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Radiological Conditions in the Dnieper River Basin

Assessment by an international expert team and recommendations for an action plan

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FOREWORD

Various locations around the world have been affected by radioactive residues, sometimes from peaceful activities, such as the mining and milling of uranium ores, and sometimes from military activities, such as nuclear weapon testing. In some cases, governments have considered it to be socially and politically desirable to obtain independent expert opinions on the radiological conditions caused by the residues. As a result, the IAEA has been requested by the governments of a number of Member States to provide assistance in this context. The assistance has been provided by the IAEA under its statutory obligation "to establish… standards of safety for protection of health… and to provide for the application of these standards… at the request of a State".

In 1986, in the Dnieper River basin, a densely populated area in the middle of eastern Europe, the most severe nuclear accident in human history happened at the Chernobyl nuclear power plant in Ukraine. The accident destroyed a high power nuclear reactor and resulted in the release of large amounts of radionuclides into the environment. In other areas of Ukraine adjacent to the middle reaches of the Dnieper River, uranium mining and milling facilities have been in operation since 1948, which have left substantial tailings containing naturally occurring radioactive material. These events resulted in the contamination of substantial areas with radioactive residues, and some associated health effects. More questions arose regarding the possible radiological consequences of the radioactive residues for local populations and the environment, and the governments of the affected States were obliged to respond.

After the Ministers of the Environment of the three riparian countries (i.e. Belarus, the Russian Federation and Ukraine) expressed in June 1996 their intention to develop an international programme for the environmental rehabilitation of the Dnieper River basin, the first transboundary diagnostic analysis (TDA) was developed in 1997. In assessing the Dnieper River basin, the United Nations Development Programme — Global Environment Facility (UNDP–GEF) identified radioactive contamination as one of the significant issues. Subsequently, the IAEA was requested to contribute its expertise in radiation and environmental protection to a more detailed analysis involving a revision of the TDA and preparation of a strategic action plan.

The present project was started in 2001 within the framework of the Dnieper Basin Environmental Programme (DBEP) under the UNDP–GEF. The project was executed by the IAEA as Regional Technical Cooperation Project RER/9/072, Preparation of Strategic Action Plan (SAP) for the Dnieper River Basin and Development of SAP Implementation Mechanism.

The international expert team for this study assembled by the IAEA included scientists from Belarus, the Russian Federation and Ukraine familiar with radioactive contamination in the Dnieper River basin and experienced in radiological assessments; the team was led by D. Levins from Australia. This report includes the findings and conclusions of the international expert team and recommendations to the Governments of Belarus, the Russian Federation and Ukraine.

The IAEA project officer for this project was M. Samiei of the Division for Europe, Latin America and West Asia and the technical officer was M. Balonov of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

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1. SUMMARY

1.1. INTRODUCTION

As a contribution to the Dnieper Basin Environmental Programme (DBEP), an international team of scientists, under the direction of the IAEA, carried out an assessment of radioactive contamination in the Dnieper River basin. The DBEP is being carried out under the United Nations Development Programme — Global Environment Facility (UNDP–GEF).

The current phase of the DBEP involved a major revision of the previous transboundary diagnostic analysis (TDA) for the Dnieper River basin and preparation of a strategic action plan (SAP) and national action plans (NAPs). This report is a detailed technical report of the IAEA's contribution to this programme and elaborates upon a summary document provided to the UNDP–GEF in November 2002. The IAEA assessment involved two fact finding missions, two meetings of the international expert team and participation by team members in a number of workshops organized by the UNDP–GEF.

1.2. RADIOACTIVE SOURCE TERMS

The main sources (actual and potential) of radioactivity and radiation exposure within the Dnieper River basin were identified as follows:

(a) Areas affected by the Chernobyl nuclear accident;
(b) Nuclear power plants;
(c) Uranium mining and ore processing;
(d) Radioactive waste storage and disposal sites;
(e) Non-power sources (e.g. from the use of radiation and radioisotopes in medicine, industry and research).

The study considered the public exposure levels (past, present, projected and potential) and associated adverse effects of these sources on human health and the environment.

Of the above sources, Chernobyl affected areas currently produce transboundary effects. Nuclear power plants have the potential to produce major transboundary impacts in the event of a nuclear accident. The transboundary impacts of the other source terms are likely to be small, although their impact could be considerable within a local region or a single country.

1.3. CHERNOBYL AFFECTED AREAS

The Chernobyl nuclear power plant site lies in northern Ukraine within the Dnieper River basin and very close to the border with Belarus. The Chernobyl accident on 26 April 1986 released large amounts of radioactivity into the air: 1760 PBq[1] of ^{131}I, 85 PBq of ^{137}Cs, 54 PBq of ^{134}Cs, 10 PBq of ^{90}Sr and 0.07 PBq of ^{239,240}Pu, as well as many shorter lived radionuclides of lesser radioecological significance. The fallout of this activity was dependent on the vagaries of the wind direction and rainfall over the period of the releases. The deposition was greatest in the three countries (Belarus, the Russian Federation and Ukraine) that lie within the Dnieper River basin.

The most serious consequences of the Chernobyl accident to the public were caused by exposure to short lived radionuclides, especially ^{131}I, which resulted in many thyroid cancers [1.1]. Other health effects may be expected in the future from the exposures received by some individuals during the accident phase.

This assessment is concerned with the current and future exposures resulting from contamination of the Dnieper River basin with radionuclides. Of those radionuclides still remaining from the Chernobyl accident, ^{137}Cs (half-life 30 years) and ^{90}Sr (half-life 29.1 years) are the most important from an environmental and public health perspective. Caesium-137, with its short lived daughter, ^{137m}Ba, emits beta and gamma radiation; ^{90}Sr, with its short lived daughter, ^{90}Y, emits strong beta radiation.

Caesium is volatile at the high temperatures that were experienced during the Chernobyl accident. Consequently, it tended to travel substantial distances before being deposited. Both in the environment and in the human body, caesium radionuclides behave like potassium. Strontium, however, is not particularly volatile and was mainly associated with fuel particles, which were deposited

[1] 1 PBq = 1×10^{15} Bq ≈ 27 000 Ci.

much closer to the release point. In the environment and in the human body, strontium radionuclides behave like calcium (hence strontium is a 'bone seeker').

Within the catchment area of the Dnieper River basin, an area of about 85 000 km^2 has a surface contamination of ^{137}Cs above 37 kBq/m^2 (1 Ci/km^2). On the territory of Belarus, the worst affected areas are the Gomel and Mogilev regions. Within the Russian Federation, the south-west part of the Bryansk region was the most affected. In Ukraine, contamination was particularly high in the Kiev, Zhytomyr and Chernihiv regions.

The Pripyat basin within Belarus and Ukraine, and especially the Chernobyl exclusion zone (CEZ), received the highest contamination of ^{90}Sr and plutonium isotopes.

1.3.1. Transboundary migration of radionuclides

One of the more serious long term ecological effects of the Chernobyl fallout was the secondary runoff ('wash-off') of radionuclides from the initially contaminated areas through the river networks of Belarus, the Russian Federation and Ukraine into the Dnieper reservoir system, thereby expanding the spatial scale of the accident and exposing the millions of people who use the downstream resources of the Dnieper River.

Since the Chernobyl accident, water monitoring stations have been established within the CEZ and along the major rivers to determine the concentration of radionuclides and their total flow. Although these stations are not ideally suited for monitoring transboundary fluxes, estimates have been made for ^{137}Cs and ^{90}Sr (see Table 1.1).

The transboundary migration of ^{137}Cs has decreased markedly with time. However, the transboundary migration of ^{90}Sr has fluctuated from year to year, depending on the extent of annual flooding along the banks of the Pripyat River. The extent of washout of radionuclides is, however, only a very small percentage of the total inventory in the catchment area (see Table 1.1).

1.3.2. Behaviour of caesium-137 and strontium-90 in the environment

The migration characteristics of ^{137}Cs and ^{90}Sr can be understood from an appreciation of the chemistry of their respectively elements, caesium and strontium. Caesium has an affinity for clay minerals frequently occurring in natural soils. Binding of caesium to soil retards its lateral and vertical migration. Strontium is less firmly bound to mineral sites and is consequently more mobile in the environment. The soils of the CEZ are heavily contaminated with ^{90}Sr, and some is washed off during flood events when the low lying areas become inundated.

The chemistry of the respective elements also explains their behaviour upon entering the Dnieper cascade. Caesium-137 tends to become fixed to clay sediments, which are deposited in the deeper sections of the reservoirs, especially the Kiev reservoir. Very little ^{137}Cs flows through the cascades because of this process and consequently the present concentration entering the Black Sea is indistinguishable from background. However, although ^{90}Sr concentration decreases with distance from the source (mainly due to dilution), about

TABLE 1.1. ESTIMATES OF TRANSBOUNDARY TRANSPORT OF CAESIUM-137 AND STRONTIUM-90 BY MAJOR RIVERS FLOWING THROUGH CHERNOBYL AFFECTED REGIONS

	Years	Iput River	Besed River	Pripyat River	Dnieper River
Section Border		Dobrush Belarus–Russian Federation	Svetilovichi Belarus–Russian Federation	Belaya Soroka Belarus–Ukraine	Nedanchichi Belarus–Ukraine
Caesium-137 outflow (TBq)	1987–1999	9.1	1.9	31.3	43.1
Caesium-137 (% catchment inventory)		0.4	0.1	0.7	0.56
Strontium-90 outflow (TBq)	1990–1999	0.9	0.7	52.6	34.3
Strontium-90 (% catchment inventory)		2.2	1.9	4.3	3.6

40–60% passes through the cascade and reaches the Black Sea.

The concentrations of ^{137}Cs and ^{90}Sr in flowing rivers are now well below the permissible levels set by the national authorities and below international guideline levels for drinking water. However, lakes with no regular outflows still present a radiological problem that will continue for some time. In such systems, which are usually associated with underlying peat deposits, there is no mechanism for fixation of ^{137}Cs. Consequently, ^{137}Cs concentrations in water are close to the permissible levels for drinking water, while the levels in fish exceed the permissible levels by one to two orders of magnitude. Moreover, higher than permissible radionuclide levels are measured in forest foods (wild game, mushrooms, berries) as well as in milk and beef produced by cattle grazing on contaminated floodplains. These areas were identified as possible local 'hot spots' for more detailed consideration.

1.3.3. Chernobyl exclusion zone

The CEZ contains a number of discrete contamination sources that represent separate problems: flood prone land along the banks of the Pripyat River, the Chernobyl nuclear power plant cooling pond, waste burial sites and the shelter that houses the crippled Chernobyl reactor.

1.3.4. Contaminated floodplain

The floodplain along the Pripyat River is highly contaminated from the Chernobyl accident, especially with ^{90}Sr, where concentrations exceed 4000 kBq/m^2 over large areas. This area is regularly inundated, especially during spring floods. Moreover, some of the waste burial sites are located within the floodplain. Engineering works have been undertaken to mitigate the flooding but have not been completed because of financial problems. Radioactivity, especially ^{90}Sr, is washed off the floodplain during times of high flood and transported via the Pripyat River to the Dnieper reservoir system.

1.3.5. Chernobyl cooling pond

The cooling pond of the Chernobyl nuclear power plant is an artificial lake built to provide the cooling water for the condensers of the four Chernobyl reactor units. It was completed in 1982, covers an area of approximately 23 km^2 and contains approximately 149×10^6 m^3 of water. The cooling pond is located less than 1 km from the Chernobyl nuclear power plant; a dam separates the pond from the Pripyat River.

The pond was heavily contaminated during the Chernobyl accident and by subsequent dumping of radioactive liquid waste into it. The total inventory of radionuclides is estimated to be at present in excess of 200 TBq, with the deep sediments containing most of this activity. Currently, the water level is kept artificially high; however, this will change when the cooling systems at the Chernobyl nuclear power plant are finally shut down and pumping of water into the pond is terminated. This will leave the sediments partly exposed and subject to dispersal. Contamination of the Pripyat River could also occur if the dam were breached or otherwise damaged.

1.3.6. Chernobyl shelter

The Chernobyl shelter was constructed upon the ruins of the destroyed reactor building of Chernobyl unit 4 and was completed in November 1986. This containment was erected under difficult circumstances in very high radiation fields using remote construction methods. Unfortunately, as a result of construction difficulties, there are now openings and breaks in the walls and the roof of the shelter, which is estimated to total about 1200 m^2 in area.

The shelter contains between 173 and 200 t of nuclear fuel with an activity of up to 750 PBq (20 MCi) of ^{238}U and ^{235}U and their daughter products, as well as long lived fission and neutron activation products, including ^{137}Cs, ^{90}Sr, plutonium radionuclides and ^{241}Am. Most of the fuel is now contained in a lava-like matrix containing many inclusions of various uranium compounds, finely dispersed high level active fuel dust, and aerosols. Contamination of the environment by radioactive substances from the shelter may occur in two principal ways: (a) release of fuel dust into the atmosphere through openings in the shelter if there is a collapse of internal structures; and (b) migration of radionuclides through the subsurface together with water that is inside the shelter. A new safe confinement is planned above the existing shelter after 2007.

1.4. NUCLEAR POWER PLANTS

There are 17 operating nuclear power reactors in the Dnieper River basin, ten in Ukraine at three sites (Zaporozhe, Rovno and Khmelnitski) and seven in the Russian Federation at two sites (Kursk and Smolensk). In addition, there are three nuclear power reactors (South Ukraine nuclear power plant) in the southern Bug River basin. Ukraine is heavily dependent on nuclear power, which supplies about 45% of its electricity needs. The Zaporozhe nuclear power plant, comprising six 1000 MW(e) units adjacent to the Kakhovka reservoir, is one of the largest in the world. Currently, one 1000 MW(e) nuclear power reactor is being commissioned at Rovno, while another is under construction at Khmelnitski.

Our examination of discharge and monitoring data for nuclear power plants in Ukraine and in the Russian Federation shows that routine discharges are generally well below authorized limits and do not contribute to significant contamination of the environment. Waste management facilities (including spent fuel storage) do not present a problem, although storage facilities in several cases are close to capacity and new facilities are required in Ukraine to accommodate the increasing quantity of spent fuel. Previously, spent fuel was sent to the Russian Federation for reprocessing, and a policy for the long term management of spent fuel needs to be developed. The provision of dry storage facilities, as at the Zaporozhe nuclear power plant, is an acceptable midterm strategy.

A major accident at a nuclear power plant can result in major transboundary impacts. The accident at Chernobyl nuclear power plant unit 4, which was a high power channel type (RBMK) reactor, is an example of the transboundary effects of a near worst case nuclear disaster. Since that accident, Russian built reactors have been subject to many internal and international reviews, and upgrades have been undertaken with the aim of improving nuclear safety.

Immediately after the Chernobyl accident, urgent measures were taken to improve the inherent safety of the first generation RBMKs. These measures included reduction of the positive void effect and increased neutron absorbers. This was followed by the first stage of modernization, which took place in the 1990s. The second stage of modernization is ongoing. These engineering upgrades have been complemented by increased licensing requirements and regulatory scrutiny.

The Ukrainian reactors are water cooled, water moderated units (WWERs), which belong to the category of pressurized water reactors (PWRs), the most common reactor type in the world. The main WWER design criteria are consistent with current international safety practices. Efforts are under way to improve emergency operating procedures and to develop accident management guidelines. An international in-depth safety assessment process is under way to optimize the improvement programmes.

The system for emergency preparedness and response in Ukrainian and Russian nuclear power plants is based on the recommendations of the IAEA. Strengthening of this system requires further development of the automatic monitoring (early warning) system around each nuclear power plant and of the real time decision support system for off-site emergency management. The enhanced decision support system should include modules that forecast post-accident contamination of water bodies after accidental fallout or direct releases into the water. Information exchange between nuclear power plant emergency units and regional authorities should also be improved.

1.5. URANIUM MINING AND PROCESSING

The only uranium mining and ore processing in the Dnieper River basin is in Ukraine. Uranium exploration started in 1944 and led to the discovery of 21 deposits. Many of the deposits are within the watershed of the Dnieper River basin, while some are within the basins of the southern Bug and Seversky Donets Rivers.

The first uranium processing plant was the Prydniprovsky chemical plant, which started operations in 1948 using ores shipped from countries in central Europe. It is situated a few kilometres from the Dnieper River in the city of Dniprodzerzhinsk and ceased operations in 1991.

The Zhovti Vody hydrometallurgical plant commenced production in January 1959 to process ores from the region. Current production is about 1000 t U/a. Most of the current production comes from the Ingulsky mine, developed on the Michurynske deposit.

There are plans to mine the Severinske deposit, which has reserves of 64 000 t U at an average grade of 0.1% uranium. Doubling of the capacity of the ore processing plant to 2000 t U/a is envisaged.

Three ore bodies — Bratske, Devladovske and Safonovske — have been exploited by the in situ leaching method. This involves injection of sulphuric acid into the ore body and avoids the problems of tailings management, but, under unfavourable conditions, can result in contamination of groundwater.

Uranium mining and milling has a number of potential impacts on human health and the environment. They include:

(a) Contamination of mine water with uranium and other radionuclides;
(b) Release of mill wastewaters to surface waters (usually after treatment);
(c) Runoff of water from contaminated areas of the mine or mill;
(d) Radon release from mines, waste rock dumps and mill tailings piles;
(e) Leaching of radionuclides from tailings and their subsequent transport in water;
(f) Erosion of tailings storage systems, leading to dispersal of tailings by wind and water;
(g) Contamination of underground and surface waters by toxic non-radioactive substances such as heavy metals and the chemicals used in processing.

The most important waste from the milling of uranium is the finely divided solid residue known as tailings. Tailings typically contain 70% of the radioactivity in the original ore, including the long lived radionuclides ^{230}Th (half-life 80 000 years) and ^{226}Ra (half-life 1600 years). Radium is a continual source of ^{222}Rn (half-life 3.8 days), which, being a gas, is readily dispersed. Radon daughters are a source of radiation exposure and a known cause of lung cancer in uranium miners.

The mining and processing of uranium ores at Zhovti Vody has negatively affected the environment as well as the sanitary state of the town since the start of operations in the 1950s. The main sources of radioactive contamination are the following three tailings sites:

(i) Tailings site KBZh has an area of 55 ha and contains 19×10^6 t of radioactive waste, deposited from 1964 until 1982. Restoration of the site began in 1991 and is still incomplete because of financial problems. At present, most of the tailings are covered with 0.4 m of clay to prevent dispersion of tailings dust.
(ii) Tailings site Sch consists of two sections with a total area of 250 ha and contains about 45×10^6 t of radioactive waste. The new section was commissioned in 1979 and is still operating.
(iii) Tailings site R has an area of 230 ha. It was originally used as a storage pond for iron ore milling sludge and was also used as a settling pond for uranium mine drainage waters.

Runoff and seepage from the tailings, mines and other contaminated sites leads to elevated levels of radionuclides in local rivers; however, levels are below the permissible levels for drinking water.

The former Prydniprovsky chemical plant is located alongside the Dnieper River on a large industrial complex with other industries, such as coke, and other metallurgical plants. During operation of the plant, nine tailings dumps were created containing about 42×10^6 t of radioactive waste with a total activity of about 4×10^{15} Bq (≈100 000 Ci).

Of the tailings dumps in the area, tailings D is considered to have the greatest potential for pollution of the environment. The group has assessed this site as a potential major hot spot because of the large amount of radioactivity (1500 TBq), the long half-life of the main radionuclides, the proximity to the Dnieper River, the evidence of current seepage and the possibility of catastrophic failure of the impoundment.

The Prydniprovsky chemical plant and related facilities are responsible for elevated levels of uranium and its daughters in the Konoplyanka and Dnieper Rivers. In order to determine the effects of uranium mining and ore processing in the region, it is necessary to carry out a pathway analysis. Such an analysis requires information on radioactivity levels in air, vegetation and food products. Currently such information is lacking and needs to be obtained before remedial actions are prioritized and undertaken.

There is a need to stabilize tailings impoundments against failure over long time periods based on international consensus, having regard for the long half-lives of the radionuclides in the tailings. It is also in accord with Principle 4 (Protection of Future Generations) and Principle 5 (Burden on Future Generations) of Ref. [1.2].

1.6. RADIOACTIVE WASTE STORAGE AND DISPOSAL SITES

Radioactive waste disposal sites in the Dnieper River basin include:

(a) The Ecores State facility near Minsk, which comprises two closed trenches and two repositories that are being progressively filled. This facility accepts radioactive waste from the nearby Institute of Radiation Physics and Chemistry Problems, National Academy of Sciences of Belarus (Sosny), and from more than 100 organizations from the industrial, research and medical sectors. The facility is 2 km from the Slouch River; the nearest pond is 1.6 km away. This facility is below current international standards for engineered disposal of low and intermediate level waste. However, the repository is remote from the Dnieper River and any environmental impact in the future will be localized.

(b) Two disposal sites operated by the RADON State enterprise at Kiev and Dnipropetrovsk. These sites handle both radioactive waste and spent radiation sources from the non-nuclear power plant sector, including the industrial, medical and agricultural sectors.

(c) Many disposal or 'temporary' storage sites in Belarus and Ukraine for waste from the Chernobyl nuclear power plant. The largest of these is the Buriakovka repository, which consists of 30 trenches with a 1 m thick bottom isolation clay.

These facilities have the potential for moderate impact within the local area. There are no significant radioactive waste disposal sites in the Russian section of the Dnieper River basin.

Waste storage sites are not considered to have a major impact because of the high degree of engineered containment. However, most radioactive waste storage sites at nuclear power plants are close to capacity.

1.7. NON-POWER SOURCES

Non-power sources include research reactors and those arising from the application of radioisotopes and radiation in medicine, industry and research.

The research reactors at the Sosny Institute near Minsk and the Institute for Nuclear Research at Kiev are shut down. The decommissioning of these reactors will be a significant source of radioactive waste. However, in their current state they do not directly impact on the environment.

Disused radiation sources are a potential source of exposure if not properly managed. They are often very intense sources of radiation, and in the past poor management has resulted in high exposures of individuals in several countries. Regulatory authorities need to maintain a register of sources and ensure that they are properly licensed and managed.

Overall, non-power sources have a limited and localized impact on the environment and public health.

1.8. HUMAN RADIATION EXPOSURE FROM ENVIRONMENTAL SOURCES

Exposure to radiation at low doses, which is typical for public exposure from environmental sources, can cause stochastic detrimental health effects (i.e. malignancies and hereditary effects). The fundamental quantity used in radiation protection to characterize the level of human exposure associated with stochastic health effects is the 'effective dose'. The unit of effective dose is the sievert (Sv), but the smaller unit of millisievert (mSv) is more appropriate for normal exposures.

The worldwide level of annual natural background exposure, including external exposure, consumption of food and water containing natural radionuclides, and inhalation of radon with its daughter products, amounts on average to 2.4 mSv, with a range from 1 to 10 mSv. In Ukraine the mean background exposure is about 2.5 mSv, which is in line with worldwide levels.

The internationally recommended annual dose limit for controlled exposures of the general public is equal to 1 mSv. For prolonged exposure situations from all environmental radioactive sources, including natural and human-made sources, the International Commission on Radiological Protection (ICRP) recently recommended a generic intervention level of existing annual dose equal to 10 mSv as the level below which intervention is unjustified, taking into account radiological, economic and social factors.

Radiation exposure of the population of the Dnieper River basin is caused by both naturally

occurring radionuclides and human-made radionuclides, mainly nuclear fission products (^{137}Cs, ^{90}Sr and some others). The pathways of long term environmental human exposure include external exposure with gamma radiation and internal exposure via ingestion of contaminated food and drinking water as well as inhalation of airborne radionuclides.

Whereas natural radiation accompanies the whole human history, significant environmental contamination with human-made radionuclides occurred during two time periods: first in the 1950s and 1960s as a result of global stratospheric fallout from worldwide nuclear weapons tests and later in 1986 when a large radioactive release occurred directly into the Dnieper River basin due to the Chernobyl accident. Local contamination of the Dnieper River basin in 1986 led to the highest population doses caused by the Chernobyl accident in Europe.

In the long term after the Chernobyl accident, the inhabitants of areas contaminated with radionuclides in 1986 are still subjected both to external exposure from ^{137}Cs gamma radiation and to internal exposure due to consumption of local foodstuffs containing ^{137}Cs and, to a lesser extent, ^{90}Sr. Inhalation of plutonium radionuclides and ^{241}Am does not significantly contribute to human doses. In accordance with the environmental behaviour of ^{137}Cs and ^{90}Sr, external exposure prevails in areas with dominantly black soils, and the contribution of internal exposure to the total (external and internal) dose does not exceed 10%. In contrast, in areas with light sandy soils, the contributions due to internal and external exposure are comparable, and, in areas with peaty soils, the internal exposure dominates. At present, along with consumption of local agricultural vegetable and animal (milk and meat) foods, consumption of natural foods (lake fish, forest mushrooms and berries, game), which is typical for the Dnieper River basin population, significantly contributes (up to 50–70%) to ^{137}Cs intake in the human body and the associated internal dose.

After 1995, average total annual doses of inhabitants of settlements located in the Chernobyl accident areas, caused by environmental ^{137}Cs and ^{90}Sr, ranged from 0.1 to about 5 mSv; the contribution of ^{90}Sr being usually below 5%. The inhabitants of the settlements of the Gomel and Mogilev regions of Belarus and the Bryansk region of the Russian Federation, where ^{137}Cs soil contamination exceeds 1 MBq/m^2, are subjected to the highest exposure levels. In many tens of settlements, the average annual exposure level still exceeds the national action level of 1 mSv.

The contribution of freshwater pathways to public exposure is dependent on the direct consumption of water and fish containing radionuclides as well as on the flooding of land used for livestock grazing/haymaking and utilization of river water for irrigation of agricultural land, which leads to subsequent human exposure via terrestrial pathways. In the lower Dnieper River reaches, which were not subjected to direct radionuclide contamination in 1986, almost all the Chernobyl exposures are attributed to water pathways; however, the dose itself is very low. In most of the directly Chernobyl contaminated areas the human dose is much higher (see previous paragraph), but it is mostly attributable to terrestrial pathways.

The exception is a number of ‘closed’ lakes (without a regular outflow) located in peaty areas, in which the concentration of ^{137}Cs (and to a lesser extent of ^{90}Sr) in water and fish is much higher than in the nearest rivers. These concentrations do not significantly decrease with time, and in many lakes still exceed the permissible levels for drinking water and especially for fish. The consumption of contaminated fish prevails as the pathway of internal exposure of the inhabitants of the nearest settlements. In some of these settlements the average annual human dose exceeds 1 mSv, and therefore closed lakes and their inhabited surroundings are considered in this report as actual local hot spots.

Another source of internal exposure of the inhabitants of some Ukrainian riparian settlements via consumption of river water and fish is the release of uranium radionuclides and their daughter products from mining and milling facilities located in the Dnipropetrovsk region. Significantly elevated levels of ^{234}U, ^{238}U and ^{210}Po in water have recently been detected in rivers downstream of Zhovti Vody and of the uranium tailings dumps of the Prydniprovsky chemical plant. For people drinking water from contaminated rivers, an associated annual internal dose of the order of 0.1 mSv has been estimated. However, there are insufficient data from other pathways (contaminated food, radon, etc.) to determine the total exposure of individuals living in these areas. As the uranium concentration in river water approaches or could approach the national action level, both sites are identified as local hot spots.

