ryazan region, 1,600–1 ,00 (<37 kBq m^{-2}) and 1,200–1,400 (37–185 kBq m^{-2}).

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