1.9. ANALYSIS OF HOT SPOTS AND POSSIBLE ACCIDENTS

Following the UNDP Hot Spots Workshop in Kiev, the following definitions, which take account of radiation protection methodology, were proposed.

Hot spot. A technical facility, object or local natural site that is contaminated with radionuclides or, in the future, could become a source of environmental radioactive contamination above reference levels or could result in human or biota exposure above radiological criteria.

Transboundary hot spot. A hot spot that is, or in the future could become, a source of environmental radioactive contamination above reference levels or could result in human or biota exposure above radiological criteria on the territory of another country.

National hot spot. A hot spot that occupies, or in the future could occupy, a substantial national territory and that has no significant transboundary impacts.

Local hot spot. A hot spot that occupies a local area.

Initially, the group made a list of candidate hot spots. A screening process was then applied, based on the above criteria, to determine the final list as follows.

Actual hot spots:

(a) The Pripyat floodplain area within the CEZ. This is assessed to be a transboundary hot spot with a current impact and a greater impact during times of high flooding.
(b) The radioactive waste dumps on the former Prydniprovsky chemical plant site in Dniprodzerzhinsk and of the uranium processing operation in Zhovti Vody. These are actual national hot spots with a potential for a major impact over a very long period if impoundment structures erode or fail catastrophically.
(c) Inhabited areas in the three countries with high levels of Chernobyl caused radioactive contamination, including closed lakes in which concentrations of ^{137}Cs in fish or drinking water exceed the permissible levels. These are local hot spots but occur in all three countries.

Potential hot spots:

(i) The Chernobyl shelter in the event of its collapse (transboundary hot spot);
(ii) The Chernobyl cooling pond in the event of dam failure (national hot spot).
(iii) The Ecores and RADON facilities at Kiev and Dnipropetrovsk, until reconstruction is complete (local hot spots).

Possible accidents: in addition to these actual and potential hot spots, an accident at a nuclear power plant was considered. A major accident at a nuclear power plant is considered to be of very low probability, having regard for major and ongoing improvements at nuclear power plants in the Russian Federation and Ukraine. However, a large release would have considerable transboundary impacts, especially in the Black Sea if the source were in the south of Ukraine.

1.10. CONCLUSIONS

1.10.1. Chernobyl affected areas

(1) High levels of radioactivity remain within the CEZ. Important hot spots within this zone are the floodplain along the Pripyat River, the Chernobyl nuclear power plant cooling pond and the Chernobyl shelter.
(2) There is still transboundary transfer of radionuclides (mainly ^{90}Sr) by rivers within the Dnieper River basin. The most important source is the floodplain of the Pripyat River within the CEZ.
(3) The concentrations of ^{137}Cs and ^{90}Sr in river waters of the Dnieper River basin have decreased significantly and are now below the maximum permissible levels set by the national authorities and recommended by expert international organizations. Almost all the ^{137}Cs washed out of contaminated areas is immobilized in bottom sediments within the reservoirs of the Dnieper River. The impact of these sediments is low and will decline further with decay and further deposition of sediments on top of the contaminated sediments.
(4) Lakes with no regular outflows still present a radiological problem arising from higher levels of ^{137}Cs in water and fish.
(5) The levels of radioactivity in forest foods (wild game, mushrooms, berries) in some Chernobyl affected areas are above permissible levels, as are those in milk and beef produced by cattle grazing on contaminated floodplains.

1.10.2. Nuclear power plants

(6) Routine discharges from nuclear power plants in the Russian Federation and Ukraine are generally well below authorized limits and do not contribute to significant contamination of the environment.

(7) A legislative and regulatory basis established in both the Russian Federation and Ukraine ensures that all nuclear power plants operate with a valid licence. A legal mechanism exists for regulatory body review and assessment of plant safety and renewal of plant licences on a regular basis.

(8) In recent years the safety of RBMK and WWER reactors has been subject to considerable regulatory and international scrutiny. Major engineering upgrades have been undertaken to improve safety. An international in-depth safety assessment process is under way to optimize the improvement programmes. There is room for improvement in emergency preparedness and response.

1.10.3. Uranium mining and milling

(9) Uranium mining and milling in Ukraine has had a negative impact on the environment. The most serious problem is caused by about 100×10^6 t of tailings and other radioactive waste from past and current operations. Most of the tailings dumps have not been properly rehabilitated and will pose a long term problem unless they are properly stabilized. Tailings D at Dniprodzerzhinsk is considered to have the greatest potential for pollution of the environment because of its proximity to the Dnieper River, the evidence of current seepage and the possibility of catastrophic failure of the impoundment. The situation in the region of tailings C and adjacent to it needs regular control, and decisions on further use should be taken with regard to IAEA recommendations and on the basis of a cost–benefit analysis.

(10) There is a paucity of data on the levels of radionuclides in the vicinity of uranium mines and mills and radioactive waste impoundments. Consequently, it is not possible to estimate the current or future dose rates from these sources with any degree of accuracy.

(11) There is a need to urgently start the development of modern standards on the protection of the environment, radiation safety and monitoring in the zone of influence of the uranium sites, consistent with the requirements of Ukrainian law and the recommendations of international organizations such as the IAEA.

1.10.4. Other radiological sources

(12) Medical and industrial uses of radioisotopes do not pose significant risks to the population of the Dnieper River basin. Radioactive sources with a high radioactivity could be a source of local exposure. Regulatory authorities should ensure that they are properly licensed and managed.

(13) There are many disposal or temporary storage sites for Chernobyl waste in Belarus, the Russian Federation and Ukraine. There is a need to continue to monitor and characterize the most hazardous of these sites; however, their impact appears to be quite localized and does not represent a major source of contamination of surface waters.

(14) There are two RADON type waste storage facilities at Kiev and Dnipropetrovsk in the Ukrainian section of the Dnieper River basin. Further safety assessments need to be undertaken to assess their environmental impact.

(15) The Ecores State facility near Minsk does not comply with international standards for the storage or disposal of radioactive waste. This facility is a potential source of radioactive contamination of the local population, but not of the Dnieper River basin as a whole.

1.10.5. Human exposure to radiation

(16) The average dose rate to Ukrainian citizens from natural radiation sources is about 2.5 mSv/a, which is close to the global average. This value is also considered to be a reasonable estimate of the average dose rate to the population of the Dnieper River basin as a whole.

(17) The inhabitants of areas contaminated with radionuclides from the Chernobyl accident in 1986 are still being subjected both to external exposure from ^{137}Cs gamma radiation and to internal exposure due to consumption of local foodstuffs containing ^{137}Cs and, to a lesser extent, ^{90}Sr. The most important factors

controlling the mean external dose are the settlement type (rural or urban) and the level of ^{137}Cs soil deposition (in kBq/m^2). For internal exposures, the most important factors are the soil type and the level of ^{137}Cs soil deposition. On average, effective doses to the inhabitants of rural settlements are higher than those to urban dwellers.

(18) The average total annual doses to the inhabitants of settlements located in the Chernobyl accident areas, caused by environmental ^{137}Cs and ^{90}Sr, range from 0.1 to about 5 mSv. In many tens of settlements the average annual exposure level still exceeds the national action level of 1 mSv.

(19) Dosimetric models have been developed and tested to estimate past, present and future radiation exposures from all Chernobyl related pathways. The models predict that, by 2001, people in affected areas had already received at least 75% of their lifetime internal dose due to ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{89}Sr in Chernobyl fallout. Dose rates will decrease slowly with time over the next 50 years as deposited ^{137}Cs (half-life 30 years) decays and is made less available by soil redistribution processes.

(20) For critical groups in Chernobyl contaminated areas, wild foods (e.g. forest mushrooms, game, forest berries and fish) can make an important contribution to dose; for example, in one study in the Bryansk region of the Russian Federation, 'natural' foods contributed from 50% to 80% of ^{137}Cs intake. The average annual internal dose due to ^{137}Cs was estimated to be 1.2 mSv for men and 0.7 mSv for women.

(21) In most cases, aquatic pathways (drinking water, fish consumption and irrigation) make only a small contribution to the total dose from Chernobyl sources. At times of flooding of the Pripyat floodplain, dose rates increase somewhat due to washout of ^{90}Sr. Furthermore, in some closed lakes the concentration of ^{137}Cs remains high, and high levels of contamination are found in fish species. People who illegally catch and eat contaminated fish may receive internal doses in excess of 1 mSv/a from this source.

(22) Routine releases of radionuclides from operating nuclear reactors in the Dnieper River basin do not contribute significantly to radiation exposure of communities living in their vicinity.

(23) More data are required in order to make reliable estimates of exposures of people living in uranium affected areas. Estimates of exposure from the drinking water pathway suggest low dose rates, except in small areas that are unlikely sources of drinking water.

(24) Further work is needed to assess the potential short term and long term doses that might be received if uranium tailings impoundments adjacent to waterways in Ukraine were to fail and release tailings and/or contaminated water into adjacent rivers.

1.10.6. General

(25) Monitoring data are collected by various agencies for different purposes; different methodologies are used, some of which are outdated. There needs to be harmonization of results between the various organizations engaged in monitoring.

1.11. RECOMMENDATIONS

1.11.1. Chernobyl affected areas

Within the CEZ:

(1) The engineering works on the right bank of the Pripyat River within the CEZ should be completed. The works were started in 1998 but were suspended due to lack of funding.

(2) A diversionary canal should be constructed along the Belarus–Ukraine border between the settlements of Krasne and Zimovische to prevent inundation of the heavily contaminated areas on the Pripyat River's left bank.

(3) After 2007 the heavily contaminated Chernobyl cooling pond should be safely decommissioned.

(4) Appropriate measures need to be taken to monitor and prevent releases of radioactivity from the Chernobyl shelter.

(5) Technical measures should be taken to prevent significant radionuclide dispersion from the sites of temporary radioactive waste storage in the floodplain of the Pripyat River.

(6) The monitoring system for surface and underground waters in the CEZ should be improved and optimized.

Within inhabited areas:

(7) In order to reduce population exposure in the most contaminated areas, the following measures should be considered:
  (i) Restrict consumption of local foods (wild game, fish, berries, mushrooms, etc.);
  (ii) Restrict grazing and use of vegetation on floodplains;
  (iii) Provide safe water to rural communities.

(8) The monitoring system for surface and underground waters should be optimized. In particular, screening studies on closed lakes in the most contaminated areas should be performed and their impact on population exposure assessed.

(9) The radiological criteria in the Chernobyl affected countries should be harmonized.

1.11.2. Nuclear power plants

(10) Rules and regulations should be harmonized within the Dnieper River basin and made consistent with international best practice.

(11) Cooperation and information exchange between regulatory organizations should be strengthened to make use of experience gained in implementing safety upgrade programmes.

(12) To improve preparedness for a possible nuclear accident, technical measures (early warning systems, decision support systems), institutional measures (logistics) and links between nuclear power plant and regional administrative units should be improved.

(13) The scope of safety analysis reports should be compliant with national requirements and consistent with the IAEA safety standards and current international practice.

(14) Comprehensive plant specific probabilistic safety assessments need to be finalized for all nuclear power plants in the region and subjected to thorough regulatory review. The countries with nuclear power plants would benefit from participation in activities organized by the IAEA on comparison of probabilistic safety assessment studies for similar reactors.

(15) Plans established for safety improvements should be carried out as a matter of urgency.

1.11.3. Uranium mining and processing

(16) An ongoing system for radioecological monitoring of the environment (water, soil, vegetation, air and food products) in the affected regions (Zhovti Vody, mining areas and Dniprodzerzhinsk) needs to be established. This should involve provision of appropriate equipment and coordination of the efforts of the external monitoring organizations.

(17) The pollution resulting from past and present operations in the Dniprodzerzhinsk industrial complex needs to be considered holistically in order to understand its respective contribution to pollution of the Dnieper River basin and the effects of interactions between the major waste storage areas. Essentially, there needs to be an overall plan for the site, which will include rehabilitation of sites along with possible further industrial development.

(18) Rehabilitation of non-operational uranium tailings impoundments at Zhovti Vody and Dniprodzerzhinsk needs to be completed in order to ensure that they provide long term containment. In any rehabilitation plan, particular attention should be given to tailings D and to the Konoplyanka River, which is acting as a conduit for the transfer of pollutants from the tailings impoundment into the Dnieper River.

(19) Current and future operations need to be carried out in accordance with an environmental plan that includes funding provisions to ensure progressive rehabilitation of closed mines, dumps and other facilities.

1.11.4. General

(20) Existing laws, regulations and guidelines should be reviewed and revised:
  (i) To ensure that radiation safety provisions are consistent within the region and compliant with the latest international standards;
  (ii) To apply risk assessment methodologies to account for radioactive, chemical and biological contamination.

(21) More detailed impact analysis of actual and potential hot spots should be undertaken within the framework of a specialized project.

(22) Monitoring of the environmental radioactive contamination in the Dnieper River basin should be improved and harmonized among Belarus, the Russian Federation and Ukraine.

(23) Scientific research that contributes to the assessment, understanding and solution of radiological problems in the Dnieper River basin should be supported.

REFERENCES TO SECTION 1

[1.1] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), Annex J: Exposures and Effects of the Chernobyl Accident, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).

[1.2] INTERNATIONAL ATOMIC ENERGY AGENCY, The Principles of Radioactive Waste Management, Safety Series No. 111-F, IAEA, Vienna (1995).

2. INTRODUCTION

The Dnieper is the third largest river in Europe (after the Volga and the Danube). It drains an area of 511 000 km^2 and has a total length of 2200 km. Twenty per cent of the river basin lies within the territory of the Russian Federation, 23% in Belarus and the largest portion, 57%, in Ukraine. Thirty-two million people live in the Dnieper River basin [2.1]. Most of the land is arable and many crops (wheat, sugar beet, barley, rye, sunflower, flax, soybean, fruits and vegetables) are grown in the region.

Over 84% of the total annual river flow (about 45 km^3) is collected in the upper parts of the basin (within Belarus and the Russian Federation). However, most of this water is consumed by industrial and agricultural activities in Ukraine, where there is a series of large reservoirs. About 8.5 km^3 discharges into the Black Sea, which is bordered by six countries (Bulgaria, Georgia, Romania, Russian Federation, Turkey and Ukraine). The Dnieper River contributes a significant fraction of the total freshwater input to the Black Sea, along with various pollutants and contaminated sediments collected along the way [2.2–2.4].

Figure 2.1 shows the extent of the Dnieper River basin in Belarus, the Russian Federation and Ukraine. Major tributaries and towns are also shown.

FIG. 2.1. Map of the Dnieper Basin showing the network of rivers (courtesy of the UNDP).

The river has suffered severe pollution and water quality deterioration during the past decades, which has affected access to safe drinking water for the millions of people living in the three riparian countries. The basin is no longer considered a self-regulating river ecosystem and is a serious threat to biota species and their habitats. As a result, assistance was requested from the international community to develop a strategic action plan (SAP) to protect the river in a sustainable manner, and through this to contribute to the protection of regional and global international waters [2.3].

This report is a contribution to the Dnieper Basin Environmental Programme (DBEP) by an international team of scientists under the direction of the IAEA. The DBEP is being carried out under the United Nations Development Programme — Global Environment Facility (UNDP–GEF).

In assessing the Dnieper River basin, the UNDP–GEF has identified radioactive contamination as one of the significant issues. A preliminary transboundary diagnostic analysis (TDA) was published for the Dnieper River basin in 1997 [2.3]. Subsequently, the IAEA was requested to contribute its expertise in radiation and environmental protection to a more detailed analysis involving a revision of the TDA and the preparation of a SAP. A summary report by the international expert team was provided to the UNDP in November 2002 [2.5]; this included scientific findings and conclusions derived from the assessment material (see Section 10 of this report), as well as a list of recommendations for the SAP and the national action plans (NAPs) (see Section 11). This report is a detailed radiological assessment in support of the statements, conclusions and recommendations provided in that summary report.

The international expert team for this study included scientists from Belarus, the Russian Federation and Ukraine familiar with radioactive contamination in the Dnieper River basin and experienced in radiological assessments. A list of international expert team members and other contributors is given at the end of this report. To gather information for the study, two fact finding missions were undertaken. One of these was concerned with radiation and waste safety issues and the other with the safety of nuclear power plants. Meetings and discussions were held in Belarus, the Russian Federation and Ukraine with scientific specialists, plant operators, regulatory personnel, representatives of ministries and local administrators. Inspections were carried out at the Chernobyl site, at uranium tailings management sites near Dniprodzerzhinsk and at the Ecores State waste management facility near Minsk. There were two meetings of the international expert team, and team members participated in a number of workshops organized by the UNDP–GEF.

This report includes 11 sections. Following this introduction, Section 3 identifies the major radiological sources within the Dnieper River basin. Each of these sources is assessed in subsequent sections (Chernobyl in Section 4, nuclear power plants in Section 5, uranium mining and processing in Section 6, other sources, including waste disposal sites and research facilities, in Section 7). Section 8 deals with an assessment of human exposure to radiation within the Dnieper River basin and Section 9 assesses radiological hot spots. The conclusions and recommendations are presented in Sections 10 and 11, respectively.

REFERENCES TO SECTION 2

[2.1] UNITED NATIONS DEVELOPMENT PROGRAMME, Diagnostic Analysis for the Dnieper Basin, UNDP, New York (2003).

[2.2] BABCOCK, K., BARICA, J., Why the Dnieper? Water Qual. Res. J. Canada **33** (1998) 453–455.

[2.3] UNITED NATIONS DEVELOPMENT PROGRAMME, Transboundary Diagnostic Analysis for the Dnipro River Basin: Synthesis Report, UNDP–GEF, UNDP, New York (1997).

[2.4] UNITED NATIONS DEVELOPMENT PROGRAMME, The Dnipro: Partnership for Environmental Rehabilitation, Information Bulletin of the UNDP–GEF Dnieper Basin Environment Programme, No. 1 (1998).

[2.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Contamination of the Dnieper River Basin: Contribution to the Transboundary Diagnostic Analysis and Recommendations for the Strategic Action Plan, Summary Report, Regional Technical Co-operation Project RER/9/072 (UNDP Project RER/98/G31), IAEA, Vienna (2002).

3. RADIOACTIVITY IN THE DNIEPER RIVER BASIN

Radioactivity is the property of unstable atoms (called ‘radionuclides’) that spontaneously disintegrate with emission of radiation. Everyone is exposed to radiation from radioactivity in the natural environment. In addition, human activities involving the use of radiation and radioactive substances cause radiation exposure. Some of these activities, such as the mining of radioactive ores and the burning of coal containing radioactive substances, enhance exposure to natural radiation. Nuclear power plants and other nuclear installations release radioactivity into the environment and produce radioactive waste, which is a potential source of radiation exposure. Another source is the use of radiation and radioisotopes in medicine, industry and research. The medical use of radiation is the largest human-made source of radiation exposure [3.1].

Exposure to ionizing radiation can damage living organisms and cause health effects in humans, including leukaemia and other cancers. The effects of radiation on human health are discussed in Section 7.

This report deals only with the assessment of those sources of radiation and radioactivity that are of special concern in the Dnieper River basin. The first task of the project team was to identify the main sources (actual and potential) of radiation exposure meeting this criterion. The identified sources are:

(a) Areas affected by the Chernobyl nuclear accident;
(b) Nuclear power plants;
(c) Uranium mining and ore processing;
(d) Radioactive waste storage and disposal sites;
(e) Non-power sources (e.g. from the use of radiation and radioisotopes in medicine, industry and research).

Figure 3.1 shows the locations of the most important sources. Each is assessed in detail in separate sections of this report. The following sections give a brief introduction to each of these sources.

3.1. AREAS AFFECTED BY THE CHERNOBYL NUCLEAR ACCIDENT

The Chernobyl nuclear power plant is located alongside the Pripyat River in northern Ukraine, about 130 km north-east of Kiev. It is 12 km from the border with Belarus and 140 km from the border with the Russian Federation (see Fig. 3.1). On 26 April 1986 the worst ever nuclear accident occurred at unit 4 of the plant. Following a criticality excursion, two major steam explosions destroyed the reactor and badly damaged the reactor building and other structures (see Fig. 3.2). A major release of radioactivity occurred as a result of the explosions. Subsequent burning of the graphite moderator resulted in continued release of radioactivity over a period of ten days. Overall, about 50% of the ^{131}I and 30% of the ^{137}Cs in the reactor core were released [3.1, 3.2].

The fallout of this radioactivity was dependent on the vagaries of the wind direction and rainfall over the period of the releases. The most serious consequences of the Chernobyl accident to the public were caused by exposure to short lived radionuclides, especially ^{131}I, which resulted in many thyroid cancers [3.1]. Other health effects are expected in the future from the exposures received by some individuals during the accident phase. A large number of studies have been carried out on the health effects arising from exposure of reactor personnel, emergency workers and the general public during the immediate period after the accident [3.1, 3.3–3.8].

This assessment is concerned mainly with current and future exposures to radiation. Of those radionuclides still remaining from the Chernobyl accident, ^{137}Cs (half-life 30 years) and ^{90}Sr (half-life 29.1 years) are the most important from an environmental and public health perspective. Caesium-137, with its short lived daughter, ^{137m}Ba, emits beta and gamma radiation; ^{90}Sr, with its short lived daughter, ^{90}Y, emits beta radiation.

Caesium is volatile at the high temperatures that were experienced during the Chernobyl accident. Consequently, it tended to travel substantial distances before being deposited. Both in the environment and in the human body caesium radionuclides behave like potassium. However, strontium is not particularly volatile and was mainly

associated with fuel particles deposited much closer to the release point. In the environment and in the human body, strontium radionuclides behave like calcium (hence strontium is a 'bone seeker').

The area in the immediate vicinity of the Chernobyl nuclear power plant was the most contaminated. In 1986 the 30 km Chernobyl exclusion zone (CEZ) was established around the Chernobyl nuclear power plant and the public was evacuated from the area. Within the CEZ are a number of important sources:

(a) The damaged nuclear reactor. In May 1986 a decision was taken to enclose the area around unit 4 to prevent the further spread of radioactivity into the environment and to reduce the exposure of personnel working on the Chernobyl nuclear power plant site. An enclosing building, known as the shelter or 'sarcophagus', was completed in November 1986 (see Fig. 3.3)It was erected under difficult circumstances in very high radiation fields using remote construction methods. Unfortunately, as a result of construction difficulties, there are now openings and breaks in the walls and roof of the shelter, which is estimated to total about 1200 m^2 in area.

(b) The Chernobyl cooling pond. The cooling pond is an artificial lake built to provide the cooling water for the condensers of the four Chernobyl reactor units. The pond covers an area of approximately 23 km^2 and contains approximately 149 $\times$ 10^6 m^3 of water. The cooling pond is less than 1 km from the Chernobyl nuclear power plant; a dam separates the pond from the Pripyat River.

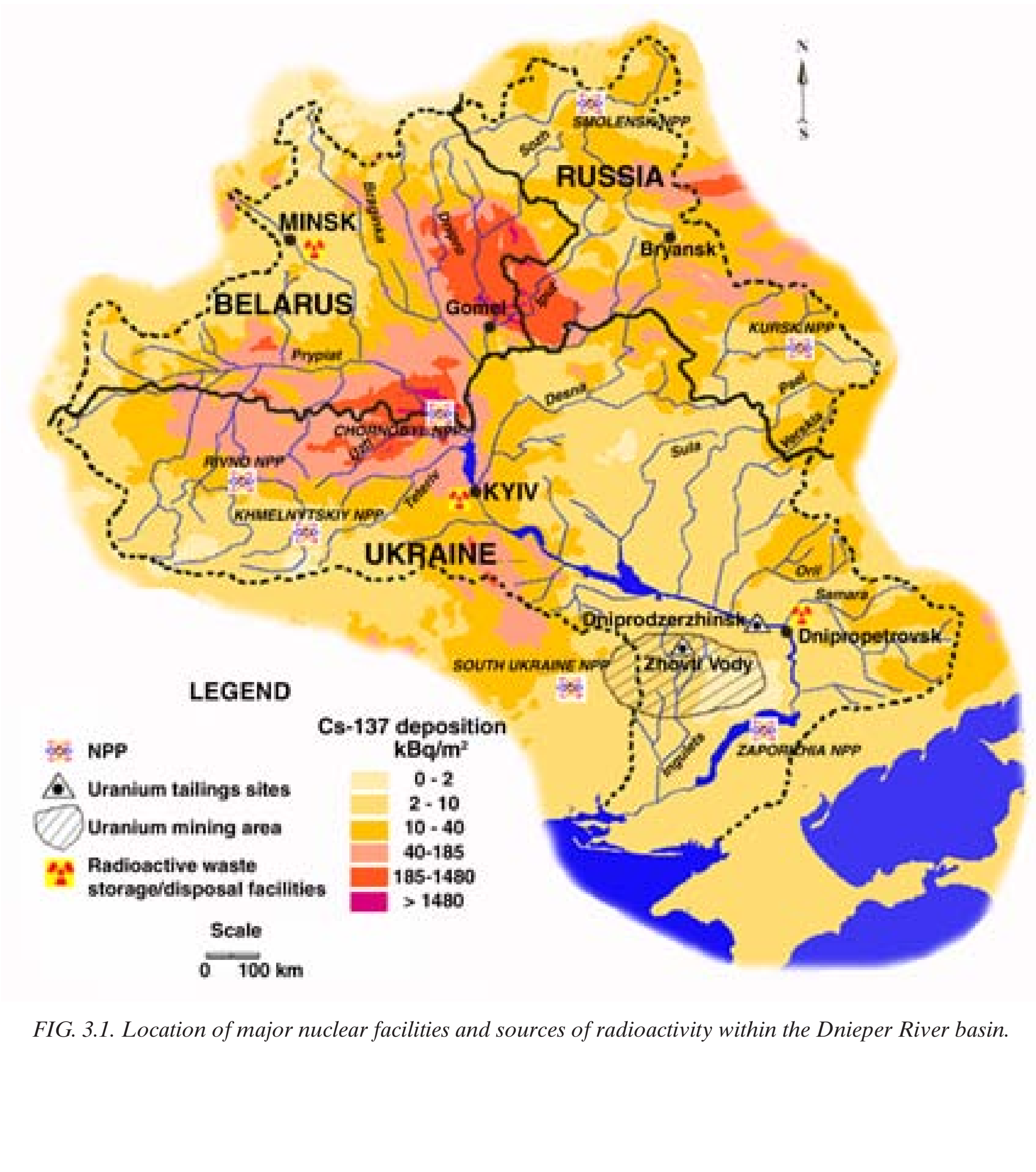

FIG. 3.1. Location of major nuclear facilities and sources of radioactivity within the Dnieper River basin.

FIG. 3.2. The damaged unit 4 of the Chernobyl nuclear power plant (from Ref. [3.2]).

FIG. 3.3. Construction of the Chernobyl shelter (from Ref. [3.2]).

The pond was heavily contaminated during the Chernobyl accident and by subsequent dumping of radioactive liquid waste into it.

(c) Waste burial sites. After the Chernobyl accident, contaminated material, including debris, structures, equipment, dead trees and contaminated soil, were buried within the CEZ in trenches and under mounds. The purpose was to reduce radiation levels near the Chernobyl nuclear power plant and to prevent dispersion of radioactivity. Leaching into groundwater and migration from these sites is a potential source of contamination of waterways.

(d) Contaminated floodplain. The floodplain along the Pripyat River is highly contaminated from the Chernobyl accident, especially with ^{90}Sr; concentrations exceed 4000 kBq/m^2 over large areas. This area is regularly inundated, especially during spring floods. Moreover, some of the waste burial sites are located within the floodplain. Engineering works have been undertaken to mitigate the flooding but have not been completed due to financial problems. Radioactivity, especially ^{90}Sr, is washed off the floodplain during times of high flood and transported via the Pripyat River to the Dnieper system.

Although the deposition of radioactivity was highest in the CEZ, significant fallout occurred throughout much of Europe. However, deposition was greatest in the three countries (Belarus, Russian Federation and Ukraine) that lie within the Dnieper River basin. Figure 3.1 shows the areas of highest contamination. On the territory of Belarus the worst affected areas are the Gomel and Mogilev regions. Within the Russian Federation the south-west part of the Bryansk region is the most affected. In Ukraine contamination is particularly high in the Kiev, Zhytomyr and Chernihiv regions. In total, about 85 000 km^2 of the Dnieper River basin received a surface contamination of ^{137}Cs above 37 kBq/m^2 (1 Ci/km^2)[1]. Section 4 gives detailed information on the deposition of radioactivity.

One of the more serious long term ecological effects of the Chernobyl fallout was the secondary runoff (wash-off) of radionuclides from the initially contaminated areas through the river networks of Belarus, the Russian Federation and Ukraine into the Dnieper reservoir system, thereby expanding the spatial scale of the accident and exposing

[1] Radioactivity is measured in units of becquerel (Bq), which is one disintegration per second. An older unit called the curie (Ci), equivalent to 3.7×10^{10} Bq, is still in common use. The becquerel is a very small unit and hence large units are commonly used, for example 1 kBq = 10^3 Bq, 1 MBq = 10^6 Bq, 1 GBq = 10^9 Bq, 1 TBq = 10^{12} Bq and 1 PBq = 10^{15} Bq.

millions of people who use the downstream resources of the Dnieper River. Section 4 discusses the water-borne dispersal of radionuclides in detail.

3.2. NUCLEAR POWER PLANTS

There are 17 operating nuclear power reactors in the Dnieper River basin (Fig. 3.1), ten in Ukraine at three sites (Zaporozhe, Rovno and Khmelnitski) and seven in the Russian Federation at two sites (Kursk, Smolensk). In addition, there are three nuclear power reactors (South Ukraine nuclear power plant) in the Bug River basin. The Zaporozhe nuclear power plant, comprising six 1000 MW(e) units, is one of the largest in the world (see Fig. 3.4). Currently, one 1000 MW(e) nuclear power reactor is being commissioned at Rovno, while another is under construction at Khmelnitski.

Nuclear power plants can release radioactivity to the environment in a number of ways:

(a) By routine releases to air and water;
(b) By releases from spent nuclear fuel storage facilities;
(c) By releases from radioactive waste storage facilities;
(d) By transport accidents;
(e) By major accidents affecting the nuclear core, where releases are difficult to control.

Under normal conditions, nuclear power plants release small amounts of radioactivity into the air and sometimes into cooling water systems. However, such releases do not result in significant radiation exposures of the general public. Data on normal releases from nuclear reactors in the Dnieper River basin are presented in Section 5.

FIG. 3.4. Zaporozhe nuclear power plant and the cooling pond and Kakhovka reservoir on the Dnieper River.

Radioactive material resulting from reactor operations (such as spent nuclear fuel and radioactive waste) is stored in specially designated facilities that are subject to regular inspection by regulatory authorities. Release of radioactivity is possible, especially from liquid waste storage facilities, but would normally require a breakdown in a number of barriers. Monitoring systems are designed to detect any release of radioactivity at an early stage.

Accidents can occur during transport, but transport containers are designed to withstand the most serious credible accidents. Worldwide, the nuclear industry has a very safe record in the transport of nuclear material.

A major reactor accident (such as occurred at Chernobyl) can have very serious consequences. The adequacy of ongoing measures taken to prevent nuclear accidents in the Dnieper River basin is assessed in Section 5, while Section 9 reports on the consequences of a hypothetical accident affecting the Dnieper River basin and the Black Sea.

3.3. URANIUM MINING AND PROCESSING

The only uranium mining and ore processing in the Dnieper River basin is in Ukraine. Uranium exploration started in 1944 and led to the discovery of 21 deposits. Many of the deposits are within the watershed of the Dnieper River basin, while some are within the basins of the southern Bug and Seversky Donets Rivers. Figure 3.1 shows the locations of the deposits and the ore processing operations. The effects of uranium mining and processing are localized and only affect the Dnieper River basin in southern Ukraine.

The first uranium processing plant in Ukraine was the Prydniprovsky chemical plant, which started up in 1948 using ores shipped from countries in central Europe. It is situated a few kilometres from the Dnieper River in the city of Dniprodzerzhinsk and ceased operations in 1991.

The Zhovti Vody hydrometallurgical plant commenced production in January 1959 to process ores from the region. Current production is about 1000 t U/a. Most of the current production comes from the Ingulsky mine developed on the Michurynske deposit.

Uranium mining and milling have a number of potential impacts on human health and the environment. These include:

(a) Contamination of mine water with uranium and other radionuclides;
(b) Release of mill wastewaters to surface waters (usually after treatment);
(c) Runoff of water from contaminated areas of the mine or mill;
(d) Radon release from mines, waste rock dumps and mill tailings piles;
(e) Leaching of radionuclides from tailings and their subsequent transport in water;
(f) Erosion of tailings storage systems, leading to dispersal of tailings by wind and water;
(g) Contamination of underground and surface waters by toxic non-radioactive substances such as heavy metals and the chemicals used in processing.

The most important waste from the milling of uranium is the finely divided solid residue known as tailings. Tailings typically contain 70% of the radioactivity in the original ore and remain radioactive for hundreds of thousands of years. The main long lived radionuclides are residual uranium, ^{230}Th (half-life 80 000 years) and ^{226}Ra (half-life 1600 years). Radium is a continual source of ^{222}Rn (half-life 3.8 days), which, being a gas, is readily dispersed. Radon daughters are a source of radiation exposure and a known cause of lung cancer in uranium miners.

Section 6 gives information on uranium mining and processing in Ukraine and on their impact on the environment and public health. Where available, monitoring data are presented and an assessment is made of the long term stability of the tailings and the need for countermeasures.

3.4. RADIOACTIVE WASTE STORAGE AND DISPOSAL SITES

Radioactive storage and disposal sites in the Dnieper River basin include:

(a) The Ecores State facility near Minsk, which comprises two closed trenches and two repositories that are being progressively filled. This facility accepts radioactive waste from the nearby Sosny Institute and from more than 100 organizations from the industrial, research and medical sectors.
(b) Two disposal sites operated by the RADON State enterprise at Kiev and Dnipropetrovsk. These sites handle both radioactive waste and spent radiation sources from the non-nuclear power plant sector, including the industrial, medical and agricultural sectors.
(c) Many disposal or ‘temporary’ storage sites for Chernobyl waste in Belarus and Ukraine.

These sites are assessed in Section 7.

3.5. NON-POWER SOURCES

Non-power sources include research reactors and those arising from the application of radioisotopes and radiation in medicine, industry and research. Radioisotopes are used in medicine for diagnosis and treatment in all three countries.

Nuclear research facilities in the Dnieper River basin are limited. The research reactors at the Sosny Institute near Minsk and the Institute for Nuclear Research at Kiev are shut down. Radioactive waste from these facilities is stored in dedicated waste storage sites.

Non-power sources of radioactivity are discussed briefly in Section 7.

REFERENCES TO SECTION 3

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4. CHERNOBYL AFFECTED AREAS

4.1. SCOPE

This section presents detailed information on the distribution of radioactivity from the Chernobyl accident, the systems used to monitor the dispersion of the radioactivity, the characteristics of radioactivity in water-borne runoff, the fate of radionuclides in the Dnieper reservoirs and the transboundary movement of radioactivity from Chernobyl affected areas.

The storage and/or disposal by burial of Chernobyl contaminated waste is discussed in Section 7. Section 8 assesses current and future exposure to radiation from Chernobyl affected areas. Section 9 describes the identification and analysis of Chernobyl hot spots.

4.2. DISTRIBUTION OF FALLOUT FROM THE CHERNOBYL ACCIDENT

As a result of the Chernobyl accident, about 85 PBq of ^{137}Cs, 54 PBq of ^{134}Cs, 1760 PBq of ^{131}I, 10 PBq of ^{90}Sr and 0.07 PBq of ^{239,240}Pu were released, as well as many shorter lived radionuclides of lesser radioecological significance [4.1]. Major releases occurred over a period of ten days, during which time there were a number of changes in wind direction. As a consequence, fallout was deposited over most of Europe; however, the largest areas of contamination were in Belarus, the Russian Federation and Ukraine (see Table 4.1). Much of the fallout in these three countries was deposited in the Dnieper River basin.

After the Chernobyl accident, the responsible agencies in many countries gathered data on soil contamination in their territories. These data were published in the form of reviews, maps and lists of contamination density in populated areas. Much of the data applies to areas within the Dnieper River basin. In 1992–1995 a European Union–Commonwealth of Independent States programme was carried out to study the consequences of the Chernobyl accident [4.2], and within that programme data on soil contamination density were gathered, processed and published as an atlas [4.3], including a CD-ROM version [4.4]. The maps were prepared using the geographic information system ARC/INFO, Version 6.1. The information from participating countries was received in the form of geographically located data for about 400 000 sampling sites selected in 31 European countries,

TABLE 4.1. AREAS IN EUROPE CONTAMINATED BY CHERNOBYL FALLOUT IN 1986 [4.1, 4.4]

	Area with ^{137}Cs deposition density range (km^2)			
	37–185 kBq/m^2	185–555 kBq/m^2	555–1480 kBq/m^2	>1480 kBq/m^2
Russian Federation	49 800	5 700	2100	300
Belarus	29 900	10 200	4200	2200
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	—	—	—

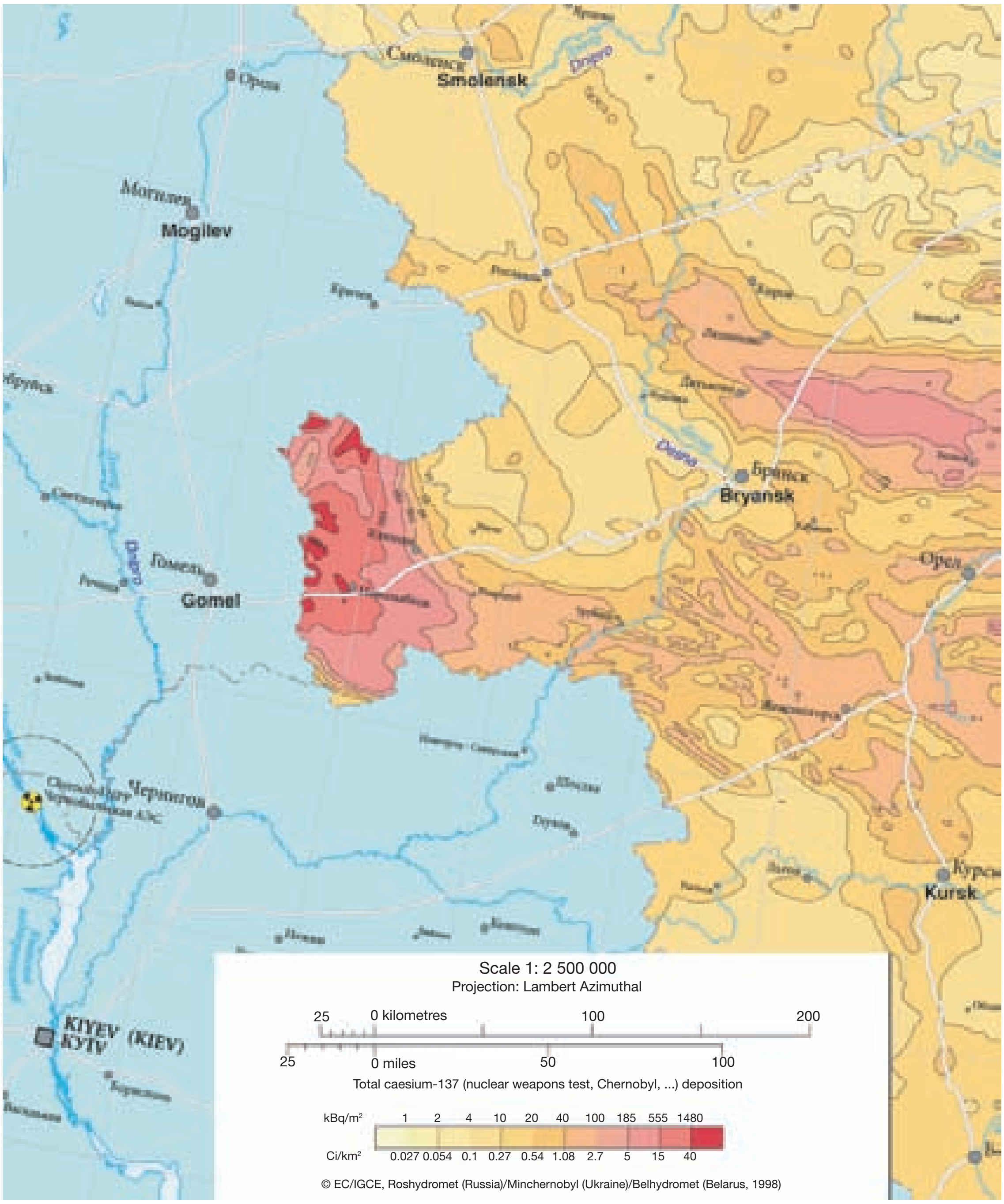

FIG. 4.1. Distribution of deposited ^{137}Cs in the Russian part of the Dnieper River basin (May 1986) [4.4].

including 19 058, 176 971 and 11 569 sampling points in Belarus, the Russian Federation and Ukraine, respectively.

Figures 4.1–4.3 show ^{137}Cs deposition in the Russian Federation, Belarus and Ukraine areas of the Dnieper River basin based on these sources[1]. Figure 4.4 is a closer view showing the areas of greatest ^{137}Cs contamination. Radionuclide fallout was concentrated in the upper Dnieper watershed in Russian and Belarusian territory and in the whole Pripyat watershed. Of the ^{137}Cs deposited in the

[1] See Fig. 3.1 for the boundaries of the Dnieper River basin.

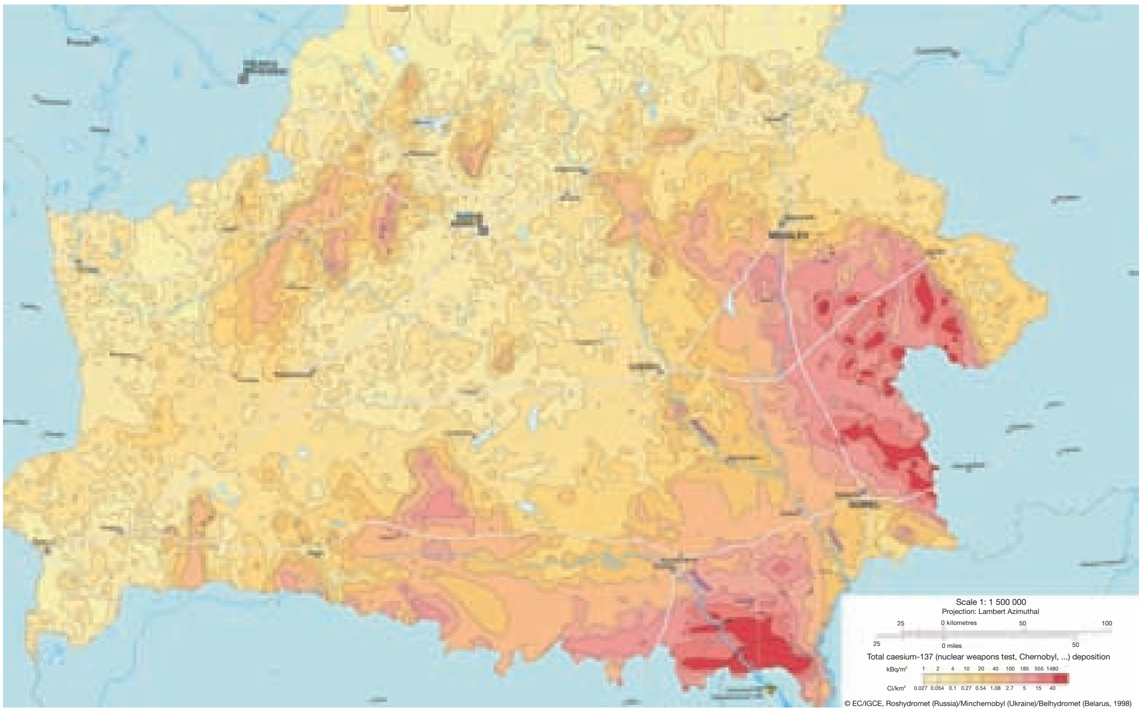

FIG. 4.2. Distribution of deposited ^{137}Cs in the Belarusian part of the Dnieper River basin (May 1986) [4.4].

FIG. 4.3. Distribution of deposited ^{137}Cs in the Ukrainian part of the Dnieper River basin (May 1986) [4.4].

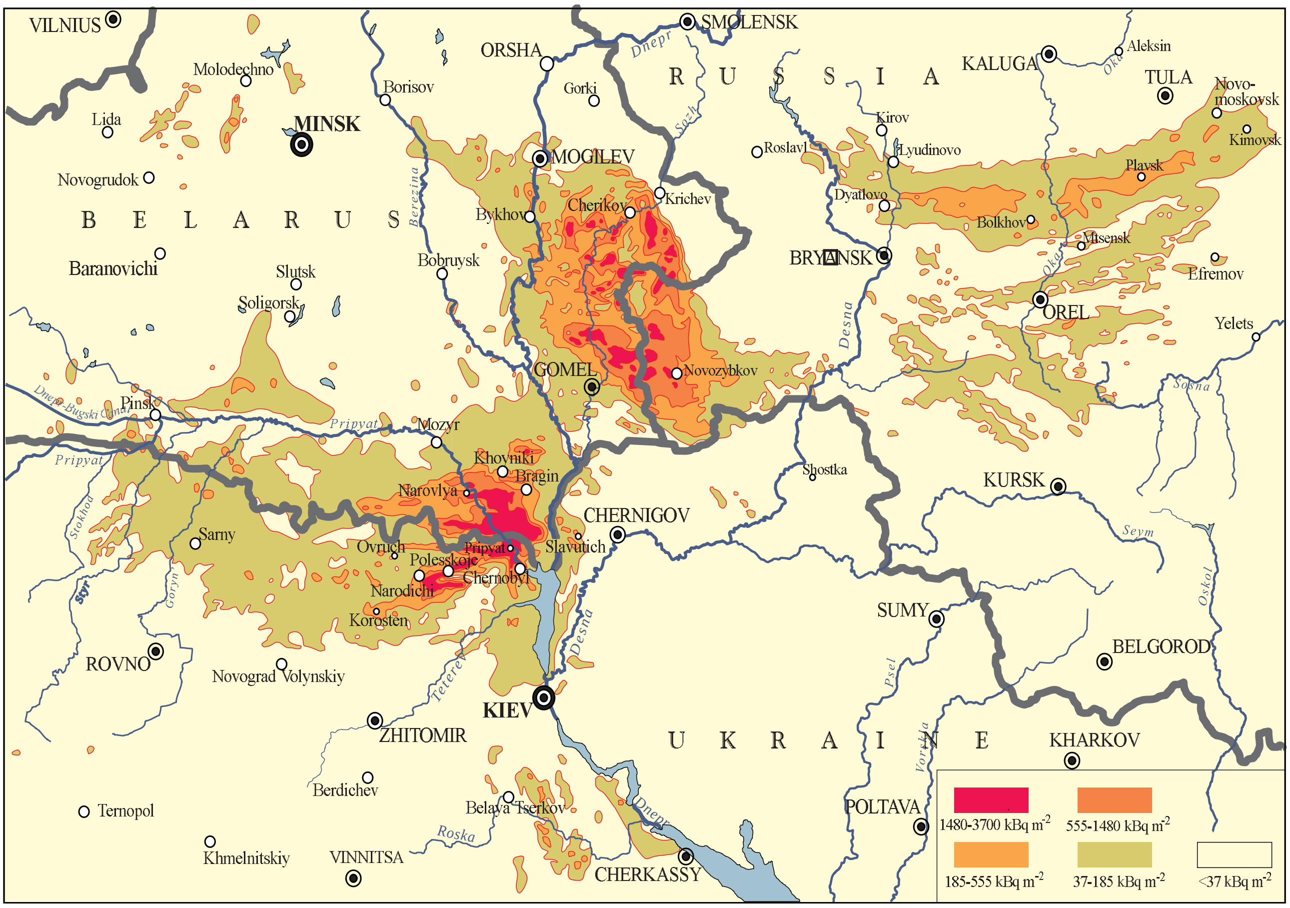

FIG. 4.4. Distribution of deposited ^{137}Cs in the most contaminated areas of the Dnieper River basin (December 1989)[4.1].

Dnieper River basin, approximately 30% was in the CEZ (see Fig. 4.5), 30% in the far zone of the Belarusian and Ukrainian sections of the Pripyat River basin and about 40% in the basins of the Sozh and Iput Rivers, in the so called Gomel and Bryansk–Tula hot spots. Table 4.2 shows data on contamination levels in the administrative regions of Belarus, the Russian Federation and Ukraine within the Dnieper River basin.

More detailed information on these three countries is contained in the atlas of the radioactive contamination of the European part of the Russian Federation, Belarus and Ukraine [4.5]. The maps were generated from the databases and electronic maps of the hydrometeorological service organizations of the three countries.

There are also maps and databases of the radionuclide deposition density in specific regions contaminated following the Chernobyl accident. Less data are available for radionuclides other than ^{137}Cs because they are not as easily measured and because they were deposited closer to their source, due to their lower volatility under the accident conditions.

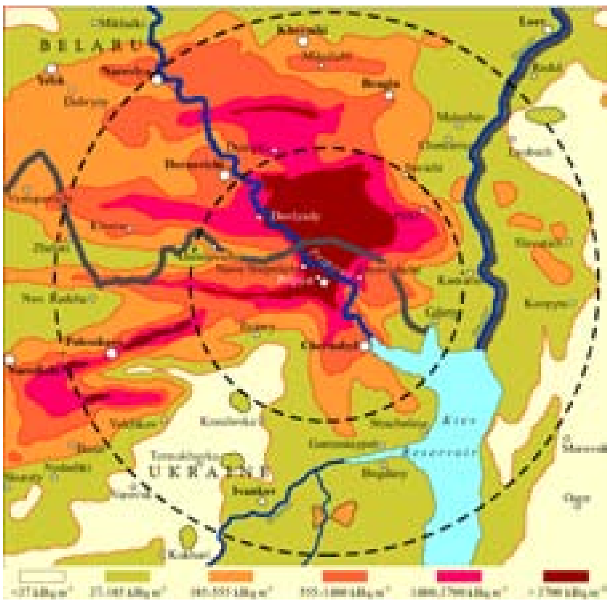

FIG. 4.5. Distribution of ^{137}Cs within the CEZ, 1986 [4.1].

TABLE 4.2. AREAS (THOUSANDS OF km^2) WITH ELEVATED CAESIUM-137 DEPOSITION IN THE REGIONS WITHIN THE DNIEPER RIVER BASIN (AS OF 1993–1995)

	Caesium-137 soil deposition (MBq/m^2)				
	0.04–0.2	0.2–0.6	0.6–1.5	>1.5	Total >0.04
		Belarus			
Gomel	16.9	6.7	2.8	1.6	28.0
Minsk	2.0	0.05	—	—	2.1
Mogilev	5.5	2.9	1.5	0.5	10.4
Subtotal	24.4	9.7	4.2	2.1	40.4
		Russian Federation			
Bryansk	6.7	2.7	1.9	0.3	11.6
Kaluga	3.4	1.4	—	—	4.8
Kursk	1.4	—	—	—	1.4
Smolensk	0.08	—	—	—	0.08
Subtotal	11.6	4.1	1.9	0.3	17.9
		Ukraine			
Cherkassy	3.2	0.07	—	—	3.3
Chernihiv	2.2	0.14	—	—	2.3
Dnipropetrovsk	0.04	—	–	—	0.04
Kiev	7.7	1.0	0.6	0.4	9.7
Nikolaev	0.02	—	—	—	0.02
Rovno	0.2	—	—	—	0.2
Zhytomyr	9.2	1.8	0.3	0.15	11.5
Subtotal		3.0	0.9	0.6	27.1
Total	58.6	16.8	7.0	3.0	85.4

Figure 4.6 shows the distribution of deposited ^{90}Sr; of the ^{90}Sr deposited in the Dnieper River basin, about 70% was deposited on the catchments and floodplain areas of the CEZ within Belarus and Ukraine, and the remainder was deposited in the far catchment areas of the basin. The Russian part of the Dnieper River basin received less than 10% of the ^{90}Sr inventory of the Dnieper River basin as a whole. This explains the importance of the CEZ as a source of ^{90}Sr contamination. Plutonium, which was associated with fuel particles that became airborne, was even more localized (see Fig. 4.7). The only areas with plutonium levels exceeding 4 kBq/m^2 are located within the CEZ.

A significant portion of the point type data on soil contamination density in the Dnieper River basin obtained by organizations within Belarus, the Russian Federation and Ukraine from 1986 to the present day was entered into the databases of subprojects of Project 2, Radioecology, of the French–German Chernobyl Initiative [4.6]. The database contains several thousand determinations of ^{137}Cs and ^{90}Sr densities on agricultural land; data on contamination density, speciation and vertical distribution of ^{137}Cs and ^{90}Sr in soils on the catchments of the rivers flowing in the Dnieper River basin; and data on ^{137}Cs and ^{90}Sr soil contamination density in population centres. As part of these projects a series of electronic maps was generated for the six most contaminated regions of Belarus, the Russian Federation and Ukraine (Gomel, Mogilev, Bryansk, Kaluga, Kiev and Zhytomyr regions), including maps of ^{137}Cs contamination density.

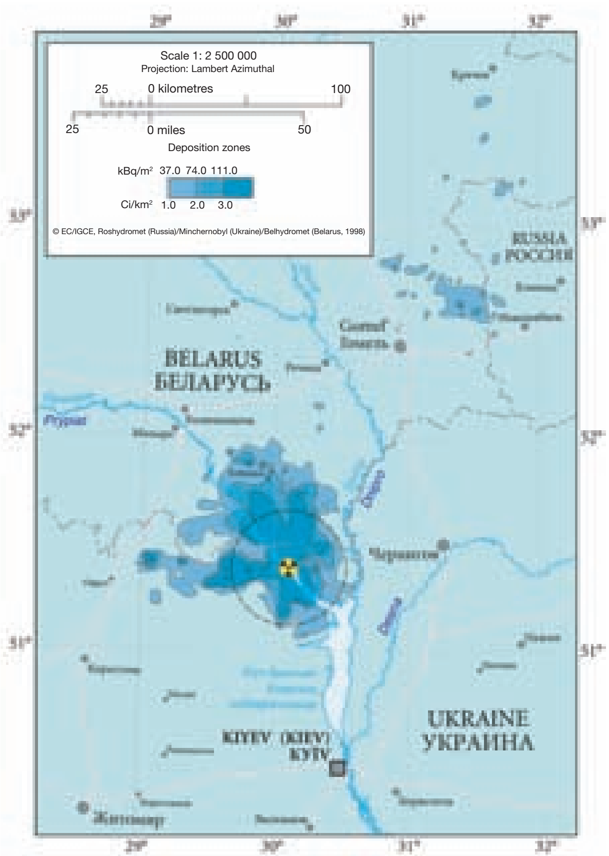

FIG. 4.6. Distribution of deposited ^{90}Sr (December 1989) [4.4].

FIG. 4.7. Distribution of deposited ^{239,240}Pu (December 1989) [4.4].

4.3. MONITORING OF RADIOACTIVITY IN THE ENVIRONMENT

Radioactivity deposited in the Dnieper River basin is subject to dispersal in the environment by airborne and water-borne processes. The monitoring of radioactivity in the environment is important in understanding these processes and in estimating radiation exposure to individuals and the population. Following the Chernobyl accident, an extensive monitoring network was established in the three countries, focusing on water-borne pathways.

4.3.1. Types of environmental monitoring

The hydrometeorological services of Belarus, the Russian Federation and Ukraine carry out monitoring for radioactivity in air, atmospheric precipitation and surface waters. Determination of environmental contamination is based on similar methods and equipment. Gamma radiation is also measured on a regular basis at meteorological stations. Soil sampling for further radionuclide analysis is carried out during special surveys.

The methods recommended for implementation and used by the monitoring networks of the Russian Federation, Belarus and Ukraine and are described in Refs [4.7–4.12]. The recommended sampling methods provide for:

(a) Selection of an appropriate strategy to locate representative monitoring sites, sampling sites and methods, and to ensure the required accuracy of laboratory measurements;
(b) Correct selection and location of measuring sections in conformity with the programme of hydrological monitoring and allowing for specific geometrical and hydrological characteristics of water bodies (river, lakes, reservoirs);
(c) Fulfilment of the requirements for proper averaging of measurements in time and space for a given water body, taking into account specific monitoring goals;

(d) Proper filtration of natural waters, using systems for concentration of natural waters where appropriate;
(e) Compliance with the requirements of analytical procedures involving radiospectrometric and radiochemical measurements;
(f) Selection of appropriate sampling methods to study radionuclides in bottom sediments.

4.3.1.1. Airborne monitoring

Monitoring of radioactive contamination in near surface air is based on round the clock sampling of aerosol particles using FPP-15-1.5 air filters. Collected samples are subject to analysis for:

(a) Total beta activity, one and four days after sampling, using a thin film scintillation detector or a Geiger counter;
(b) Radionuclide composition of samples using gamma spectrometry;
(c) Measurement of radioactivity of plutonium isotopes and ^{90}Sr by radiochemical methods.

Atmospheric fallout is collected on gauze collectors after a sampling time of one day. The methodologies for sample preparation and measurement are similar to those used for aerosol particles.

4.3.1.2. Surface waters

In surface waters, ^{90}Sr, ^{137}Cs and tritium are routinely monitored. Sampling and preconcentration for ^{90}Sr analysis are undertaken at hydrological stations and radiometric network stations, whereas radiochemical analysis is done in regional laboratories.

One of the key tasks in the design phase of water monitoring, given water bodies with different contamination levels, is to estimate correctly the volumes of samples to be collected for radiometric measurements.

The appropriate sample volume depends on the concentration of a specific radionuclide; for example, for ^{137}Cs determination in the Kiev reservoir the sample volume should be not less than 20 L. For water bodies at a greater distance from the contamination source, where contamination levels are low (Dnieper reservoirs, sea areas, etc.), the water volume should be at least 100 L for confident determination of a given radionuclide in water. Precise determination of ^{137}Cs in water requires sampling an even greater volume (up to 500 L). With this in mind, in 1986 the Midiya system developed by SPA Typhoon was adopted for filtration and concentration of radionuclides on to sorbents (Fig. 4.8).

Spectrometric measurements are carried out separately on the sorbent (to determine dissolved nuclides) and on the filters (to determine suspended matter). A fairly low detection limit for samplers of the Midiya type makes it possible to determine, with satisfactory accuracy, the concentration of radionuclides in rivers over the whole territory contaminated after the Chernobyl accident. Reference [4.12] provides recommendations on how to use this system under field conditions.

4.3.1.3. Bottom sediments

The experience gained in studies of bottom sediment contamination after the Chernobyl accident has shown that it is critical to select the right type of sampler for bottom sediments, depending on the required task. Most discrepancies in measurements by different specialists with respect to the amount and pattern of the distribution of radionuclides on sediments are due to failure to select appropriate sampling equipment, differences in methods of averaging individual data over the whole water area and/or differences in interpretation of results.

The samplers used in the first year after the accident had design shortcomings that precluded sampling of undisturbed cores, leading to loss of material during lifting of the cores to the surface. Better sampling systems began to be used from

FIG. 4.8. Midiya sampling system. 1: pipe; 2: filter block; 3: chamber for sorbent with flow meter; 4: portable electric power station.

1990. The DTSh-3 sampler (manufactured by Ecotechnics in the Russian Federation) enables sampling of any undisturbed core 30 cm long, and a more sophisticated pneumatic sampling system manufactured by McKereth in the UK permits sampling of silt cores up to 1 m long. Using these samplers it is possible to determine sediment contamination density and specific activity as a function of depth.

4.3.2. Monitoring sites

The monitoring of radioactive aerosols in the Dnieper River basin is carried out daily at six points in Belarus (Minsk, Gomel, Mogilev, Pinsk, Mozyr and Mstislavl), eight points in Ukraine (Kiev, Baryshevka, Odessa, Rakhov, Sevastopol, Chernobyl, Shepetovka and Shchors) and 40 points in the Russian Federation, among them Kursk, Kurchatov and Bryansk. Deposited radioactivity is monitored at a larger number of points, numbering from 30 in Belarus to more than 300 in the Russian Federation. Recommendations on how to use different samplers for various types of bottom sediment (mud, sand, etc.) at different depths are described in Ref. [4.12].

4.3.2.1. Belarus

The monitoring of surface waters for radioactivity is carried out mainly in five rivers in Belarus: Dnieper (at Rechitsa), Sozh (at Gomel), Pripyat (at Mozyr), Iput (at Dobrush) and Besed (at Svetilovichi). Until 1990, the hydrometeorological service of Belarus conducted monitoring in the rivers Chechera (at Derbichi) and Pokot (at Krasny Dubok). Sampling is organized on a monthly basis and, simultaneously, river water discharge is measured. Samples of surface water are analysed for ^{137}Cs (monthly), ^{90}Sr (quarterly) and total beta activity (monthly).

Belarus Hydromet and a number of other agencies carry out monitoring. Belgiprovodkhoz conducts radiation monitoring of surface waters in the small rivers of Belarus (20 points) and water reservoirs (three points) with a frequency of one to two times per year. Water samples are collected, water discharges are measured and ^{137}Cs is determined in samples.

The Institute of Radiobiology (IRB) is involved in radiation monitoring of the surface waters of small rivers, including those flowing through the CEZ. Water sampling is organized one to two times per year. Belarusgeologia is in charge of radiation monitoring of groundwater. Currently, attention is focused on monitoring of the radiation status of underground waters used for the centralized water supply of the major population centres in the contaminated areas (Gomel, Mozyr, Kalinkovichi, Narovlya, Khoiniki, Rechitsa, Slavgorod, Zhlobin and Dobrush). The Republican Center of Hygiene and Sanitary Service, Ministry of Health of Belarus, is engaged in monitoring of the radioactivity in drinking water in the populated areas of the Chernobyl contamination zone. Minzhilcomunkhoz carries out monitoring of ^{137}Cs in wastewaters and aeration zones of the major populated areas of the Chernobyl contaminated zone. Table 4.3 summarizes information on the frequency of sampling at existing and closed observation stations.

The Republican Center of Radiation and Environment Monitoring (RCREM) monitors the radioactive contamination of soils. The monitoring network includes 181 sites at which measurements of gamma dose rate are performed with varying frequency, depending on radioactive contamination levels. Soil samples are collected for subsequent analysis of ^{137}Cs and ^{90}Sr. Studies of the vertical migration of radionuclides are carried out at 18 locations having different types of soils and different radioecological and physicogeographical conditions. Migration studies are conducted with respect to ^{137}Cs, ^{90}Sr, plutonium isotopes and americium.

4.3.2.2. Russian Federation

Within the Russian Federation there are no stations on the Dnieper River that continuously monitor surface water for radioactivity. However, the contamination levels of rivers and lakes are monitored through special purpose surveys within national and international programmes.

In the Russian Federation during 1987–1988 the concentrations of ^{137}Cs and ^{90}Sr were measured several times each year, mainly during periods of flooding on the rivers Iput (two measuring sections), Snov (one measuring section) and Besed (one measuring section). During 1991–1993 specialized studies were performed on the Iput catchment area. The content of ^{137}Cs and ^{90}Sr in river water was measured several times a year at eight sections.

TABLE 4.3. AVAILABILITY OF DATA ON RADIOACTIVE CONTAMINATION OF RIVERS IN THE BELARUSIAN PART OF THE DNIEPER RIVER BASIN

	Measuring section	Monitoring organization	Observation period	Frequency per year	
				Caesium-137	Strontium-90
Dnieper	Rechitsa	RCREM	1987–2002	12	4
Sozh	Gomel	RCREM	1987–2002	12	4
Iput	Dobrush	RCREM	1987–2002	12	4
Besed	Svetilovichi	RCREM	1987–2002	12	4
Pripyat	Mozyr	RCREM	1987–2002	12	4
Braginka	Btragin	Belgiprovodkhoz	1991–1997	2	—
	Pirki	IRB	1991–2002	2	2
	Gden	IRB	1991–2002	2	2
Slovechno	Kuzmichi	IRB	1991–2002	2	2
	Gazhin	IRB	1991–2002	2	2
	Belyi Bereg	IRB	1991–2002	2	2
Nesvich	Kulazhin	IRB	1991–2002	2	2
	Posudovo	IRB	1991–2002	2	2
Senna	Chudyany	IRB	1991–2002	2	2
	Pilnya	Belgiprovodkhoz	1991–1997	2	—
Lipa	Lipa	IRB, National Academy of Science of Belarus	1991–2001	2	2
Kolpita	Vydrinka	Belgiprovodkhoz	1991–1997	2	—

The latest large scale study of radioactive contamination of the rivers in the Bryansk region was performed in 1998–1999 as part of a UNDP project [4.13]. The activity of ^{137}Cs and, in some cases, ^{90}Sr was determined in the rivers Iput (seven measuring sections), Snov (three measuring sections) and Besed (two measuring sections) and in nine other rivers and canals (one to two measuring sections).

Following the Chernobyl accident, the monitoring of the radioactive contamination levels in surface water and wastewater of some selected enterprises became the responsibility of the water inspection authorities. In the Bryansk region there were 52 measuring sections, of which 14 were operating continuously up to the early 1990s. Data were transmitted to the Civil Defence Headquarters of the region and to Minvodkhoz of the USSR. During floods, samples were collected on a quarterly basis. Starting from the early 1990s, the number of hydrological sections of continuous monitoring was cut back and the frequency was reduced to annual testing.

Radioecological surveys of the state of groundwater contamination after the Chernobyl accident have been conducted in the Russian Federation since 1988. Joint work on this project is now under way involving Bryanskgeologia, the All-Russian Research Institute for Hydrogeology and Engineering Geology (VSEGINGEO) and the All-Russian Research Institute for Mineral Resources (VIMS). The observational network includes 35 boreholes and 26 wells.

4.3.2.3. *Ukraine*

The Hydrometeorological Service of Ukraine conducts radioactivity monitoring of surface waters in 13 measuring sections, of which 11 are in the Dnieper River basin. The concentrations of ^{137}Cs and ^{90}Sr are monitored at different time intervals, depending on the season, in two measuring sections on the Pripyat River (at Belaya Soroka and Chernobyl), one measuring section on the Uzh River (at Cherevach), one section on the Desna River (at Litki) and ten measuring sections on the

FIG. 4.9. Surface water monitoring stations under observation by CREM in the near zone of the Chernobyl nuclear power plant.

Dnieper River located over the stretch from Nedanchichi to the Dnieper–Bug estuary.

Radiation monitoring of surface and ground waters in the CEZ is undertaken by the Center of Radiation and Environmental Monitoring (CREM), part of the Chernobyl Radioecological Center. Monitoring of surface and ground waters in the CEZ includes the following:

(a) The Pripyat River and its tributaries;
(b) The north-east part of the Kiev reservoir;
(c) The Chernobyl nuclear power plant cooling pond;
(d) The off-take point at unit 4 of the Chernobyl nuclear power plant;
(e) Lakes and backwaters on the right bank floodplain that are cut off from the primary channel of the Pripyat River;
(f) Water bodies of the left bank floodplain and groundwater within the CEZ.

The locations of surface monitoring points are shown in Fig. 4.9. Monitoring covers 22 watercourses and ten water bodies, the total number of monitoring points being 40. The monitoring programme provides for measurement of hydrological characteristics, the dynamics of radioactive contamination characteristics and hydraulic structures (e.g. water levels and discharge rates).

Water sampling is carried out in accordance with the methodologies recommended by the Ministry of Emergencies of Ukraine and the Department of the Hydrometeorological Service and Monitoring. Hydrometric activities are carried out using the volume necessary for reliable determination of water runoff flow and radionuclide outflow. The frequency of measurements is established by relevant protocols and varies from weekly to quarterly. During floods and emergencies the frequency of sampling is increased.

All water samples are analysed for ^{90}Sr and ^{137}Cs. In addition, the specific activities of ^{241}Am, ^{238}Pu and ^{239,240}Pu are determined in water bodies with higher concentrations of ^{90}Sr and ^{137}Cs and those of key importance.

Monitoring of groundwater near the Chernobyl nuclear power plant is performed in the Quaternary, Eocene and Senoman–Cretaceous horizons. The Quaternary aquifer is monitored as a priority, as it lies closer to the surface and is more subject to radioactive contamination. Groundwater from the Eocene deposits (used for the centralized water supply of the Chernobyl nuclear power plant) is monitored at the point of water intake of the Chernobyl nuclear power plant (Pripyat), and groundwater of the Senoman–Cretaceous deposits (used for centralized water supply of the town of Chernobyl) is monitored at the water intake at Chernobyl.

The monitoring of the radiation status of groundwater in the Quaternary deposits is arranged within specific sites (radioactive waste disposal sites, sites of temporary containment of radioactive waste, cooling pond) and on a regional basis.

At the beginning of 2002 the groundwater monitoring system included 158 observation wells. The frequency of observations in dug wells is governed by the extent of radionuclide migration, allowing for the specificity of their accumulation in geological rocks. In areas with significant groundwater contamination, observations are conducted on a monthly basis, whereas in other areas they take place on a quarterly or six monthly basis. At present, for seven wells located within the Red Forest in the area of the Yanov dam and Staraya Stroibaza, measurements are made on a monthly basis, for 25 wells of the regional network on a six monthly basis and for the remaining 126 wells on a quarterly basis. Measurements of the groundwater level are made using a belt type level gauge, the accuracy of measurements being about 1 cm.

Monitoring of radioactive contamination of rivers and reservoirs of the middle and lower Dnieper River is the responsibility of the Hydrometeorological Service of Ukraine and the Ukrainian Hydrometeorological Institute (UHMI). The protocol of observations is presented in Table 4.4.

4.3.3. Databases on surface waters

All organizations operating as part of hydrometeorological services (RCREM, SPA Typhoon, UHMI) maintain their own databases. The principal shortcoming of these databases is that they mainly contain results of radionuclide determinations in surface waters obtained by the national institutions. The exceptions are results derived prior to 1991, which are partly available in the databases of neighbouring countries. This drawback has been overcome in the RUNOFF database, which was developed within subproject SP-3c of Project 2, Radioecology, of the French–German Initiative on Chernobyl [4.6]. This database contains data for all three countries from 1986 to the present. Using the database, the following tasks can be addressed:

(a) Reconstruction of radiation doses received by the population of contaminated areas through the aquatic pathway;
(b) Testing and validation of models of radionuclide wash-off to rivers from contaminated watersheds, of models of radionuclide transport to river systems, of models of vertical migration and transformation of radionuclide species in soils, and of hydrological models and methods for estimating parameters of the above models;
(c) Studying of physicochemical mechanisms to describe the behaviour of radionuclides in rivers;
(d) Calibration of model parameters using experimental data;
(e) Calculation of transborder movement of radionuclides by rivers.

The RUNOFF database includes the following information arrays:

(i) Radionuclide concentrations in river water. Data on the concentration of ^{137}Cs and ^{90}Sr in solution and on suspended matter in 20 rivers flowing through the territory contaminated after the Chernobyl accident are available. These data were obtained in the period from 1986 to 1999 from national monitoring programmes and special experiments by organizations of Belarus, the Russian Federation and Ukraine.
(ii) Experiments on runoff plots. Results are available from nearly 100 experiments to study radionuclide wash-off by rainfall and surface runoff from melting snow. These experiments were conducted in the contaminated territories in the period from 1986 to 1998 on runoff plots of 1–1000 m^2. The data

TABLE 4.4. SCHEDULE OF CONTROL OF SURFACE WATER RADIOACTIVE CONTAMINATION BY THE UKRAINIAN HYDROMETEOROLOGICAL SERVICE

Observation point	Sampling periodicity	Organization responsible for sampling
Dnieper: Nedanchichi	Twice per month (more than twice per month during spring flooding)	Chernihiv central hydrometeorological station
Desna: Chernihiv	Twice per month (more than twice per month during spring flooding)	Chernihiv hydrometeorological observatory
Southern Bug: Gurievka	Monthly (more than once per month during spring flooding)	Nikolaev central hydrometeorological station
Kiev reservoir: Vyshgorod (power station)	April–October: three times per month; November–March: twice per month	Hydrometeorological station, Kiev
Kiev reservoir: Kiev (hydropark)	Monthly	Hydrometeorological station, Kiev
Kiev reservoir: Kanev (power station)	April–October: twice per month; November–March: once per month	Hydrometeorological station, Kanev
Kremenchug reservoir: Svetlovodsk (power station)	April–October: twice per month, ^{90}Sr; November–March: once per month, ^{90}Sr	Svetlovodsk hydrometeorological observatory
Zaporozhe reservoir: Zaporozhe (power station)	Monthly, ^{90}Sr	Zaporozhe hydrometeorological station
Kakhovka reservoir: Novaya Kakhovka (power station)	April–October: twice per month; November–March: once per month	Novaya Kakhovka hydrometeorological station
Dnieper (southern Bug estuary): Ochakov	Four times per year	Nikolaev hydrometeorological observatory
Cascade of Dnieper reservoirs	Twice per year	UHMI, central geophysical observatory

include the properties and content of ^{137}Cs and ^{90}Sr in soil, rain and runoff hydrographs, the concentration of ^{137}Cs and ^{90}Sr in solution and on suspended matter in the runoff, the chemical composition of runoff and the radionuclide species in soil for selected runoff plots.

(iii) Hydrological and meteorological data. Results are available from hydrological and meteorological observations conducted in the contaminated areas by the hydrometeorological services of Belarus, the Russian Federation and Ukraine. Both mean characteristics (over several years) and daily measurements at meteorological and hydrological stations in the Chernobyl contaminated territories are entered into the database.

(iv) Radionuclide characteristics. Data are also available on the content, species and vertical distribution of radionuclides in soils and on soil properties of river watersheds in contaminated territories.

The RUNOFF database contains about 10 000 filled lines on ^{137}Cs and ^{90}Sr activity concentration in 20 rivers. Table 4.5 lists these rivers, the observation periods and a number of measuring sections for which data are available. For most of the measuring sections, data on the radioactive contamination of river water up to the present time are available from the hydrometeorological service of each country.

The RUNOFF database contains almost all available data on radioactive contamination of river water in the basin of the upper Dnieper River, including data on the rivers involved in the transboundary transport of radionuclides (except the Desna and Seim Rivers). Data on the Desna River and the lower Dnieper River are available in the UHMI database, Cascade of the Dnieper Reservoirs.

Since contamination of lakes and reservoirs (excluding the nuclear power plant cooling ponds) is not monitored on a continuous basis, such data are more limited as compared with the rivers. Results of determinations of the radioactive contamination of some Belarusian, Russian and Ukrainian lakes can be found in the database generated in the course of the INCO-Copernicus Project Aquascope and the database of subproject

TABLE 4.5. RIVERS, OBSERVATION PERIODS AND NUMBER OF CROSS-SECTIONS FOR WHICH DATA ARE AVAILABLE IN THE RUNOFF DATABASE

	Cross-sections[a]	Period of observations
Dnieper	3	1986–1999
Sozh	1	1987–1998
Besed	1	1987–2000
Iput	9	1986–2000
Pripyat	4	1986–1999
Glinitza	1	1987–1999
Sakhan	2	1986–1999
Slovetchno	2	1992–1998
Uzh	3	1986–1999
Ilya	1	1986–1999
Vialcha	1	1988
Ilcha	1	1988
Rudava	1	1988
Braginka	4	1986–1999
Nesvich	2	1988–1998
Right tributary of Braginka	1	1992–1999
Irpen	1	1987–1999
Teterev	1	1987–1992
Lipa	2	1992–1998
Senna	2	1992–1998

[a] Number of cross-sections on the river for which data on radionuclide concentrations are available.

SP3d, Project 2, Radioecology, of the French–German Initiative on Chernobyl [4.14].

The database of subproject SP3d also contains data on fish contamination (predatory and prey species), as well as on a wide range of macrophite algae, phytoplankton and periphyton, and on contamination of bottom sediments and benthic organisms. In addition are recommended parameters for the validation of mathematical models and the prediction of migration of radionuclides through the food chain of aquatic ecosystems affected by the Chernobyl accident [4.14].

4.3.4. Data quality

One of the most important functions of the organizations (such as the UHMI, the RCREM and SPA Typhoon) responsible for the gathering and scientific analysis of data is evaluation of the fidelity of data. Scientific methods must also be developed to identify and reject untrustworthy data. Laboratories involved in routine monitoring need to implement external controls to ensure that data continue to be of a high quality. For this purpose, the following external control tools are used in the three countries:

(a) Intercalibrations (national and international);
(b) Intercomparison of data obtained by the UHMI, the RCREM and SPA Typhoon with data of other monitoring laboratories (parallel sampling);
(c) Control measurements in the laboratories of the UHMI, the RCREM and SPA Typhoon using samples measured earlier in the laboratories of different agencies;
(d) Scientific evaluation of monitoring data.

The quality of data on the radionuclide content in rivers depends on the quality of sampling

and on analysis. Analysis of errors that may arise in the course of such procedures and how they influence the uncertainty in radionuclide data are discussed below.

Sampling is the most crucial stage of measurement. Correct sampling procedures and allowance for hydrological factors are critical if representative samples are to be obtained. If there is adequate mixing across a cross-section, it makes no difference which point of the cross-section is used for sampling. Therefore, samples collected from the water surface near the bank are fairly representative of the whole cross-section for determination of ^{137}Cs and ^{90}Sr concentrations in the dissolved phase.

It is more difficult to collect a suspended sediment sample that is representative with respect to the radionuclide content. The distribution of suspended sediment concentrations across a cross-section is extremely non-uniform and is determined by the complexities of the turbulent river flow. Generally, concentrations of suspended sediments increase from the river bank towards the river middle and from the water's surface to the bottom [4.15, 4.16]. Water samples collected in the surface layer near the bank contain the minimum amount of suspended sediments and are not representative of the whole cross-section. Therefore, in rivers with a fairly high level of radioactive contamination (given 50 L of water or less is enough for gamma spectrometric measurements), sampling for determination of ^{137}Cs concentrations on suspended sediments should be based on the methodology used for measuring discharges of water and suspended sediments. This can involve either the detailed or the basic procedure of sampling at a minimum of two points for every velocity, using a bottle sampler or vacuum sampler; in other words, the same standard means as used in the measurement of sediment discharges in rivers. It is generally taken that the accuracy of these methods of measuring sediment discharges is not less than 20%.

To illustrate the importance of representative sampling, a data sample was taken from the RUNOFF database of ^{137}Cs determinations in river bank samples with the same date and of samples averaged over the whole effective cross-section. It can be seen from Table 4.6 that the discrepancy between the activities on the bank and the averaged samples occurs during the flood period and occasionally can be as high as an order of magnitude. It is worth noting that the volumetric concentration of ^{137}Cs in the bank sample was never higher than in the sample averaged over the flow cross-section and collected on the same day.

In many cases, the laboratories involved in the monitoring of watercourses carry out water sampling by submerging a container in water. Even though a container is filled gradually, most of the large fractions of the suspended matter do not enter the container and, consequently, both the quantity and the radionuclide activity on suspended sediments are underestimated.

Table 4.7 compares the turbidity and volumetric activity of suspended ^{137}Cs in samples collected with a bottle sampler averaged over the river flow cross-section and samples collected directly in the container at several points across the channel. Using the second sampling technique gives rise to two errors that result in underestimation of turbidity and volumetric activity: (a) water samples collected from the flow surface contain less suspended material than those averaged over the whole effective cross-section; (b) during water sampling directly in a container most of the sand fraction does not enter the sample.

It is well known that the details of the sampling method are important. With this in mind, the RUNOFF database and the Cascade of the Dnieper Reservoirs database include a description of the sampling method along with the measured concentrations. This facilitates assessment of the uncertainty in the data.

The procedures for primary treatment of the samples and their preparation for radionuclide analysis are described in Refs [4.8, 4.9, 4.17, 4.18]. All the laboratories involved in observations on the watercourses in the Chernobyl zone base their procedures on these guidelines. Application of these methodologies, given appropriate sampling, qualified personnel and sensitive instrumentation, makes it possible to determine the concentration with an accuracy of not less than 20% for ^{90}Sr and not less than 10% for ^{137}Cs. In reality, however, this is not always the case, mostly due to lack of appropriate equipment.

The monitoring services rely on sanitary norms prescribed by law, such as the maximum permissible concentrations, the temporary permissible levels (TPLs) and the control levels. Many department laboratories perform monitoring to check whether the radionuclide content in water used for municipal water supply (drinking and industrial water supply, irrigation, recreation, etc.) agrees with the applicable sanitary standards. It is worth noting that since 1987 there have been only

TABLE 4.6. COMPARISON OF VOLUMETRIC ACTIVITY (Bq/L) OF CAESIUM-137 ON SUSPENDED SEDIMENTS IN BANK SAMPLES WITH THE SAMPLES AVERAGED OVER THE FLOW CROSS-SECTION

Date of sampling	Sample averaged over cross-section	Bank sample	Ratio average/bank
26 March 1988	0.151	0.112	1.3
26 March 1988	0.570	0.256	2.2
29 March 1988	0.529	0.241	2.2
26 March 1988	0.307	0.218	1.4
1 April 1988	0.215	0.174	1.2
6 April 1988	0.418	0.168	2.5
8 April 1988	0.272	0.159	1.7
9 April 1988	0.470	0.210	2.2
11 April 1988	0.781	0.258	3.0
12 April 1988	0.574	0.210	2.7
16 April 1988	0.403	0.038	10.7
19 April 1988	0.407	0.189	2.2
21 April 1988	0.297	0.245	1.2
24 April 1988	0.496	0.167	3.0
28 April 1988	0.218	0.152	1.4
18 May 1988	0.268	0.127	2.1
14 June 1988	0.426	0.122	3.5

individual cases of levels above the sanitary standards in the Pripyat and Dnieper Rivers. From 1990 onwards, the concentrations of these radionuclides were one or two orders of magnitude below the TPL, and beyond the CEZ two to three orders of magnitude below. Such a big difference in the control and actual concentrations of radionuclides has led to less attention being given to measurement accuracy in many laboratories.

The fact that the monitoring system is still far from optimal can be illustrated by the results of monitoring ^{137}Cs in the Dnieper River at the measuring section at Vyshgorod, Ukraine, obtained by different laboratories in 1999 (Fig. 4.10). It is obvious that determination of the actual ^{137}Cs content with such a wide spread is quite problematic without knowing the specifics of sampling and measurement in each laboratory.

After department guidelines were prepared, the scientific and methodological control of data quality by the Hydrometeorological Service of Ukraine was put in place and its local units were

TABLE 4.7. COMPARISON OF THE TURBIDITY AND CONTENT OF SUSPENDED CAESIUM-137 IN SAMPLES COLLECTED BY DIFFERENT METHODS

Date of sampling	Turbidity (g/m^3)			Caesium-137 (Bq/m^3)		
	AOC[a]	AOS[b]	Ratio AOC/AOS	AOC[a]	AOS[b]	Ratio AOC/AOS
16 April 1999	104	10.8	9.5	96.0	16.0	6.0
24 April 1999	86.6	2.4	36	81.6	8.0	10
7 October 1999	30.2	6.45	5	73.0	21.0	3.5

[a] AOC: averaged over the river flow cross-section.
[b] AOS: sample collected at several points across the channel at the surface (averaged over the flow surface).

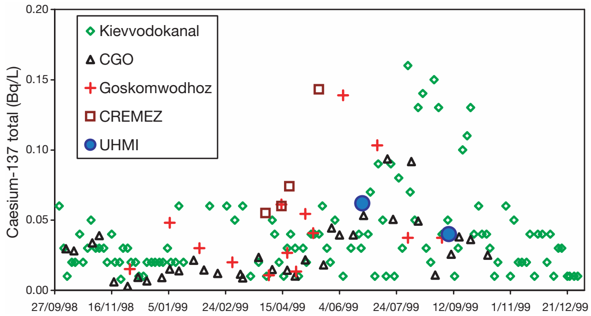

FIG. 4.10. Results of determinations of ^{137}Cs in water by different laboratories in the Dnieper–Vyshgorod measuring section [4.19].

equipped with systems for sampling the concentration of radionuclides contained in large water volumes, observational results became closer to the reference values considered to be the actual ^{137}Cs concentrations.

The most common causes of systematic errors in many agencies are the following:

(a) Insufficient qualification of personnel;
(b) Outdated technology for sampling and filtration and sample preparation unsuitable for measuring low levels of radioactivity;
(c) Samples are measured with low sensitivity gamma spectrometers or scintillators;
(d) Spectra are processed manually or inappropriate software is used;
(e) Requirements for the correction of results for radiation background in the laboratory and shielding instrumentation are not observed;
(f) Lack of consistency in the radiochemical preparation of samples and in determining the efficiency of strontium chemical yield (for ^{90}Sr analysis).

Owing to high variability in data on radionuclide content in river water, results are not very informative unless they have uncertainty estimates. Therefore, in the RUNOFF and Cascade of Dnieper Reservoirs databases, the bulk of the data on radionuclide concentrations in rivers are accompanied by expert judgements on uncertainty made by UHMI specialists, with allowance for errors in sampling and analysis. Most radionuclide concentrations in the dissolved form have uncertainties of not less than 30%. The uncertainty in volumetric activities of radionuclides associated with suspended particles is normally not less than 50%. The uncertainty of the total content of radionuclides in water is close to the uncertainty of the normally dominating ^{90}Sr dissolved form.

In summary, for the reasons indicated, data from different sources are often inconsistent, which makes it difficult to harmonize monitoring of radioactive contamination in surface waters within the Dnieper River basin.

4.3.5. Storage, publication and use of monitoring data

Storage, analysis and publication of monitoring data are carried out by the following organizations in each of the three countries:

(a) In Belarus: the RCREM.
(b) In the Russian Federation: the Institute of Experimental Meteorology of SPA Typhoon.
(c) In Ukraine: the UHMI.

These organizations also use the data to understand the physicochemical processes involved and to forecast changes with time.

The users of the radiation monitoring information are concerned ministries and agencies, regional authorities, institutes of national hydrometeorological services and academies of the three countries. Within inter-State agreements (Belarus, the Russian Federation and Ukraine), continuous exchange of data occurs. Data from Belarus and Ukraine are supplied on an annual basis to SPA Typhoon and published in the annual collection Radiation Situation in the Territory of the Russian Federation and Adjacent Countries. These collections are the main source for informing the public about the results of radiation monitoring in Belarus, the Russian Federation and Ukraine carried out by the hydrometeorological services of these countries.

4.4. CHARACTERISTICS OF RADIONUCLIDE RUNOFF

Table 4.8 shows the estimated inventories of ^{137}Cs and ^{90}Sr in the main rivers and tributaries of the Dnieper River catchment area. In total, about 19 PBq (500 kCi) of ^{137}Cs and 2.2 PBq (60 kCi) of ^{90}Sr were deposited within the Dnieper system within the limits of the main river basins.

TABLE 4.8. ESTIMATE OF INVENTORIES[a] (1986) OF CAESIUM-137 AND STRONTIUM-90 IN SOILS OF THE DNIEPER RIVER CATCHMENT AREA UPSTREAM OF KIEV [4.20]

	Catchment area (10^3 km^2)		Inventory (PBq)	
	Total	Activity >37 kBq/m^2	Caesium-137	Strontium-90
Upper Dnieper (upstream of Kiev reservoir)	105	29	10.2	0.22
Pripyat, mouth	115	27	6.7	1.5
Braginka and area between Dnieper and Pripyat Rivers	2	2	2.1	0.44
Desna	89	6	0.3	0.04

[a] Does not include the radionuclide inventory at the industrial site of the Chernobyl nuclear power plant.

4.4.1. Radionuclide dynamics in catchment areas

The extent to which the source term contributes to the contamination of water bodies depends not only on the initial inventory but also on factors affecting the dynamics and availability of each radionuclide. These factors include:

(a) The extent of radioactive decay;
(b) The reduction of radionuclide activity in the upper layer of the soil as a result of vertical migration;
(c) The transformation of the initial physical and chemical forms of radionuclides in the soils of the watersheds and floodplains of the rivers;
(d) Local and climatic factors affecting water runoff and erosion.

In the earliest phase after the accident — from hours to weeks — fallout of short lived radionuclides (especially ^{131}I) dominated the dose rate. In the period from weeks to a few years, ^{106}Ru, ^{144}Ce and ^{134}Cs were important. From a few years to a few hundred years, secondary transport processes become increasingly important and the dominant radionuclides are ^{137}Cs and ^{90}Sr. The dose rate is reduced by radioactive decay so that, as of September 2003, the activity of ^{137}Cs and ^{90}Sr is about 33% less than in 1986. Finally, for periods beyond a few hundred years, most of the ^{137}Cs and ^{90}Sr will have decayed and other radionuclides such as ^{241}Am and ^{239}Pu will become relatively more important, although the overall impact will be much lower.

Since radionuclides are transferred into the surface runoff mainly from the upper layer of the soil, the extent of radioactive contamination of waterways depends on the vertical distribution of radionuclides in the soil. Depending on the chemical properties of the radionuclide, soil type, landscape and geochemical factors, the activity will have migrated to a greater or lesser extent into the soil over the past 17 years. Thus the inventory of radionuclides available for migration by surface transport decreases with time.

The chemical and physical forces that bind radionuclides to the soil determine the extent of their transfer to water. The nature of the binding depends on both the characteristics of the radionuclide and the properties of the soil, and hence will vary with soil type. The traditional way of experimentally determining the type of binding is the method of sequential extraction [4.21]. In this method, the water soluble form is first extracted from the soil using distilled water. The exchangeable form is then extracted using a concentrated solution of an electrolyte, usually 1M CH_3COONH_4. The portion remaining in the solid phase after the two extractions is considered to be the non-exchangeable form.

Table 4.9 shows data for the sequential extraction of ^{137}Cs and ^{90}Sr from contaminated soils of the Gomel and Bryansk regions collected in the mid-1990s as determined by SPA Typhoon. The data demonstrate that, independent of soil type, the fraction of ^{137}Cs that is exchangeable is much lower than that of ^{90}Sr. Some generalized data on the form of ^{137}Cs in soils of the CEZ are presented in Table 4.10.

Analysis of these data allows a better understanding of why, ten or more years after the accident, radionuclides have different rates of release depending on the specific radionuclide, the soil type and region; for example, even when most contaminated lowland of the Chernobyl zone was covered by water during the highest flood

TABLE 4.9. PER CENT CONTENT OF FORMS OF CAESIUM-137 AND STRONTIUM-90 IN SOILS OF THE BRYANSK AND GOMEL REGIONS IN THE MID-1990s

Soil	Soil type[a]	Water extract		Extract 1M CH_3COONH_4		Ref.
		Caesium-137	Strontium-90	Caesium-137	Strontium-90	
Sod–podzol	1	0.2 ± 0.2	6.1 ± 1.4	2.8 ± 0.7	67.1 ± 2.8	[4.22]
Sandy	2	0.2 ± 0.1	1.9 ± 0.2	2.6 ± 0.4	51.4 ± 4.2	[4.22]
Loamy sand	2	0.5 ± 0.1	5.2 ± 3.1	8.3 ± 0.2	69.0 ± 0.5	[4.22]
Sod–podzol loamy sand	3	0.2 ± 0.1	1.7 ± 0.8	4.2 ± 0.2	71.9 ± 3.4	[4.6]
Sod–podzol	1	0.5 ± 0.5	8.3 ± 6.7	23.2 ± 2.4	57.3 ± 9.3	[4.22]
On moraine	2	0.7 ± 0.1	1.7 ± 0.1	25.6 ± 1.4	57.4 ± 3.8	[4.22]
Sod–podzol	1	0.4 ± 0.3	5.8 ± 7.6	7.2 ± 1.4	67.3 ± 9.6	[4.22]
On sand	2	0.5	1.1	23.3	64.4	[4.22]
Sod–podzol gley loamy sand	1	1.4 ± 0.6	1.9 ± 1.2	16.1 ± 2.0	60.5 ± 6.9	[4.23]
Grey forest soil	1	0.8	1.9	10.3	58.7	[4.22]
Grey forest soil	1	0.9	1.5	3.2	42.9	[4.22]
Marsh low lying	1	0.3 ± 0.1	2.2 ± 1.7	1.0 ± 0.2	40.8 ± 3.8	[4.22]
Marsh low lying humus peaty	3	0.1 ± 0.02	1.3 ± 0.5	1.9 ± 0.7	53.2 ± 7.9	[4.23]
Boggy soils	1	7.4 ± 1.2	5.6 ± 3.8	16.7 ± 3.0	57.5 ± 6.6	[4.22]
Peaty podzol–gley	4			9.4[b]		[4.24]
Peaty sod–podzol	4			18.1[b]		[4.24]
Humus–peaty	4			24[b]		[4.24]
Alluvial sod acid loamy sand	1	0.1 ± 0.05	2.8 ± 1.1	0.8 ± 0.2	68.8 ± 7.8	[4.6]

[a] 1: non-arable; 2: agricultural; 3: arable; 4: forest.
[b] Sum of water soluble and exchangeable forms.

TABLE 4.10. EXCHANGEABLE FORMS OF CAESIUM-137 IN SOILS OF THE CHERNOBYL EXCLUSION ZONE

Type of soil	Sector (distance from nuclear power plant)	Per cent exchangeable form
Automorphic	Northern (2–15 km)	6–15
Automorphic	Northern (15–50 km)	15–30
Hydromorphic	Northern (2–15 km)	2–9
Hydromorphic	Northern (15–50 km)	2–28
Peat–bog soil	Northern (15–50 km)	6–9
Podzol–sandy soil	Northern (3–4 km)	2–13
Peat–podzol soil	Western (3–4 km)	1–10
Podzol–sandy soil	Western (4–5 km)	3–6

inundation in 1999, the flux of ^{137}Cs into the Pripyat River was much less than that of ^{90}Sr. At present, the percentage of mobile caesium in the upper contact layer of CEZ soils does not exceed 2–3%. The same data and the nature of ^{90}Sr distribution (see Fig. 4.6) demonstrate that the only significant source of ^{90}Sr wash-off at present is the floodplain territories and watercourses crossing the near zone of the Chernobyl nuclear power plant.

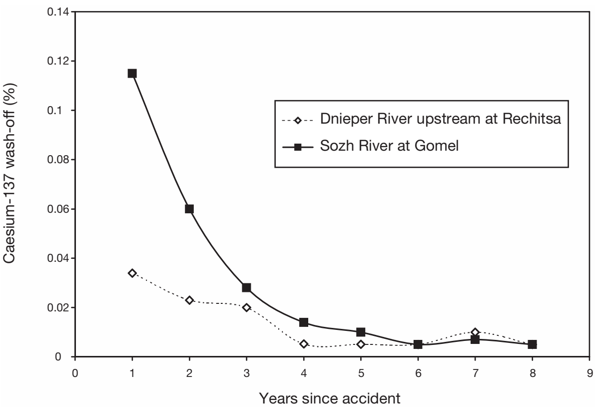

FIG. 4.11. Reduction in ^{137}*Cs wash-off from the watersheds of the Dnieper River (upstream of the Rechitsa observation point) and of the Sozh River at Gomel [4.26].*

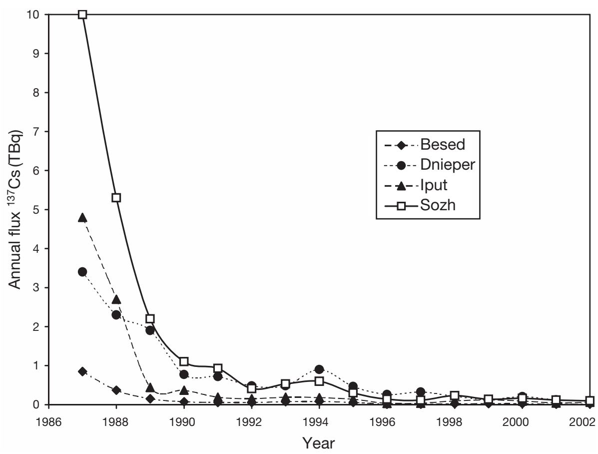

FIG. 4.12. Annual fluxes of ^{137}*Cs in the Dnieper River and its tributaries from the far zone of radioactive fallout [4.25].*

4.4.2. Characteristics of runoff in Belarus

In the Belarusian section of the Dnieper River basin about 40 000 km^2 was contaminated with fallout of ^{137}Cs in excess of 37 kBq/m^2 (see Table 4.2). The worst affected areas were the Gomel and Mogilev regions (see Fig. 4.4). The contamination of the watershed areas is characterized by extreme heterogeneity. The levels of contamination of soils with ^{137}Cs generally ranged from 37 to 1480 kBq/m^2 (1–40 Ci/km^2), with some localized areas above this range. Thus in the Kolyban settlement of the Bragin district in the Gomel region, the levels of contamination with ^{137}Cs vary from 170 to 2400 kBq/m^2. The maximum concentration of ^{137}Cs in the soils of the far zone was 5100 kBq/m^2, occurring at the Chudyany settlement of the Cherikov district in the Mogilev region. The main part of ^{137}Cs fallout entered the watersheds of the rivers Sozh, Iput, Besed, Chechera, Pokot and Braginka (all in the Dnieper River basin).

The left side tributaries of the Pripyat River release radionuclides mainly from the territory of Belarus, whereas the right side tributaries mainly carry radionuclides from the Ukrainian part of the watershed. The key points of observation on transfer from watersheds is Mozyr for the Pripyat River and Mogilev and Gomel (Sozh River) for the upper Dnieper River basin.

The contamination of the watersheds of the upper Dnieper and Pripyat Rivers with ^{90}Sr is much less (1–100 kBq/m^2) than that recorded within the Belarusian part of the CEZ (e.g. the Hoiniki district of the Gomel region has a concentration of 1800 kBq/m^2). High soil concentrations of ^{90}Sr were also recorded in the watersheds of the Sozh River at a distance of about 250 km from the Chernobyl nuclear power plant (e.g. the watershed of the Senna River received a ^{90}Sr contamination of about 30 kBq/m^2, compared with about 140 kBq/m^2 in the Gomel region). However, most ^{90}Sr contamination occurred in the catchments of the CEZ, including both the Ukrainian and Belarusian parts of this area (see Fig. 4.6).

The monitoring data from Belarus indicate that the radionuclide fluxes into the Dnieper River system have stabilized over the past 7–10 years and are now relatively low. The mean annual concentrations of ^{137}Cs during the period 1987–2001 in the water of the large and medium rivers of Belarus was less than 0.01% of the total radionuclide inventories in the watersheds (see Fig. 4.11). At present, ^{137}Cs runoff from the Belarus watershed does not represent a substantial contribution to contamination of the Dnieper reservoirs.

The level of water contamination also does not pose any significant risks for water use because, according to the data of Belhydromet, the ^{137}Cs concentration in surface waters during the past five years remained at the level of 0.01–0.03 Bq/L, which is over 100 times lower than the provisional national limit for drinking water (10 Bq/L) for ^{137}Cs and the equivalent limit (2 Bq/L) established in Ukraine. Although the wash-off of radionuclides should continue to be monitored, there is no justification for remedial actions in the upper Dnieper River system from a radiation safety viewpoint.

Figure 4.12 shows the annual fluxes of ^{137}Cs from the tributaries of the Dnieper River. The total releases of ^{137}Cs from the rivers of the upper

Dnieper River basin during the period 1987–2000 were as follows [4.25]:

(a) Sozh (Gomel): 22.2 TBq.
(b) Dnieper (Rechitsa): 12.6 TBq.
(c) Iput (Dobrush): 9.5 TBq.
(d) Besed (Svetilovichi): 1.9 TBq.

The total releases of ^{90}Sr from the rivers of the upper Dnieper River basin during the period 1990–2000 were as follows:

(i) Sozh (Gomel): 3.4 TBq.
(ii) Dnieper (Rechitsa): 2.9 TBq.
(iii) Iput (Dobrush): 0.9 TBq.
(iv) Besed (Svetilovichi): 0.7 TBq.
(v) Pripyat (Mozyr): 4.2 TBq.

By comparison, the wash-off of ^{90}Sr from the territory of the near zone of the Chernobyl nuclear power plant during 1999 was about 3.7–4.4 TBq (100–120 Ci). From the above data, we conclude that the near zone of the Chernobyl nuclear power plant contributes the major fraction of total wash-off of ^{90}Sr to the Dnieper River system.

Although ^{137}Cs concentrations in the surface waters of the upper Dnieper River have reduced markedly, those in the lakes have remained high. Within the territory of Belarus there are several hundred such water bodies of both natural and artificial origin. To date, detailed studies have been carried out on only a few lakes. Analysis of available data (see Table 4.11) for Lakes Svyatskoe (watershed of the Besed River) and Revucheye (watershed of the Iput River) shows that the current radionuclide levels in water of ^{137}Cs (8–9 Bq/L) and ^{90}Sr (0.4–0.6 Bq/L) are close to the national provisional permissible levels for drinking water (^{137}Cs =10 Bq/L, ^{90}Sr = 0.37 Bq/L) [4.27]. This topic is discussed further in Section 9.3.5.

4.4.3. Characteristics of runoff in the Russian Federation

Within the Russian Federation, the Bryansk region has suffered most from Chernobyl fallout (see Fig. 4.4 and Table 4.2). The most contaminated areas are five administrative districts in the south-west of the region (Gordeyevsky, Zlynkovsky, Klintsovsky, Krasnogorsky and Novozybkovsky). In August 1995 the sites with levels of ^{137}Cs contamination of 37–185 kBq/m^2 (1–5 Ci/km^2) covered an area of 6680 km^2, those with 185–555 kBq/m^2 (5–15 Ci/km^2) an area of 2700 km^2, those with 555–1500 kBq/m^2 (15–40 Ci/km^2) an area of 1900 km^2 and those with more than 1500 kBq/m^2 (40 Ci/km^2) an area of 310 km^2 [4.13].

TABLE 4.11. CONCENTRATIONS OF CAESIUM-137 AND STRONTIUM-90 IN THE WATERS OF LAKES SVYATSKOE AND REVUCHEYE

	Date of sampling	Caesium-137 (Bq/L)		Strontium-90 (Bq/L)
		Water, solution	Water, suspension	Water, solution
Svyatskoe	5 September 1995	6.8	0.12	—
	6 June 1996	4.5	0.07	—
	9 October 1996	4.9	0.07	—
	25 May 1998	4.7	0.06	0.3
	25 May 1998	5.8	0.08	0.4
	5 June 1998	1.5	0.23	—
	5 June 1998	1.6	0.16	—
	15 June 1999	9.0	0.008	0.007
		8.0	0.05	0.02
Revucheye	5 June 1996	8.1	0.1	—
	9 July 1997	5.4	—	—
	9 July 1997	5.2	—	—
	5 June 1998	6.0	—	—

Determination of ^{90}Sr and plutonium isotopes in the soil was performed mainly in the settlements of the Bryansk region with the highest ^{137}Cs depositions. In August 1995 there were 163 settlements in areas with ^{90}Sr contamination of less than 3.7 kBq/m^2 (0.1 Ci/km^2), 281 settlements within the range 3.7–18.5 kBq/m^2 (0.1–0.5 Ci/km^2), 40 settlements within the range 18.5–37 kBq/m^2 (0.5–1 Ci/km^2) and seven settlements within the range 37–55.5 kBq/m^2 (1–1.5 Ci/km^2) [4.13]. The areas most contaminated with ^{90}Sr are seven settlements in the Zlynkovsky district. The density of contamination of soil with $^{239,240}Pu$ in most investigated settlements was within the range 37–185 Bq/m^2 (0.001–0.005 Ci/km^2), and none exceeded 740 Bq/m^2 (0.02 Ci/km^2) [4.13].

There are no natural radiation abnormalities in the Bryansk region. In the central regions of the European part of the USSR, the level of soil contamination from global fallout prior to the Chernobyl nuclear power plant accident was, on average, about 2.5 kBq/m^2 of ^{137}Cs, and about 1.6 kBq/m^2 of ^{90}Sr [4.1, 4.5]. Within the Bryansk region there are several watersheds that drain into tributaries of the Sozh and Iput Rivers. These remained the main sources of radionuclide wash-off from Russian territory after the Chernobyl accident. Caesium-137 was considered to be the key radionuclide washed out from this catchment. Its release into the rivers decreased with time, firstly because of a gradual reduction in the mobile forms of ^{137}Cs in the soil and secondly because of vertical migration into the deeper soil layers.

Prior to the Chernobyl nuclear power plant accident in 1986, the State Hydrometeorological Service of the USSR carried out regular monitoring of the content of ^{90}Sr and tritium in surface waters and individual measurements of ^{137}Cs concentrations. Based on the results of these measurements, the pre-Chernobyl concentrations in river waters of the Bryansk region were assumed to range from 14 to 20 Bq/m^3 for ^{90}Sr and from 0.2 to 1.3 Bq/m^3 for ^{137}Cs [4.13]. After the accident, the radioactive contamination of the rivers in the territories of the south-western districts of the Bryansk region increased markedly. During the period of the spring inundation of 1987, the content of ^{137}Cs in the Iput and Besed Rivers reached 5000 Bq/m^3 and exceeded the pre-Chernobyl level by three to four orders of magnitude [4.28]. At present, the concentrations of ^{137}Cs in the rivers of the Bryansk region have reduced significantly and, as a rule, do not exceed 10 Bq/m^3 [4.13].

The main rivers that flow through the most contaminated territory (Bryansk region) of the Dnieper River basin are the Iput, Besed and Snov. Their main characteristics are presented in Tables 4.12 and 4.13. The Iput and Besed Rivers are tributaries of the Sozh River, and the Snov is a tributary of the Desna River (see Fig. 2.1). The Snov River originates in the Bryansk region and runs into the territory of Ukraine. The sources of the Besed and Iput Rivers are situated in Belarus and the Smolensk region of the Russian Federation, respectively. Both rivers empty into the Sozh in the territory of Belarus. The main part of the Besed River runs through Belarus, the main part of the Iput River is in the Bryansk region.

Assessment studies show that, just as in Belarus, the levels of contamination in the rivers flowing through the affected areas of the Russian Federation have decreased with time and now approach pre-Chernobyl levels. Consequently, there are now no limitations on local water use from the Sozh and Iput Rivers.

The most contaminated areas after the Chernobyl accident have been, and remain, the closed lakes. Thus in lake Svyatoe, located in the floodland of the river Besed, the ^{137}Cs concentration at the beginning of the 1990s was twice the national intervention level for drinking water (11 Bq/L), and in 2000 it remained at about 10 Bq/L [4.13, 4.30, 4.31].

TABLE 4.12. MAIN RIVERS OF THE CONTAMINATED DISTRICTS OF THE BRYANSK REGION [4.13, 4.29]

	Total length (km)	Length in the region (km)	Total watershed area (km^2)	Watershed in the region (km^2)	Annual flow (km^3)
Iput	475	290	10 694	7520	1.00
Besed	256	54	5 406	1610	0.33
Snov	253	125	8 700	2620	0.16

TABLE 4.13. RADIONUCLIDE INVENTORY IN THE WATERSHED OF THE IPUT RIVER IN INDICATED SECTIONS IN THE RUSSIAN FEDERATION

	Distance from the Chernobyl nuclear power plant (km)	Watershed area (km^2)	Inventory in watershed (10^{12} Bq)	
			Caesium-137	Strontium-90
Iput–Krutoyar	170	4 019	34	2.2
Iput–Belovodka	230	5 356	48	3.3
Iput–Kazarichi	250	5 864	64	4.1
Iput–Tvorishino	260	6 041	122	4.9
Iput–Uscherpie	300	8 319	604	13.7
Iput–Bobovichi	330	9 174	1265	24.1
Iput–Vyshkov	360	9 614	1676	33.2
Iput–Dobrush (Belarus)	405	10 100	2240	—

4.4.4. Chernobyl exclusion zone, Ukraine

During the initial accident release period after 26 April 1986, the neighbouring areas (water catchments, floodplains and surface water bodies around the Chernobyl nuclear power plant (see Fig. 4.5)) were directly contaminated by atmospheric fallout. Surface water contamination was characterized by a high level of radiation from a wide spectrum of short lived radionuclides. The total beta contamination of the open water bodies near the Chernobyl nuclear power plant reached approximately 37 000 Bq/L (1 μCi/L). The beta activity of the Pripyat River water downstream of the Chernobyl nuclear power plant in early May 1986 exceeded 370 Bq/L. The range of radioactivity in the Dnieper River near the main water intake of Kiev city (130 km downstream from the Chernobyl nuclear power plant) was 3.7–370 Bq/L in May and June 1986. The largest contribution to water contamination in the first months after the accident was caused by ^{131}I. Since 1987, ^{137}Cs and ^{90}Sr have become the most important radionuclides in terms of contamination and dose to the population.

Detailed studies of pollution from watersheds have shown that the most contaminated areas that could be flooded are portions of the left and right banks of the Pripyat River floodplain upstream of the Chernobyl nuclear power plant (Fig. 4.13). Figure 4.14 shows the contaminated zones and catchment areas; the activity of ^{90}Sr in each area is given in Table 4.14.

In the first phase of the mitigation of the consequences of the Chernobyl accident, considerable effort and resources were spent on actions to reduce contamination of surface waters. In undertaking these actions, emphasis was placed on the prevention of secondary contamination of water systems due to wash-off of radionuclides from catchments and transport of radionuclides by river systems from the near zone of the Chernobyl nuclear power plant to relatively clean areas. The primary countermeasures undertaken included:

(a) Dispersion of sorbents in the Pripyat River (1986);
(b) Building an embankment along the Pripyat River in the near zone of the Chernobyl nuclear power plant (1986);
(c) Setting up bottom traps (1986–1987);
(d) Building filter systems for dams (1986–1987);
(e) Setting up a drainage barrier around the cooling pond (1987–1988);
(f) Establishing the left bank flood control dyke (1993);
(g) Establishing the right bank flood control dyke (1998).

The soil in this area is heavily contaminated with ^{137}Cs and isotopes of plutonium. Figure 4.15 shows ^{137}Cs and ^{239,240}Pu spatial contamination of the most contaminated catchments in the CEZ. These radionuclides are firmly bound to soil particles and their wash-off from the floodplain areas of the CEZ is of much less importance in terms of secondary contamination and human dose via aquatic pathways.

The contribution of all possible sources of ^{137}Cs runoff from the far zone into the Pripyat River basin has stabilized at a level of about 1 TBq/a (25–30 Ci/a). This represents about 80–85% of the total input of ^{137}Cs into the Kiev reservoir over the past

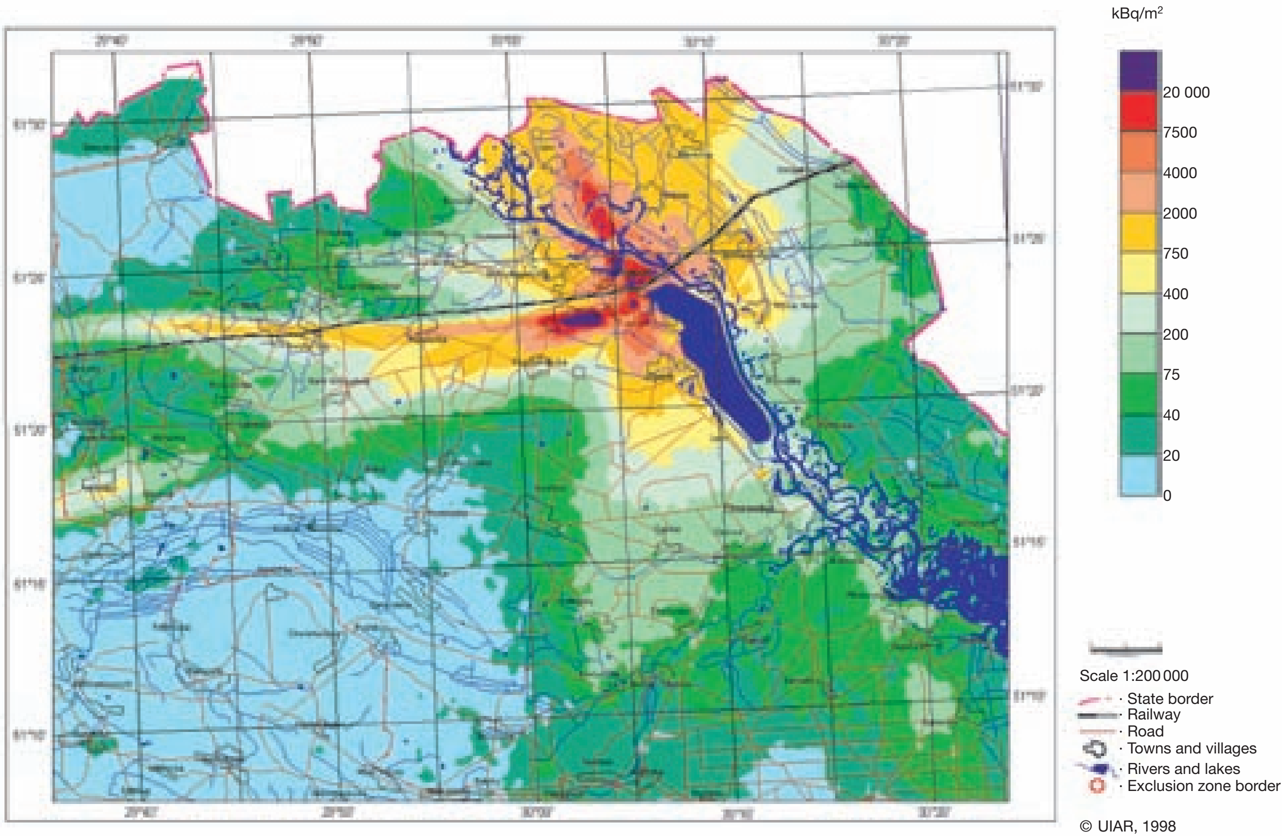

FIG. 4.13. Contamination density of ^{90}Sr within the floodplain areas near the Chernobyl nuclear power plant [4.32].

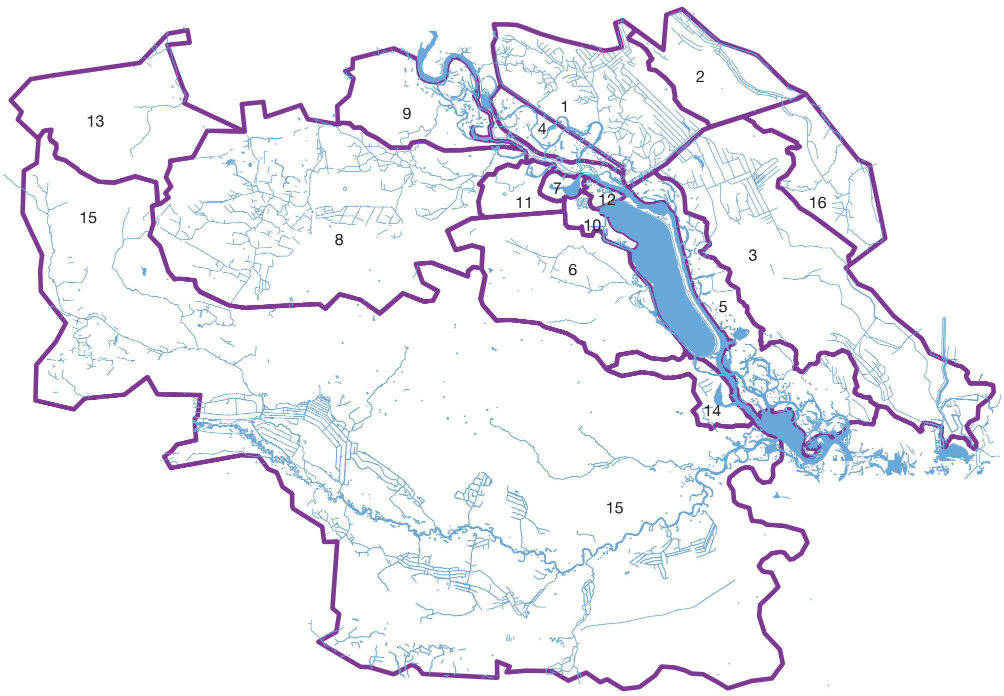

FIG. 4.14. Contaminated zones and catchment areas in the vicinity of the Chernobyl nuclear power plant. The ^{90}Sr activities in areas 1–16 are listed in Table 4.14.

TABLE 4.14. ACTIVITY OF STRONTIUM-90 (1997) IN THE CONTAMINATED ZONES AND CATCHMENT AREAS SHOWN IN FIGURE 4.14

Area	Description of area	Size of area (km^2)	Strontium-90 activity (TBq)
1	Left bank water reclamation area	71.5	138
2	Braginka River catchment (upper part)	37.1	24
3	Pripyat water reclamation system	147	31
4	Area inside of the left water protective dyke and flood control dyke (polder)	14.7	72
5	Left bank floodplain area	61.3	22
6	Kopaci water reclamation system	79.6	212
7	Catchment of the Yanov River (Pripyat Bay)	3.86	24
8	Sakhan River catchment	204	78
9	Benevka floodplain area	45.6	17
10	Chernobyl nuclear power plant industrial site	6.89	50
11	Sandy plateau waste storage site	13.4	23
12	Catchment of Lake Azbuchin	2.81	32
13	Catchment of Rozhave River	71.0	1
14	Chernobyl city	15.8	4
15	Uzh River catchment	803	53
16	Braginka River catchment (middle part)	39.4	4
Total		1617	786

10–12 years. The contribution of sources located in the near zone of the Chernobyl nuclear power plant increases in high water years (e.g. 1999), in periods of continuous showers (e.g. 1993) and during other extreme hydrological events (such as occurred in 1991 and 1994) that result in flooding of the most contaminated zone. In contrast, the main contribution of ^{90}Sr contamination (60–75%) comes from the contaminated floodplains of the Pripyat River in the near zone of the Chernobyl nuclear power plant and from direct drainage from the contaminated water bodies and polder systems.

At present, the CEZ zone may be considered as a regional hot spot from which the main flux of radioactive contamination into the Pripyat River originates. The radioactive contamination of the Pripyat River arises from several sources. The contributions of various sources based upon observations by Ecocentre are presented in Table 4.15 for a typical low water year (1997), a high water year (1999) and an average water year (2001).

Drainage from the left bank polder through the water protective structure No. 7 depends on the water flow and constitutes 10–16% of the total. As a result of engineering works performed at the polder in 2001 (cleaning of the waterbed of the reclamation channels and reconstruction of the inlet facility for water discharge into the Pripyat River), the average water level at the polder was reduced by 1.8 m, and the specific activity of ^{90}Sr was reduced by a factor of two. As a consequence, it is expected that radionuclide release from the polder into the Pripyat River will continue to decrease. The release from the Chernobyl nuclear power plant cooling pond can be determined from measurements at the filtration streams, the southern drainage canal and the Glinnitsa River. This release is the most stable when measured in activity units (GBq or Ci); in percentage terms it increases during low water periods and constitutes from 8% during a high water year up to 15% during a low water year. Annual releases to the Pripyat River are shown in Fig. 4.16. The main source of water contamination is the radionuclides in the bottom sediments. The activity of the major radionuclides in the sediments (as of 2001) is as follows: $^{137}Cs = 160 \pm 25$ TBq, $^{90}Sr = 24 \pm 5$ TBq, $^{239,240}Pu = 0.52 \pm 0.15$ TBq, $^{238}Pu = 0.26 \pm 0.07$ TBq,

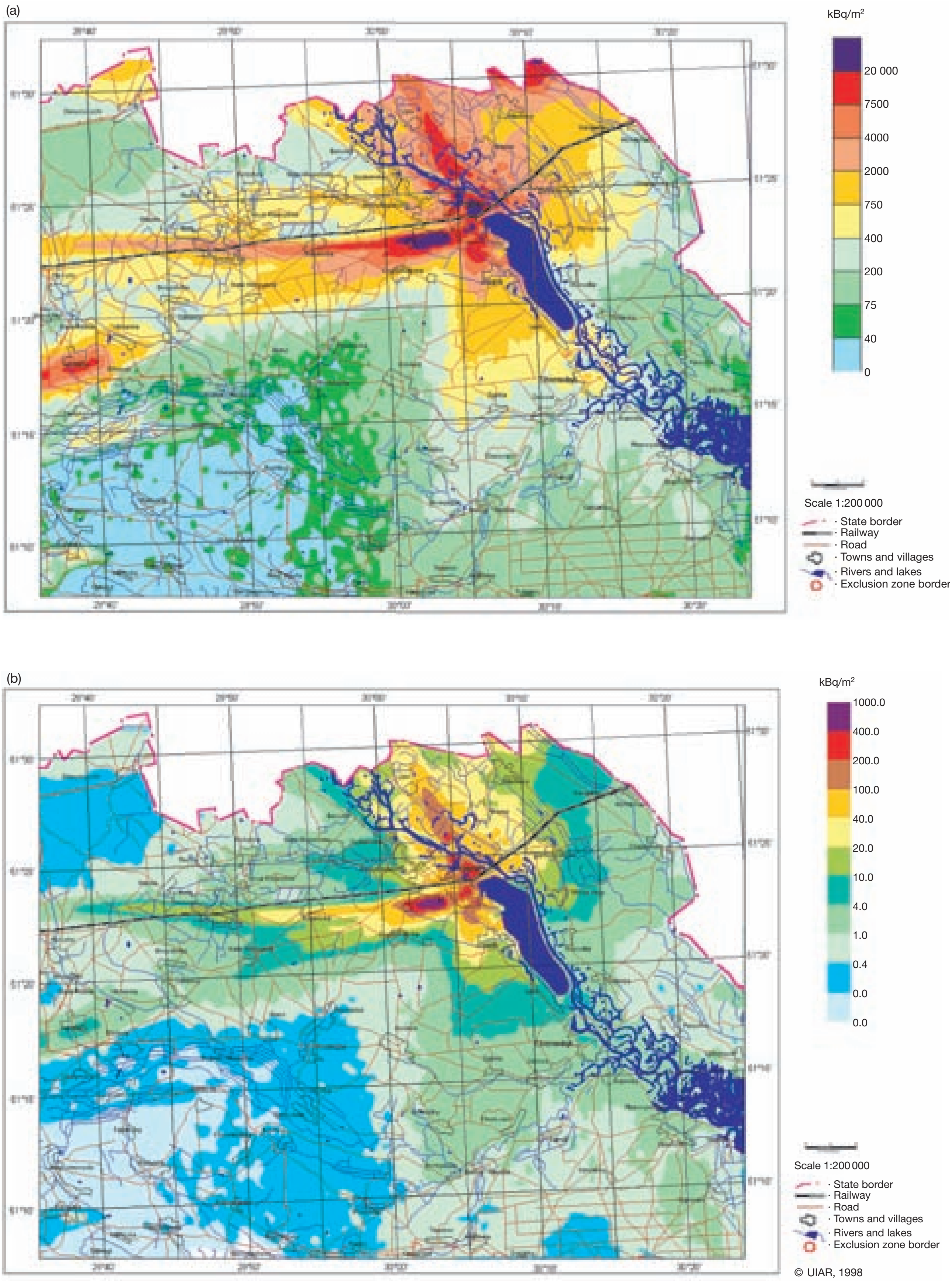

FIG. 4.15. Spatial radioactive contamination by ^{137}Cs (a) and ^{239,240}Pu (b) within the CEZ.

TABLE 4.15. MAIN SOURCES OF STRONTIUM-90 TRANSFER INTO THE PRIPYAT RIVER DURING TYPICAL YEARS

	Strontium-90 migration (TBq)			Relative contribution (%)		
	1997	1999	2001	1997	1999	2001
Pripyat River: entrance into the CEZ	0.80	3.21	1.29	26.1	29.9	36.2
Drainage from the left bank polder	0.33	1.39	0.57	10.8	12.9	16.0
Surface wash-off, groundwaters	1.18	5.21	0.92	38.6	48.5	25.8
Filtration streams of the cooling pond	0.13	0.08	0.10	4.2	0.7	2.8
Glinnitsa River	0.22	0.27	0.21	7.2	2.5	5.9
Sakhan River	0.02	0.04	0.05	0.7	0.4	1.4
Uzh River	0.17	0.27	0.20	5.6	2.5	5.6
Braginka River	0.21	0.28	0.22	6.9	2.6	6.2
Total within the limits of the CEZ	2.26	7.54	2.27	73.9	70.1	63.8
Total migration beyond the limits of the CEZ	3.06	10.75	3.56	100	100	100

^{241}Am = 0.67 ± 0.19 TBq and ^{241}Pu = 20 ± 5 TBq. The cooling pond is assessed as a hot spot in Section 9.3.2.

The total contribution of Pripyat River tributaries (Uzh, Braginka, Sakhan) over the past five years did not exceed 9–13% (see Table 4.15). Accordingly, remedial measures in the floodland of the Braginka River and at the reclamation systems in the CEZ are not considered nowadays as a priority.

The annual contribution into the river of various groundwater and surface sources from localized areas within the Chernobyl nuclear power plant zone may contribute from 25% to 50% of the ^{90}Sr release, depending on the water flow that year and the peculiarities of the flooding of the contaminated territory.

Thus the main potentially regulated sources of the current secondary contamination are the following:

(i) Flood prone sections along the river in the near zone of the Chernobyl nuclear power plant that have yet to be dyked;
(ii) Areas of the first over-floodplain terrace along the Chernobyl nuclear power plant cooling pond;
(iii) Seepage into the river;
(iv) Controlled surface creeks from the polder reclamation system of the left bank within the CEZ.

According to the assessments of Ecocentre, the present transfer of ^{90}Sr via groundwater (without consideration of the Chernobyl nuclear power plant industrial site, the Chernobyl shelter or the cooling pond) does not exceed 0.04 TBq/a. Taking into account the transfer of the filtration waters from the water body and the groundwater flow under the shelter, the contribution of the underground waters may constitute 0.2–0.4 TBq/a.

As noted in Section 3, some contaminated material from the Chernobyl site was buried within the CEZ. During periods of inundation of the floodplain, the waste disposal sites contribute to the release into the Pripyat River. Further information on these burial sites is provided in Section 7, and a detailed description is available in the documents of the administration of the CEZ, in the annual reports on the results of radiation monitoring in the CEZ and in the literature (e.g. Refs [4.33–4.35]). This literature indicates that, at present, the need for redisposal of the majority of the dumps in the Chernobyl nuclear power plant zone is not apparent, since the total release of the most mobile radionuclide, ^{90}Sr, from all disposal sites into the Pripyat River does not exceed 0.04–0.08 TBq/a. The only concern is direct flooding of the near surface disposal pits located along Yanov Creek.

The Institute of Geological Science of the National Academy of Science of Ukraine has made a long term conservative prediction of ^{90}Sr transfer from the waste disposal sites into Pripyat Bay and Lake Azbuchin. On the territory between the bay and the lake there are point sources such as the Red Forest, Stroibaza, Yanov and Neftebaza radioactive waste temporary storage sites (see Section 7 for further information on these sources). The groundwaters from the Chernobyl nuclear power plant

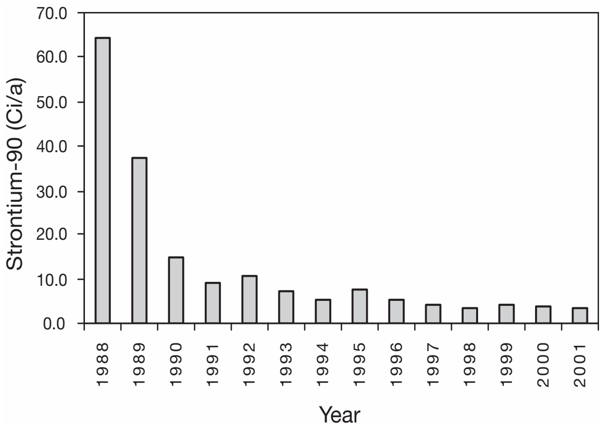

FIG. 4.16. Annual ^{90}Sr radionuclide releases from the cooling pond to the Pripyat River. Data of the CREM (Chernobyl Ecocentre). Note: 1 Ci = 37 GBq.

industrial site and the shelter are released into Lake Azbuchin. The results of the simulation are presented in Table 4.16. Conservative modelling predicts that the total amount of ^{90}Sr transferred from the disposal sites over 300 years will not exceed 15 TBq.

Thus, according to the forecasts, the underground fluxes from the disposal sites and the most contaminated spots within the near zone of the Chernobyl nuclear power plant will, even in 60–100 years' time, release relatively small quantities of ^{90}Sr into the Pripyat River (i.e. a maximum of 130 GBq/a). The transfer from the CEZ as a whole may reach 0.8 TBq/a. The maximum ^{90}Sr contamination from underground waters is expected in the 20th to 30th year after the accident, and thereafter the contribution from underground sources will decrease due to radioactive decay.

It should be noted that there is considerable uncertainty in the assessment of the contribution of the Chernobyl nuclear power plant industrial site and the shelter to groundwater contamination, due to many factors, including the complexity of the radionuclide migration conditions. Section 9.3.3 gives a detailed assessment of potential groundwater contamination from the shelter.

The main feature of radionuclide release from the contaminated watersheds to the Kiev reservoir over the 17 years since the accident is the significant decrease in ^{137}Cs influx to the reservoir; however, ^{90}Sr release to the river network continues to be significant. Since 1992 the rate of ^{90}Sr release to the Pripyat River has been reduced due to water protection measures (dyke construction) on the floodplain near the Chernobyl nuclear power plant.

The annual total inputs of ^{137}Cs and ^{90}Sr into the cascade of reservoirs from the Pripyat and Dnieper catchments after the accident are as follows:

— 0.59 TBq and 0.7 TBq, respectively, in 1986;
— 0.49 TBq and 7.7 TBq, respectively, in 1989;
— 0.30 TBq and 7.8 TBq, respectively, in 1991;
— 0.03 TBq and 8.2 TBq, respectively, in 1999.

The differences in the behaviour of the radionuclides are also apparent in the fact that a large part of the ^{137}Cs, as well as some other radionuclides, is associated with suspended particles in the water, whereas essentially all the ^{90}Sr is in the dissolved state.

After the spring and summer of 1986 (when direct radioactive fallout on to the surface of water bodies took place), the most significant sources of surface water contamination of the Dnieper River have been surface runoff from the contaminated floodplains and catchment areas as well as infiltration of heavily contaminated water from the cooling pond and other water bodies into the river. The first flood period in 1987 showed that the main sources were the whole catchment of the upper part of the Pripyat River basin and a significant part of the upper Dnieper River catchment (mainly the Sozh River). From 1996 to the present, more than 70% of annual radionuclide input has been due to sources situated inside the CEZ.

Since the Chernobyl accident, no long periods of high river water or flooding have occurred in the contaminated areas. The spring water flow of the Pripyat River, with discharges of 800–2200 m^3/s, has not exceeded the normal flood condition. The maximum possible Pripyat River discharge can exceed 5000 m^3/s (as occurred in 1979). After flooding of the riverplain in 1988 and 1991, it became clear that, unless mitigation actions were implemented in the contaminated area, the floodplain would remain a potential hazard well into the future. For this reason, after 1992 remedial actions focused on the prevention of further significant removal of radionuclides from the Pripyat River floodplain. Significant flood events took place in 1994 and during the spring of 1999, when the maximal water discharge reached about 3000 m^3/s. In particular, during the high flood of 1999 the heavily contaminated terraces of the river floodplain near the Chernobyl nuclear power plant were inundated significantly (the flooding event lasted for about two weeks), and radionuclide

TABLE 4.16. FORECAST OF STRONTIUM-90 RELEASE VIA GROUNDWATERS TO SURFACE WATERS IN THE NEAR ZONE OF THE CHERNOBYL NUCLEAR POWER PLANT [4.36]

	Receiving water body	Watershed area (km^2)	Strontium-90 inventory (TBq)	Maximal release (GBq/a)	Time to maximal release (a)	Integral release over 300 years (TBq)
Watershed of Pripyat Creek	Pripyat Creek	7	111	63	65	4.2
Watershed of Lake Azbuchin	Lake Azbuchin	1.8	37	63	33	3.9
Watershed of Semikhody Creek	Semikhody Bay	8	19	6.3	65	0.4
Red Forest radioactive waste temporary storage site	Pripyat Creek	1	74	3.3	200	0.23
Yanov radioactive waste temporary storage site	Pripyat Creek	4	15	0.22	220	0.015
Stroibaza radioactive waste temporary storage site	Pripyat Creek	1.8	222	81.4	110	5.3
Chernobyl nuclear power plant industrial site	Lake Azbuchin	0.25	59	37	145	1.4
Total		23.85	537	129.5		15.4

releases occurred mainly from the right bank (see Fig. 4.17). Figure 4.18 shows peaks corresponding to significant wash-off of ^{90}Sr during the spring floods of 1988, 1991, 1994 and 1999.

In the initial period after the accident, ^{90}Sr wash-off from the far water catchments was higher than from the Chernobyl nuclear power plant accident zone. This can be explained by the relatively low mobility of ^{90}Sr in fuel particles during that period. Subsequently, as the fuel particles disintegrated, the mobility of radionuclides of ^{90}Sr increased. In contrast, ^{137}Cs quickly became fixed to the soil minerals (especially clays). Over time, the relative contribution of ^{90}Sr increased, and it is now the most important radionuclide in terms of contamination of the Dnieper water system. Figure 4.19 shows the ratio of dissolved ^{90}Sr to dissolved ^{137}Cs as a function of time. Again, the

FIG. 4.17. Dyke at Pripyat Bay and inundated riverside land within the CEZ during the spring flood, April 1999.

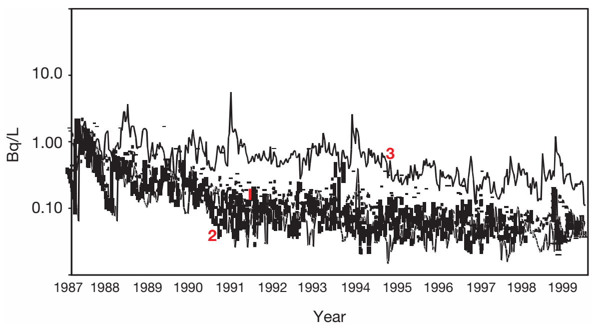

FIG. 4.18. Radionuclide concentration (10 day averages) in the Pripyat River. 1: ^{137}Cs, dissolved; 2: ^{137}Cs, particulate phase; 3: ^{90}Sr.

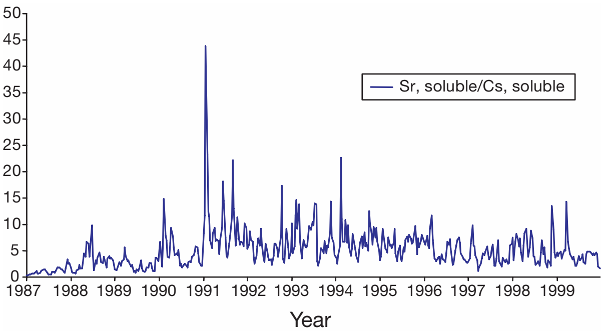

FIG. 4.19. Ratio of ^{90}Sr to ^{137}Cs activity concentration in Pripyat River water in the city of Chernobyl.

spring flood events in 1991, 1994 and 1999 are clearly discernible as sharp peaks when the floodplains became inundated.

Significant reduction in ^{90}Sr release from the CEZ is expected after completion of a whole series of flood control (water protective) measures on the right bank of the river, drying-up of the cooling pond and completion of the water runoff control system on the left bank polder. In particular, during 2001, 10 km of canals of the left bank polder (reclamation) system were dredged and many engineering works such as flow gates, drains and others were restored and repaired. These works allowed better control of runoff from the polder system.

Recently, the water management authorities in Belarus and Ukraine agreed to justify actions concerning construction of a bypass channel along the Belarusian–Ukrainian border in the CEZ. The construction of a 10 km long channel (between the settlements of Krasne and Zimovishche) would direct surface runoff from Belarusian catchments during high water periods straight to the Braginka River, which flows into the Kiev reservoir, thus avoiding the most contaminated lowland areas within the CEZ. This proposal has considerable merit, since it would reduce the downstream ^{90}Sr source term during flood conditions.

4.5. ANALYSIS OF KEY PROCESSES GOVERNING THE LONG TERM DYNAMICS OF RADIOACTIVE CONTAMINATION OF THE DNIEPER WATER SYSTEM

The initial radioactive contamination after the Chernobyl accident resulted from direct fallout on the water surface. Thereafter, the dynamics of radioactivity in river water were controlled by the redistribution of radionuclides between the water and the bottom sediments. In the following period, which started approximately one year after the fallout [4.37], the contamination of river water depended on inflow of radionuclides from the catchment areas. The model proposed in Ref. [4.37] assumes that the radionuclide concentration in river water during this time period is directly proportional to the average concentration of its exchangeable form in the surface soil layer on the catchment. This means that the key processes responsible for the long term dynamics of radionuclides in river water are vertical migration and exchange of radionuclide species in soils on the catchment. For the case where the bulk of the radionuclides deposited on the catchment are in the form of condensation particles, the time dependence of radionuclide concentration in the dissolved phase can be expressed as follows:

$$C_{\mathrm{w}} = \frac{K}{\sqrt{\pi D_{\mathrm{E}} t}}\left(1+\frac{\delta}{\sqrt{t}}\right)\exp\left(-\left(\frac{u^2}{4D_{\mathrm{E}}}+\lambda t\right)\right) \tag{4.1}$$

where

K is a site specific parameter (Bq/m^2);
D_{E} is the effective diffusion coefficient in sediments (m^2/a);
u is the effective velocity of convective transport (m/a);
δ is the kinetic parameter of radionuclide fixation in soil (a$^{0.5}$);
λ is the radioactive decay constant (a^{-1});
t is the time (a).

Equation (4.1) predicts with adequate accuracy the long term dynamics of ^{137}Cs in the three rivers (Irpen, Teterev and Uzh) flowing across the southern part of the radioactive trace formed after the Chernobyl accident [4.37]. It also yields satisfactory results for the rivers flowing through other territories with similar soil and fallout characteristics. As an illustration, Fig. 4.20 shows calculated and experimental dependences of the mean annual concentration of ^{137}Cs in the Iput River (at the Dobrush measuring section). Good agreement of the calculated and measured concentrations suggests that the underlying assumptions regarding the physicochemical mechanisms are valid.

FIG. 4.20. Predicted (line) and measured (points) activity concentration of ^{137}Cs in the Iput River (cross-section at Dobrush). Experimental data were taken from Ref. [4.39].

FIG. 4.21. Reconstructed activity concentration of ^{137}Cs in the Snov River (cross-section at Khoromnoe).

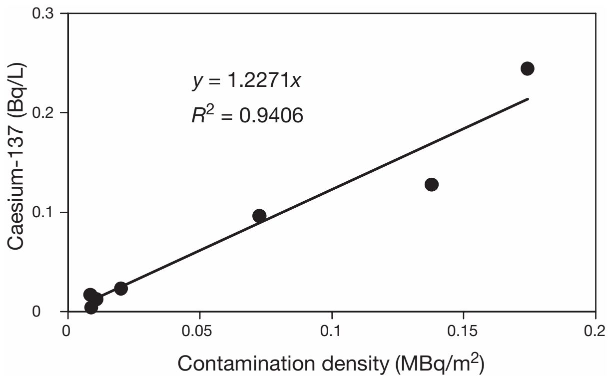

FIG. 4.22. Concentration of ^{137}Cs in the Iput River in 1991–1993 as a function of upstream watershed contamination density. Experimental data were taken from Ref. [4.40].

The advantage of Eq. (4.1) is that a prediction (or reconstruction) of the long term dynamics of radionuclide concentration in river water can be made based on measurements made over a relatively short period of time. In particular, for the Snov River, along which transboundary transport of radionuclides from the Russian Federation to Ukraine occurs, only fragmentary results of measurements of ^{137}Cs specific activity made in 1998 are available [4.13]. Based on these data, and using Eq. (4.1), the dynamics of the contamination of this river over the period starting from 1987 to the present day can be reconstructed (see Fig. 4.21).

Equation (4.1) can also, most probably, be used for estimating the distribution of radionuclides over the whole length of the river, provided data for one or several measuring sections and a catchment contamination map are available. Earlier studies suggest that the radionuclide concentration in a measuring section is directly proportional to the average contamination density of that part of the river catchment upstream of the given measuring section (see Fig. 4.22).

During the years after the Chernobyl accident the radiocaesium activity concentration in most contaminated aquatic ecosystems decreased markedly. Lakes with no permanent inflows and outflows (closed lakes), however, still present a radioecological problem that is expected to continue for some time. This is explained by the fact that the main mechanism underlying the reduction of the radionuclide concentration in the water of such lakes is a fairly slow migration to the lower layers of bottom sediments. Given negligible runoff and sedimentation, the dynamics of radiocaesium in lake water is described by a simple equation with only one unknown parameter [4.38]:

$$C_{\mathrm{w}}(t) = \frac{\sigma}{K_{\mathrm{d}}\sqrt{\pi D_{\mathrm{E}} t}} \exp(-\lambda t) = \frac{A}{\sqrt{t}} \exp(-\lambda t) \qquad (4.2)$$

where

- C_{w} is the radionuclide activity concentration in the water layer (Bq/m^3);
- A is a constant for a given lake and radionuclide;
- K_{d} is a dimensionless distribution coefficient that is equal to the ratio of radionuclide activity concentration in the water to that in the surface of the sediments (on a volume basis).

Equation (4.2) was tested against ^{137}Cs activities measured between 1993 and 1999 in Lake Svyatoe in the Bryansk region of the Russian Federation (see Fig. 4.23). It can be seen that the ^{137}Cs concentration in the lake is actually equal to the intervention level effective in the Russian Federation today (11 Bq/L) and will remain high for many years. Given the fact that the ^{137}Cs

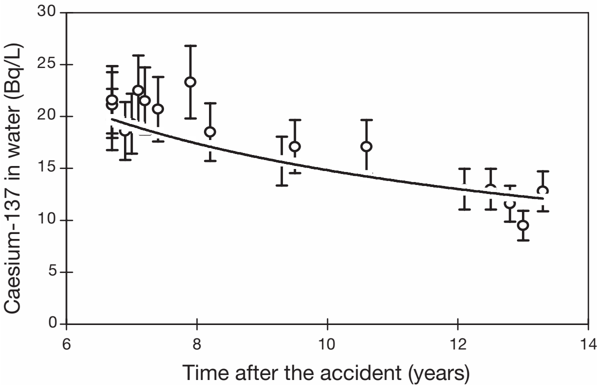

FIG. 4.23. Measured versus modelled ^{137}Cs activity concentration in Lake Svyatoe water. Modelled activity dynamics are given by the solid line, measured values by circles. Standard deviations of the mean for measured values are also shown.

concentration in fish in these lakes is also quite high, it may be concluded that, as a result of the Chernobyl accident, the lifestyle of the local inhabitants has been affected for a considerable time. Hence, the lakes without outflow, in a sense, can be considered to be significant hot spots (see Section 9.3.5).

4.6. TRANSBOUNDARY FLUXES OF RADIONUCLIDES IN THE DNIEPER RIVER BASIN

The transboundary movement of radionuclides in rivers is determined by water discharge rates and radionuclide volumetric activity at the border crossing. Table 4.17 gives the average the

TABLE 4.17. AVERAGE TRANSBOUNDARY FLOW OVER MANY YEARS OF THE MAJOR RIVERS OF THE UPPER DNIEPER RIVER BASIN MOST CONTAMINATED BY THE CHERNOBYL ACCIDENT [4.29]

	Flow from	Flow to	Annual runoff (km^3)			
			Mean	Probability		
				75%	90%	95%
Dnieper	Russian Federation	Belarus	3.65	2.96	2.51	2.25
Dnieper	Belarus	Ukraine	18.6	15.0	12.5	11.2
Pripyat	Belarus	Ukraine	12.2	9.16	7.25	6.29
Braginka	Belarus	Ukraine	0.09	—	—	—
Sozh	Russian Federation	Belarus	1.84	1.41	1.14	1.00
Iput	Russian Federation	Belarus	1.57	1.19	0.94	0.81
Besed	Belarus	Russian Federation	0.52	0.41	0.33	0.29
Besed	Russian Federation	Belarus	0.76	0.60	0.49	0.43
Snov	Russian Federation	Ukraine	0.35	0.27	0.22	0.20
Seim	Ukraine	Russian Federation	0.27	0.21	0.16	0.14
Seim	Russian Federation	Ukraine	2.61	2.03	1.64	1.44
Desna	Russian Federation	Ukraine	5.11	4.24	3.61	3.30

characteristics over many years of the trans-boundary water flow of major rivers in the regions most contaminated after the Chernobyl accident and of rivers flowing through the areas surrounding the Smolensk and Kursk nuclear power plants.

The average values in Table 4.18 can be used to forecast transboundary fluxes of radionuclides. For retrospective estimates it is better to use data from routine observations for a given time period.

Radionuclide concentration in rivers is normally measured in cross-sections lying several tens of kilometres from the border. The exceptions are two measuring sections on the Belarusian–Ukrainian border (Belaya Soroka on the Pripyat River and Gden on the Braginka River) and the Vyshkov measuring section on the Iput near the Russian–Belarusian border. For the latter cross-section, however, only limited data are available. Systematic monitoring of radioactive contamination in rivers flowing through the areas around the Kursk and Smolensk nuclear power plants (the Desna and Seim Rivers) is carried out only at measuring sections in the immediate proximity of the nuclear power plants. Therefore, in most cases to estimate radionuclide concentrations at the border, extrapolation methods are required, such as the concentration dependence on catchment contamination density (see Fig. 4.22). In those cases when limited observational series are available, extrapolation of concentration over time can be used.

Estimates of the transboundary transport of radionuclides in the Dnieper River basin have been made starting from the early phase of the accident. It was shown that, in 1987, the transport of ^{137}Cs from the Sozh catchment was about 80% of its flow to the Kiev reservoir with the water of the Dnieper River [4.28]. In turn, about half of the ^{137}Cs was transported to the Sozh River via the Iput River, whereas the input from the Besed River was only about 8%.

The concentration of radionuclides in rivers has decreased significantly with time. The dependence of annual outflow of ^{137}Cs from the territory of the Russian Federation to Belarus via the Iput River suggests that most of the radionuclides were transported across the border in the first few years after the accident. Table 4.18 contains estimates of transboundary flows of ^{137}Cs and ^{90}Sr for the period 1987–1999 based on the data derived from the measuring sections closest to the borders. It can be seen that over the 12 year period the trans-boundary transport of ^{137}Cs did not exceed 1% of the amount of radionuclides deposited on the catchment area in 1986. The transboundary movement of ^{90}Sr was somewhat higher, but did not exceed 5% for the same period.

Figures 4.24 and 4.25 show the annual fluxes on the Pripyat, Iput and Besed Rivers near the borders. The transboundary migration of ^{137}Cs has decreased markedly with time. However, the trans-boundary migration of ^{90}Sr has fluctuated from year to year depending on the rainfall and extent of flooding (see Figs 4.24(b) and 4.25(b)).

The above analysis indicates that the existing system of monitoring of radioactive contamination

TABLE 4.18. ESTIMATES OF TRANSBOUNDARY TRANSPORT OF CAESIUM-137 AND STRONTIUM-90 IN MAJOR RIVERS FLOWING THROUGH CHERNOBYL AFFECTED REGIONS [4.26, 4.41]

	Years	Iput River	Besed River	Pripyat River	Dnieper River
Section		Dobrush	Svetilovichi	Belaya Soroka	Nedanchichi
Border		Russian Federation–Belarus	Russian Federation–Belarus	Belarus–Ukraine	Belarus–Ukraine
Caesium-137 outflow (TBq)	1987–1999	9.1	1.9	31.3	43.1
Caesium-137 (per cent catchment inventory)		0.4	0.1	0.7	0.56
Strontium-90 outflow (TBq)	1990–1999	0.9	0.7	52.6	34.3
Strontium-90 (per cent catchment inventory)		2.2	1.9	4.3	3.6

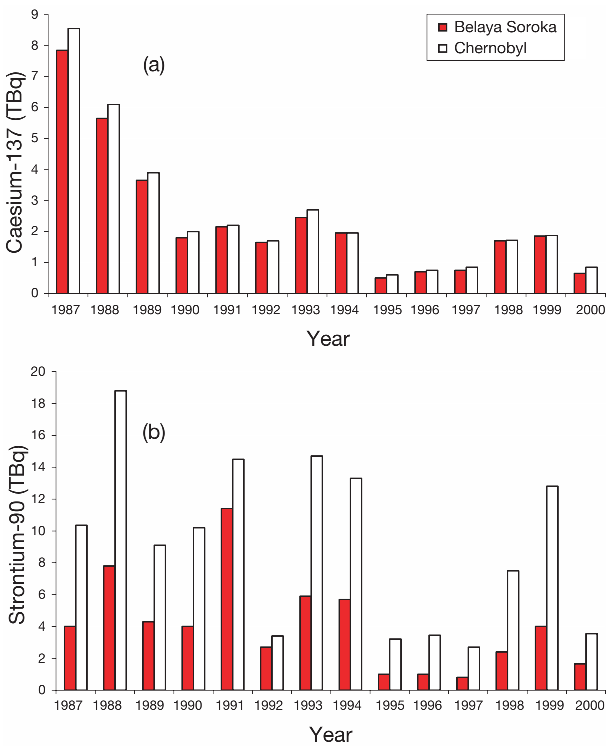

FIG. 4.24. Annual fluxes of (a) ^{137}Cs and (b) ^{90}Sr in the Pripyat River near the Belarus–Ukraine border and at Chernobyl.

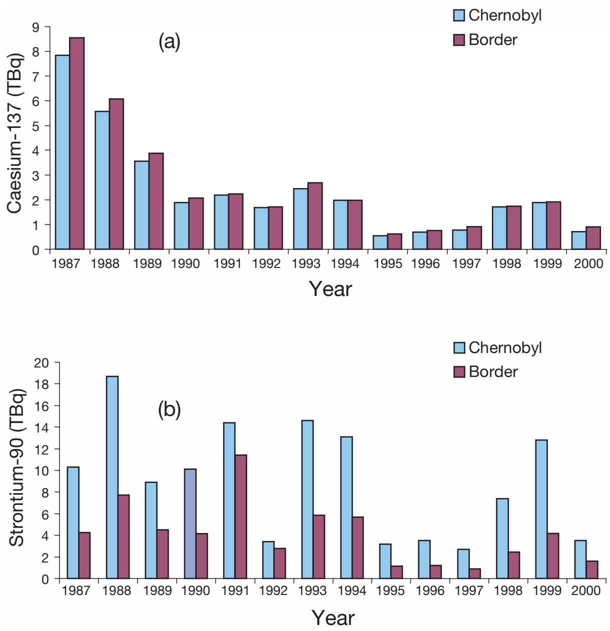

FIG. 4.25. Annual fluxes of (a) ^{137}Cs and (b) ^{90}Sr in the Iput and Besed Rivers near the Russian Federation–Belarus border.

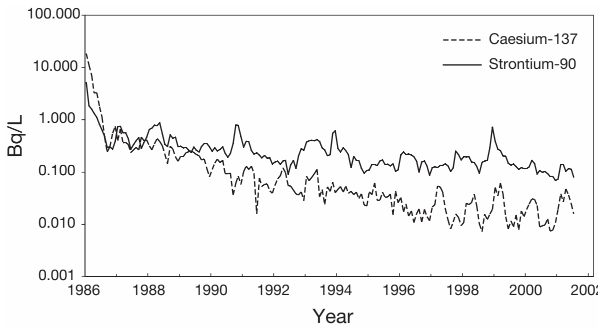

FIG. 4.26. Dynamics of radionuclide concentration in the measuring section of the Kiev hydropower plant, 1986–2001.

in the Dnieper River basin is not geared towards monitoring transboundary fluxes. In order to estimate these fluxes, various methods of time and space extrapolation have to be used. The accuracy of these methods seems to be sufficient for the current purpose, given that the transport of radioactivity across the borders of Belarus, the Russian Federation and Ukraine is very low. However, should an accident or incident occur, the deficiencies of the monitoring systems in the Dnieper River basin may preclude obtaining correct estimates of transboundary fluxes of radionuclides by the water pathway.

4.7. RADIONUCLIDES IN THE DNIEPER RESERVOIRS

4.7.1. Assessment of radionuclide influx into the cascade

The current state of radioactive contamination of the Dnieper reservoirs is determined first by the amount of radionuclides transferred by the rivers from the contaminated territories. From the moment that direct aerosol fallout on to the water surface ceased, the runoff from the contaminated watersheds on the Pripyat and upper Dnieper Rivers was the only significant source of radionuclide input into the reservoirs. The radionuclides enter these rivers mainly during periods of rain and snow melting in the contaminated territories (see Fig. 4.26) and during the periods of flooding of the river floodplain in the near zone of the Chernobyl nuclear power plant. The influence of other tributaries is unimportant.

The waters of the upper Dnieper River, though transporting some ^{137}Cs and ^{90}Sr, also dilute the more contaminated runoff waters of the Pripyat River. Another significant tributary influencing the dilution of contamination released from the Chernobyl nuclear power plant zone is the Desna River. Calculations showed that, on account of complete mixing of waters from the Pripyat River

and from the Dnieper River in the bowl of the Kiev reservoir, the concentration of ^{137}Cs in the water is reduced by a factor of two, and that of ^{90}Sr by a factor of almost three (mean annual assessments over a 15 year period of observations).

Table 4.19 shows annual data on the influx of ^{137}Cs and ^{90}Sr from various rivers into the Dnieper cascade.

The data on the dynamics of contamination of the above rivers show that the discharge of radioactivity with these rivers has significantly reduced over time, and substantial increases of radionuclide content (mainly ^{90}Sr) in the reservoir are observed only during periods of flooding.

Analysis of monitoring data reveals certain trends in radioactive contamination of the waters from the post-accident period. The main trend is the reduction of total radionuclide migration into the cascade of the Kiev reservoirs (Table 4.19). From 1987 until 1994, total ^{137}Cs migration via the Pripyat River decreased by a factor of 4.5; however, there was no trend in the migration of ^{90}Sr, although there were fluctuations from year to year. Accordingly, the structure of the radioactive runoff has changed: the contribution of ^{90}Sr has increased relative to ^{137}Cs (in 1987 the activity ratio ^{90}Sr:^{137}Cs was 0.8; in 1994 it was 4.0).

Figure 4.26 shows the trends in ^{90}Sr and ^{137}Cs concentration at the Kiev hydroelectric power station. Figure 4.27 shows corresponding data at the mouth of the Desna River. The large scatter in data for ^{137}Cs from the mid-1990s partly reflects the statistical errors in analysis at near-background concentrations.

4.7.2. Current state of the radioactive contamination of the reservoirs

The current state of the radioactive contamination of the Dnieper reservoirs is determined by the combined effect of the following factors:

TABLE 4.19. INFLUX OF CAESIUM-137 AND STRONTIUM-90 INTO THE CASCADE OF THE DNIEPER RESERVOIRS WITH RIVER WATER (TBq) (1986–2001)

	Pripyat River		Dnieper River		Desna River		Uzh River		Braginka, Teterev and Irpen Rivers	
	Caesium-137	Strontium-90	Caesium-137	Strontium-90	Caesium-137	Strontium-90	Caesium-137	Strontium-90	Caesium-137	Strontium-90
1986 (Jun.–Dec.)	21.8[a]	3.7[a]	15.4[a]	3.8[a]	(2.7[a])	(0.63)	(1.30)	(0.26)	(1.41)	(0.19)
1987	12.7	10.4	13.8	8.0	2.11	1.85	0.63	0.70	0.67	0.37
1988	9.5	18.7	9.3	5.1	1.33	2.44	0.56	0.48	0.70	0.37
1989	6.4	8.9	7.1	3.6	1.15	1.26	0.26	0.37	0.48	0.30
1990	4.6	10.1	5.1	3.7	0.85	1.78	0.30	0.70	0.30	0.26
1991	2.7	13.9	2.0	4.5	0.63	1.11	0.26	0.67	0.52	0.85
1992	1.7	4.4	1.3	0.7	0.26	0.74	0.22	0.15	0.22	0.30
1993	3.9	13.5	1.0	1.2	0.04	0.48	0.15	0.56	(0.2[a])	(0.2[a])
1994	3.3	11.0	1.0	2.8	0.04	0.56	0.22	0.67	(0.3[a])	(0.4[a])
1995	1.1	3.2	0.6	0.7	0.04	0.22	0.07	0.15	(0.1[a])	(0.2[a])
1996	1.4	2.8	—	—	—	—	—	—	—	—
1997	1.0	3.5	—	—	—	—	—	—	—	—
1998	1.4	5.9	—	—	—	—	—	—	—	—
1999	3.3	10.3	—	—	—	—	—	—	—	—
2000	1.6	3.3	—	—	—	—	0.09	0.19	0.1[b]	0.1[b]
2001	1.5	3.3	—	—	—	—	0.09	0.27	0.2[b]	0.2[b]
Total	67.1	101.5	56.6	34.1	9.18	11.1	3.96	4.70	4.81	3.33

[a] Ref. [4.42].
[b] Braginka only.
Note: Data in parentheses are an approximate assessment.

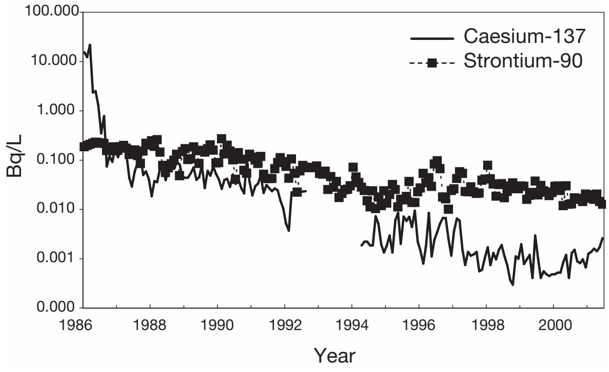

FIG. 4.27. Dynamics of ^{137}Cs and ^{90}Sr concentration at the mouth of the Desna River.

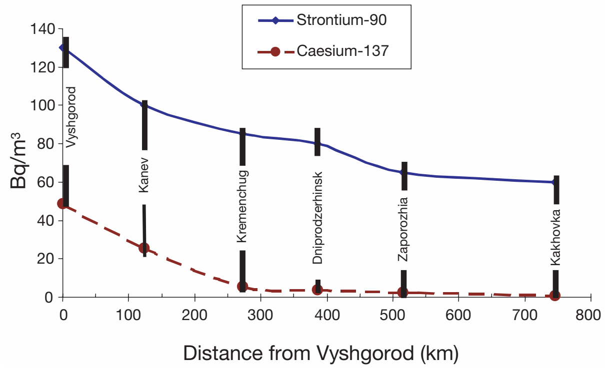

FIG. 4.28. Changes in concentration of ^{137}Cs and ^{90}Sr along the Dnieper River, July 2000.

(a) Continued wash-off of radionuclides of Chernobyl origin from the surface of the watersheds into the Dnieper River basin and, in particular, the discharge of the contaminated water from the Chernobyl nuclear power plant zone into the Pripyat River, which remains the main source of contamination of the Dnieper aquatic system.

(b) The peculiarities of the water balance within reservoirs in specific years and the regulation of flow through the cascade.

(c) Within reservoir processes that lead to redistribution of the radionuclides between the main components of the water ecosystem (the water solution, suspended alluvium, bottom sediments and biota).

(d) Other factors, including both self-cleaning of the water masses and their secondary contamination from sediments.

With regard to the system of the Dnieper reservoirs and the Dnieper estuary as a whole, the radionuclides in the soils and the rivers located in the CEZ may be called concentrated, since the main contamination enters the upper part of the Dnieper cascade via the Pripyat and upper Dnieper Rivers. Not more than 10% of the residual radioactivity from Chernobyl fallout enters the Dnieper reservoirs from the side tributaries. Of these, the most important is the influx from the Desna River. Insignificant quantities of radionuclides of Chernobyl origin enter the Dnieper River below Kiev.

The radioactivity that enters the upper part of the Dnieper cascade reaches the Black Sea after approximately one year [4.43]. Along the way the concentration of radionuclides is reduced due to dilution from clean side tributaries and due to sorption of the radionuclides on to the bottom sediments.

The reservoirs of the Dnieper cascade are essentially huge sedimentation tanks. The slow passage of water through the cascade creates ideal conditions for accumulation of radionuclides and other pollutants in all components of the ecosystem of the reservoirs.

As a consequence, the ^{137}Cs concentration in the river water is reduced by two orders of magnitude along the way from the upper part of the Dnieper cascade to the Dnieper mouth. According to data of the Hydrometeorological Service of Ukraine, from 1994 onwards the levels of ^{137}Cs contamination decreased to the levels of the pre-accident years (less than 1 Bq/m^3). Hence, due to the self-cleansing processes, practically all the ^{137}Cs entering the Dnieper reservoirs from 1994 is deposited in the bottom sediments. For the entire post-accident period in the ecosystem of the reservoirs and the Dnieper–Bug estuary, more than 99% of the ^{137}Cs that entered the Pripyat and upper Dnieper Rivers was removed on to sediments. Figure 4.28 shows the results of monitoring in 2000, which confirm the current trend in ^{137}Cs and ^{90}Sr concentrations through the reservoir cascade.

Data on the dynamics of radioactive contamination of the Dnieper reservoirs during the post-accident years are presented in many published works [4.7, 4.12, 4.44]. The main result of these works was the synthesis of data on the temporal and spatial dynamics of radionuclides of Chernobyl origin in the reservoirs as a basis for justification of the water protection works in the basin and for further use in radioecological research. Figure 4.29 shows the trend in ^{137}Cs concentration with time in the upper (at Vyshgorod) and lower (at Kakhovka) reservoirs of the cascade. The activity of ^{137}Cs in the

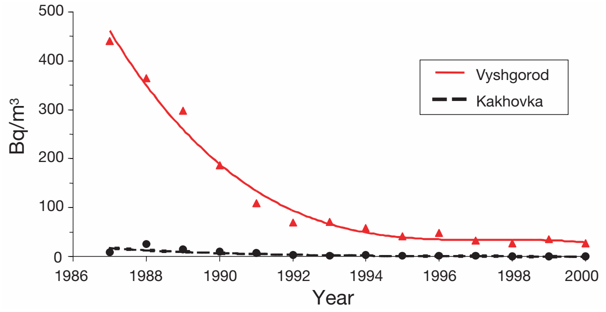

FIG. 4.29. Changes in ^{137}Cs concentration in the upper and lower parts of the Dnieper cascade.

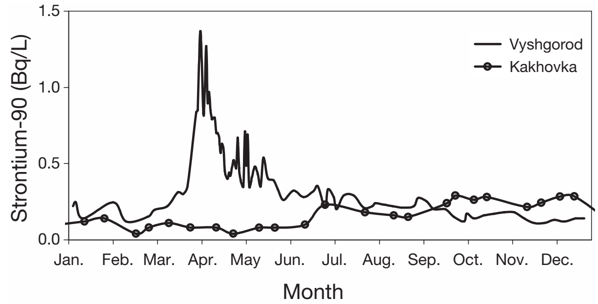

FIG. 4.30. Strontium-90 activity concentration movement in the Kiev and Kakhovka reservoirs in 1999.

waters of the Dnieper mouth in 2000–2001 was 0.3–0.9 Bq/m^3. This corresponds to the values existing before the Chernobyl accident [4.45]. Generally, more than 90% of ^{137}Cs was in the dissolved form.

Owing to the higher mobility of ^{90}Sr, the degree of its deposition (50–70%) within the Dnieper reservoirs is significantly lower than that of ^{137}Cs. One of the main reasons for the non-exchangeable behaviour of ^{90}Sr from the water column is its strong chemical fixation in the shells of growing molluscs (strontium is the chemical analogue of calcium). This is why the maximum content of ^{90}Sr in the bottom sediments was observed on the sites of mollusc colonies and in sediments containing shell debris.

The ^{90}Sr concentration in Dnieper River water is reduced by a factor of 1.5–3 from Chernobyl to the Kakhovka reservoir (according to data averaged over a year). This is determined mainly by the dilution of Pripyat waters with clean waters from the upper Dnieper River and the side tributaries. The mixing action of the Dnieper reservoirs as the ^{90}Sr passes along the cascade becomes apparent by the gradual reduction of the peak concentrations and by the offset of this peak with time. Even very high peak concentrations of ^{90}Sr in the waters of the Pripyat River and Kiev reservoir are suppressed by the time the peak reaches the Kremenchug reservoir, and in the Kakhovka reservoir one may observe only gradual fluctuations in the concentration of ^{90}Sr.

Over recent years the amplitude of the within year variations of ^{90}Sr activity concentrations at the mouth of the Dnieper River has significantly changed. This is a result of the reduction of release of ^{90}Sr into the Dnieper cascade due to natural processes (radioactive decay, migration into the soil depth, etc.) and the effectiveness of engineering works in isolating the most contaminated sites on the Pripyat floodplain within the CEZ [4.46].

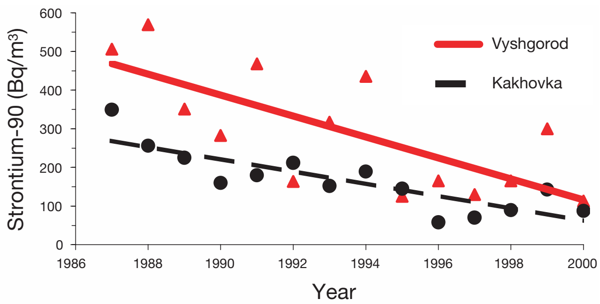

FIG. 4.31. Changes in average annual ^{90}Sr concentration in the upper (Vyshgorod) and lower (Novaya Kakhovka) parts of the cascade of the Dnieper reservoirs over time.

The situation observed in 1999 was an exception to this trend. In that year, significant quantities of ^{90}Sr were washed out into the cascade from regions of significantly contaminated flood prone sites beside the Pripyat River in the near zone of the Chernobyl nuclear power plant. The signal of radioactively contaminated waters was followed to the Kakhovka reservoir during 1999. Owing to the high river flow rates in March–June 1999, fast movement of the contaminated water down the Dnieper River was observed, and, by mid-July 1999, this front had reached the Black Sea (Fig. 4.30). The maximum value of ^{90}Sr activity measured during that period in the Dnieper River at Novaya Kakhovka was 287 ± 60 Bq/m^3, being three to four times higher than the levels of contamination observed during the previous years. This observation further demonstrates that the modern source of radioactive contamination of the Dnieper waters is the flood prone territories of the Pripyat River and other sources of contamination in the near zone of the Chernobyl nuclear power plant. However, the repetition of such situations, which only happen at times of major flooding, occurs only once in 10–15 years on average.

Figure 4.31 shows the trend in average annual ^{90}Sr concentration in the Dnieper reservoirs since

the Chernobyl accident. To some extent it reflects the effect of various events that affected the floodplains in the near zone of the Chernobyl nuclear power plant, viz.:

(i) Rain inundation in July 1988;
(ii) Ice jam and winter inundation in 1991;
(iii) Rain inundation in July 1993;
(iv) Ice jam and winter inundation in 1994;
(v) High spring flooding in 1999.

Based on regular measurements of ^{137}Cs and ^{90}Sr concentrations performed by the Hydrometeorological Service of Ukraine at the cascade of the Dnieper reservoirs, the mean monthly and mean annual concentrations of these radionuclides in the reservoirs, and mean monthly and mean annual values of radionuclide outflow, have been calculated. This enables reliable estimates to be made of radionuclide transport along the river, and timely forecasting of water quality and issuing of recommendations to water consumers, who are located predominantly in the middle and lower part of the Dnieper water system. Table 4.20 contains an example of such a calculation for the lower part of the Kakhovka reservoir (the Dnieper–Novaya Kakhovka station), while the data in Table 4.21 show the yearly average concentrations and flows into the Dnieper–Bug estuary and then into the Black Sea.

4.7.3. Current state of radioactive contamination of the bottom sediments

The bottom sediments of the reservoirs are an important component that, in some respects, determines the aquatic ecosystem. The accumulated data on the distribution of radionuclides in the system (water suspension–bottom sediments) after the Chernobyl nuclear power plant accident revealed the leading role of the sedimentation processes in the self-cleaning of the water column. On one hand, these processes positively influence the water quality; on the other hand, sediment accumulation is the main factor in the formation of the secondary contamination of the bottom sediments in which the radionuclides and other pollutants are deposited.

In recent years, as the influx of radionuclides into the system has decreased, the role of the bottom sediments as a potential source of secondary contamination of the Dnieper waters has become more important. For our purposes, the main characteristics of the bottom sediments are the radionuclide content per unit of dry mass (Bq/kg), the density of contamination (expressed in Bq/m^2 or

TABLE 4.20. MEAN MONTHLY CONCENTRATIONS (Bq/m^3) AND VALUES OF MONTHLY OUTFLOW (GBq) OF CAESIUM-137 AND STRONTIUM-90 THROUGH THE MEASURING SECTION OF THE DNIEPER–NOVAYA KAKHOVKA STATION IN 1999

	Dnieper River drainage (km^3)	Caesium-137		Strontium-90	
		Bq/m^3	GBq	Bq/m^3	GBq
January	5.62	0.65 ± 0.09	3.65	131 ± 24.0	736.5
February	5.62	0.43 ± 0.26	2.42	79.0 ± 30.0	444.1
March	7.16	0.32 ± 0.08	2.29	95.5 ± 19.0	683.7
April	8.28	0.64 ± 0.09	5.30	77.0 ± 30.0	637.5
May	8.97	0.77 ± 0.13	6.91	82.5 ± 17.0	740.0
June	4.04	0.68 ± 0.07	2.75	167 ± 65.0	675.3
July	2.78	1.15 ± 0.37	3.20	200 ± 40.0	556.6
August	1.42	0.75 ± 0.08	1.06	157 ± 35.0	222.5
September	1.42	0.60 ± 0.06	0.85	263 ± 50.0	372.9
October	3.00	0.40 ± 0.08	1.20	272 ± 55.0	817.4
November	3.88	0.38 ± 0.10	1.49	229 ± 40.0	888.5
December	4.81	0.30 ± 0.03	1.44	285 ± 70.0	1370.9
Total	57	0.57	32.6	142.8	8183

TABLE 4.21. ESTIMATED VALUES OF CAESIUM-137 AND STRONTIUM-90 INFLOW TO THE BLACK SEA (DNIEPER–BUG ESTUARY) FROM THE DNIEPER RIVER

	Dnieper runoff (km^3)	Strontium-90		Caesium-137	
		Bq/m^3	TBq	Bq/m^3	TBq
1986 (Jun.–Dec.)	20.6	34.1 ± 5.5	0.7	28.4 ± 4.3	0.59
1987	36.4	349 ± 52	12.7	9.1 ± 0.5	0.33
1988	45.8	256 ± 18	11.7	25.2 ± 1.5	1.15
1989	34.1	225 ± 14	7.68	14.3 ± 1.4	0.49
1990	37.1	160 ± 10	5.93	10.3 ± 0.4	0.38
1991	43.4	179 ± 23	7.78	6.8 ± 0.7	0.30
1992	24.9	208 ± 21	5.20	2.8 ± 0.2	0.070
1993	39.3	104 ± 5	4.07	1.8 ± 0.3	0.070
1994	48.9	129 ± 10	6.30	2.3 ± 0.3	0.063
1995	36.3	51.7 ± 6.7	1.88	1.3 ± 0.2	0.048
1996	29.0	57.6 ± 6.9	1.67	0.77 ± 0.18	0.022
1997	36.6	64.5 ± 7.1	2.36	0.82 ± 0.17	0.030
1998	58.5	90.1 ± 20.4	5.27	0.57 ± 0.28	0.034
1999	57.0	143 ± 17	8.18	0.57 ± 0.17	0.033
2000	40.9	95.1 ± 30.0	3.89	0.56 ± 0.08	0.023

Note: The data include regular measurements carried out by laboratories of the Hydrometeorological Service of Ukraine, the Ministry of Health and the Water Management State Committee of Ukraine (total 700 samples). To refine the estimates of radionuclide outflow from the Dnieper River into the Black Sea, data from irregular observations of the UHMI (1986–1999), SPA Typhoon (1986–1987), the Institute of Biology of the Southern Seas (1986–1988) and the Institute of Hydrobiology of the National Academy of Sciences of Ukraine (1987–1989) were also used.

Ci/km^2), the sediment composition, the particle size distribution and the rate of silt accumulation.

The first investigations of the radioactive contamination of the Kiev reservoir bottom were performed in May 1986 by experts from the Institute of Hydrobiology of the Academy of Sciences of Ukraine. These first surveys showed the extremely heterogeneous nature of the radioactive contamination of the bottom. According to the preliminary assessments, the total inventory of ^{137}Cs in the bottom sediments of the reservoir was estimated as up to 81 TBq, and that of ^{90}Sr was about 30 TBq.

The UHMI started investigations of the radioactive contamination of the bottom of the reservoirs in 1987, and completed mapping in the period 1989–1991 [4.47]. These maps are still the basis for the current understanding of the content of radiocaesium in the bottom sediments. Additional studies of the vertical structure of radionuclide distribution in the bottom sediments were performed by the UHMI in the period 1991–1996 [4.7].

Examples of the maps of the bottom contamination of the Kiev, Kanev and Kremenchug reservoirs are presented in Figs 4.32–4.34 (note that the units of measurement are Ci/km^2). Contamination of the reservoirs in the lower part of the Dnieper River is significantly less, and nowadays is difficult to map due to redistribution of the sediments.

Due to insufficient data and extreme heterogeneity of the spatial distribution, mapping of ^{90}Sr was not performed and only estimates of the total activity of this radionuclide in the reservoirs were obtained.

Analysis of data on the distribution of radionuclides with depth in the bottom sediments, the granulometric distribution and composition of the bottom sediments, and the forms of radionuclides contributes to an understanding of the scales and regularities of the formation of radioactive contamination of the bottom. As has already been noted, the initial radioactive contamination of the bottom occurred in the period of the intensive fallout on the

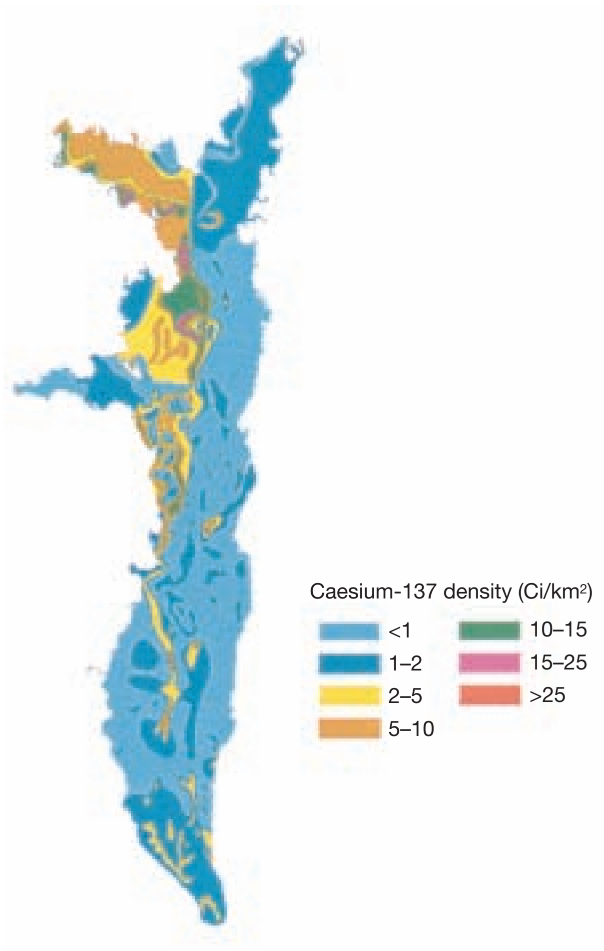

FIG. 4.32. Distribution of ^{137}Cs (Ci/km^2) in the bottom sediments of the Kiev reservoir, 1990.

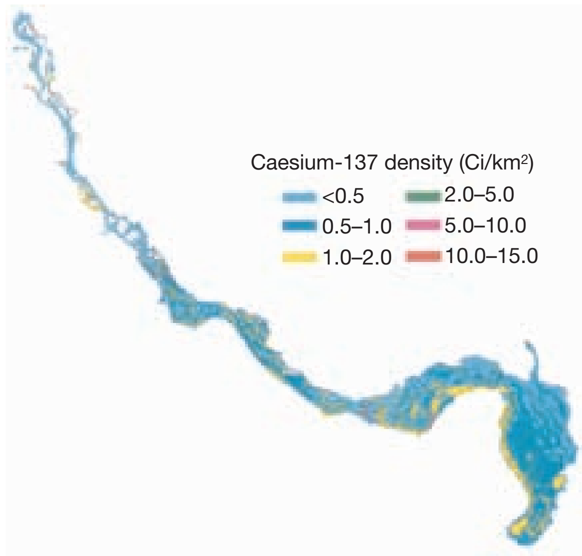

FIG. 4.33. Distribution of ^{137}Cs (Ci/km^2) in the bottom sediments of the Kanev reservoir, 1995.

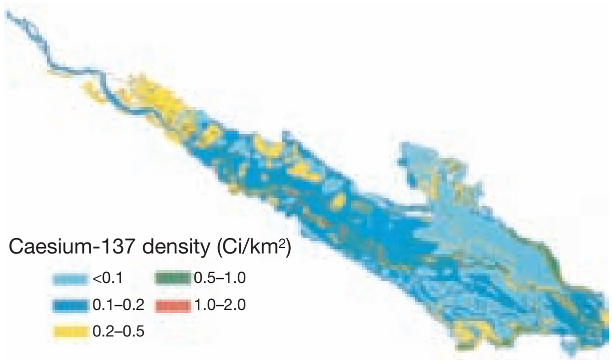

FIG. 4.34. Distribution of ^{137}Cs (Ci/km^2) in the bottom sediments of the Kremenchug reservoir, 1994.

water surface and the further fast (within several days) deposition on the bottom. For sites far down the cascade, such as the Kakhovka reservoir, aerosol fallouts became the main factor of radioactive contamination since, starting in 1987, insignificant amounts of ^{137}Cs were transported from the upper part of the basin.

The main radioactive contamination of the bottom sediments was completed in 1988, when the migration of radionuclides with the waters of the main tributaries dropped off significantly. The process of redistribution of the radioactive contamination along the bottom then became apparent. This process occurs due to hydrodynamic factors (drainage and drift fluxes, storm impact on the bottom) that remove the fine sediments with the highest contamination from shallow water into the zones of stable sediment accumulation. In such zones of all reservoirs, the maximum densities of the bottom sediment contamination are observed. Analysis of the ^{137}Cs vertical distribution within the bottom sediments shows that, in all reservoirs in the zones of stable sediment accumulation, the layer of maximum contamination in 1986 is gradually being buried. Thus, in the deep parts of the Kiev, Kakhovka and Kremenchug reservoirs, the peaks of ^{137}Cs activity in 1986–1987 are presently located at depths of 40 cm or more below the bottom surface (Fig. 4.35). The possibility of radionuclides returning to the water column is reduced with time.

The ability of ^{137}Cs to be strongly sorbed by finely dispersed mineral and organic substances prevents its diffusion and penetration into the deepest sediments. Even at those parts of the bottom consisting of well penetrating sandy deposits, the activity of ^{137}Cs quickly reduces with depth from the surface (Fig. 4.36).

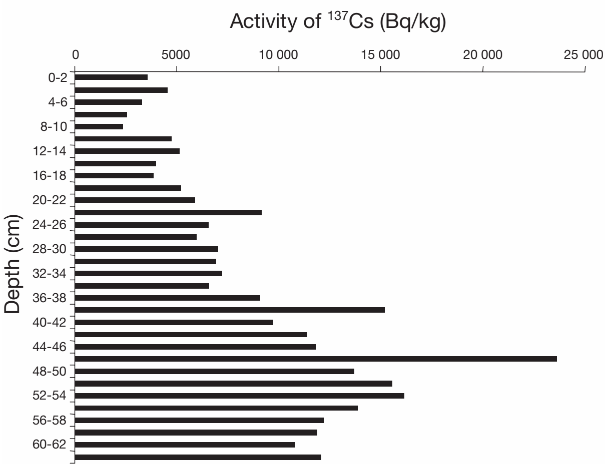

FIG. 4.35. Caesium-137 in the deep silt deposits in the upper part of the Kiev reservoir, July 2000.

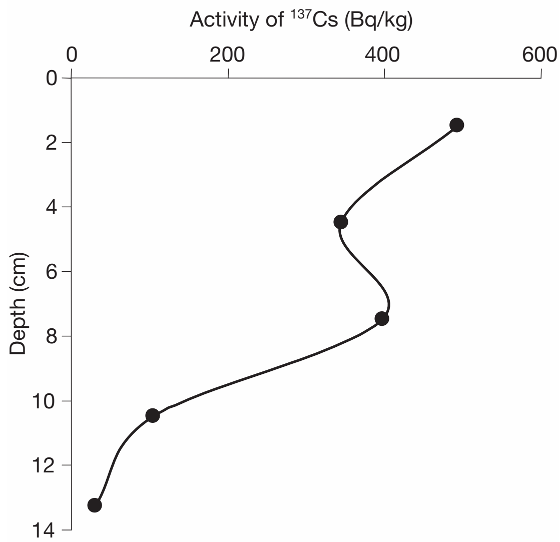

FIG. 4.36. Caesium-137 depth distribution in the sand deposits of the Kiev reservoir, May 1991.

The current activity of ^{137}Cs radionuclides in the bottom sediments can be determined from the surveys. Table 4.22 shows the dynamics of ^{137}Cs inventories in the bottom sediments of the Kiev and Kakhovka reservoirs. The calculations show that, since 1991, the ^{137}Cs inventories in the bottom sediments of the Kiev reservoir are falling, since the annual input does not compensate for the losses due to radioactive decay. In the Kakhovka reservoir, where the contamination occurred mainly from aerosol fallout on the water surface in 1986, the inventories of ^{137}Cs in the bottom sediments have been steadily declining since 1987.

TABLE 4.22. CALCULATIONS OF THE TOTAL INVENTORY (TBq) OF CAESIUM-137 IN THE BOTTOM SEDIMENTS OF THE KIEV AND KAKHOVKA RESERVOIRS

	Kiev reservoir			Kakhovka reservoir		
	Afflux	Integral inventory (no decay)	Inventory considering decay	Afflux	Integral inventory (no decay)	Inventory considering decay
1986	59.2	59.2	58.9	7.22	7.22	7.14
1987	11.9	71.1	69.3	0.63	7.84	7.62
1988	5.9	77.0	73.5	0.06	7.92	7.51
1989	4.8	81.8	76.6	0.10	8.03	7.44
1990	4.7	86.5	79.6	0.08	8.10	7.33
1991	1.7	88.2	79.4	0.04	8.14	7.22
1992	1.6	89.8	79.1	0.05	8.21	7.10
1993	2.1	91.9	79.4	0.06	8.25	6.99
1994	2.0	93.9	79.6	0.10	8.36	6.92
1995	0.7	94.7	78.5	0.07	8.44	6.85
1996	1.0	95.7	77.7	0.03	8.44	6.70
1997	0.6	96.3	76.6	0.01	8.47	6.55
1998	1.3	97.6	76.1	0.05	8.51	6.48
1999	2.4	100.0	76.8	0.07	8.58	6.40
2000	1.3	101.3	76.3	0.06	8.62	6.29

TABLE 4.23. CAESIUM-137 IN THE BOTTOM SEDIMENTS OF THE DNIEPER RESERVOIRS (JANUARY 1995)

Reservoir	Inventory (TBq)	Averaged density of contamination (kBq/m^2)
Kiev	80 ± 17	86 ± 6
Kanev	18 ± 3	31 ± 25
Kremenchug	26 ± 3	13 ± 1
Dniprodzerzhinsk	4.3 ± 0.4	7.4 ± 0.7
Dnieper	2.2 ± 0.7	5.6 ± 1.9
Kakhovka	6.8 ± 0.7	3.1 ± 0.4
Total in cascade	136 ± 26	—

Table 4.23 shows the inventory of ^{137}Cs in the bottom sediments of the Dnieper reservoirs and the averaged densities of the bottom contamination of each reservoir as of January 1995.

As noted above, the mapping of the bottom sediment contamination with ^{90}Sr was problematic. Owing to the low sorption of ^{90}Sr on to solid particles, no regularities in its spatial distribution on the bottom of the reservoirs were discovered. However, where there is an accumulation of shells of molluscs and other carbonate deposits on the bottom, there are higher levels of ^{90}Sr. It is not excluded that the strong fixation of ^{90}Sr in the carbonate structure of folds is one of the main factors of irretrievable removal of this radionuclide from the water column on to the bottom.

At present, the contaminated bottom sediments in the reservoirs do not influence significantly the secondary radioactive contamination of the water and aquatic organisms. In all places the deposition of cleaner sediments over the more contaminated ones is observed. Thus the general rule for exploitation of the reservoirs (mainly Kiev) is to minimize scooping and mechanical operations at the places with increased bottom contamination. The natural processes of self-cleaning are working in all the reservoirs. As a consequence, there is a gradual reduction in the radionuclide levels in fish and other aquatic species living in the reservoirs.

Results of modelling of the sediment redistribution following a major flood are given in Section 9.3.6.

4.8. CONCLUSIONS

(a) The levels of ^{137}Cs and ^{90}Sr in flowing rivers are now well below the permissible levels set by the national authorities and below internationally acceptable levels for drinking water.

(b) Surface water runoff from watersheds and floodplains contaminated with ^{90}Sr remains the major contributor to contamination of the Dnieper reservoirs. The main sources contributing to radionuclide releases into the Dnieper cascade are located within the CEZ. The water remedial actions carried out during recent years (1993–2000) significantly reduced actual and potential fluxes into the river.

(c) Almost all the ^{137}Cs washed out of contaminated areas is immobilized in bottom sediments within the reservoirs of the Dnieper River. The impact of these sediments is low and will decline further with decay and further deposition of sediments on top of the contaminated sediments. The overall strategy should be to leave these sediments as is and avoid processes that will lead to their resuspension.

(d) Identification of the main sources within the Chernobyl zone shows that the heavily contaminated floodplain areas still remain the main source for releases. The waste disposal sites in the flood prone areas are of secondary priority for possible remedial actions.

(e) Monitoring systems have been developed for the river systems and are important inputs to the decision making process on possible further water protection measures in the Chernobyl area.

(f) Monitoring data are collected by various agencies for different purposes; different methodologies are used, some of which are outdated. There needs to be harmonization of results between the various organizations engaged in monitoring.

(g) Mathematical models have been developed to describe the wash-off of radioactivity from

contaminated land. These models can be used to predict the discharge of radioactivity into rivers and reservoirs from knowledge of the rainfall distribution.

(h) Only a small fraction of the radioactivity deposited on ground via fallout has entered the Dnieper River system, and most of the ^{137}Cs and ^{90}Sr will decay in the ground.

(i) Levels of ^{137}Cs in the lower sections of the Dnieper River have returned to pre-Chernobyl accident levels. Strontium-90 is more persistent because it does not adsorb as readily on to sediments.

(j) Lakes with no regular inflows and outflows still present a radiological problem that will continue for some time. There is a need for improved understanding of processes occurring within lakes, especially transfer to fish.

(k) Transboundary movement of radionuclides from the Chernobyl accident was greatest prior to 1990. The annual flows of ^{137}Cs across national borders have continued to decline steadily, whereas those of ^{90}Sr continue to fluctuate, depending on the extent of flooding of contaminated land (especially the floodplain area of the CEZ). Currently, the annual flow of ^{137}Cs into the Black Sea is negligible, whereas 1–8 TBq of ^{90}Sr reaches the Black Sea.

(l) There is a need for improved understanding of the ^{90}Sr inventory in sediments and ^{90}Sr fixation processes. Strontium-90 becomes more important with time because of its greater mobility.

(m) The large database developed by SPA Typhoon, the UHMI and the RCREM is very useful in understanding and interpreting data, and should be maintained. Ideally it should be expanded to include aquatic species data and data from the lower parts of the Dnieper River.

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5. NUCLEAR POWER PLANTS

5.1. SCOPE

Section 3.2 gives general information on the location and potential radiological impacts of nuclear power plants in the Dnieper River basin.

This section is an overview of the nuclear power plants in, and in the vicinity of, the Dnieper River basin. It contains a description and assessment of operational characteristics, safety features, licensing status, management of spent fuel and radioactive waste, normal releases to the environment and the status of safety improvements and emergency preparedness.

Section 8.2 provides information on radiation doses received by the general public living in the vicinity of operating nuclear power plants. Section 9.6 considers releases from a hypothetical severe nuclear accident at a reactor close to the Dnieper River.

5.2. NUCLEAR REACTORS IN THE REGION

5.2.1. Russian reactors within the Dnieper River basin

In the Russian part of the Dnieper River basin are seven reactor units in operation at two locations: Kursk and Smolensk (see Table 5.1). All reactors are graphite moderated, light water cooled reactors of the RBMK type (the same type as the reactors at Chernobyl) with a nominal capacity of 1000 MW(e). In this design the fuel elements are contained within vertical steel tubes surrounded by graphite blocks. The steam is separated and flows directly to the turbines. The reactor loading is about 200 t of 2–4% enriched uranium.

5.2.1.1. Kursk nuclear power plant

The Kursk nuclear power plant, comprising four reactors, is located on the left bank of the Seim River, in its middle course (see Fig. 3.1). The energy workers' town is Kurchatov. It is situated in the central Chernozem area, 30 km to the west of Kursk city. The climate in the region is temperate continental with a mean annual air temperature of 5.3°C. Eastern winds prevail during winter; the rest of the time southern, south-eastern and south-western winds prevail.

A cooling pond constructed on the Seim River provides the water supply for the power plant. Its average volume, area, depth and water level are 94.6×10^6 m^3, 21.5×10^6 m^2, 4.4 m and 154.5 m, respectively. The water level in the pond is maintained by pumping water from the Seim River with a maximum flow rate of 14 m^3/s [5.2]. The design parameters of a second cooling pond, which is under construction for the fifth reactor, are 45.7×10^6 m^3 (volume), 8.9×10^6 m^2 (area), 5.1 m (depth) and 155 m (water level).

5.2.1.2. Smolensk nuclear power plant

The Smolensk nuclear power plant is located on the left bank of the Desna River in its upper

TABLE 5.1. OPERATING NUCLEAR POWER REACTORS IN THE DNIEPER RIVER BASIN REGION OF THE RUSSIAN FEDERATION [5.1]

	Unit number	Generation	Year of commissioning	Planned shutdown year
Kursk	1	I	1976	2006–2011[a]
	2	I	1979	2009–2014[a]
	3	II	1983	2013
	4	II	1985	2015
Smolensk	1	II	1982	2012
	2	II	1985	2015
	3	II	1990	2020

[a] Exact time of shutdown is yet to be decided.

course (see Fig. 3.1). The energy workers' town is Desnogorsk. It is situated in a subzone of mixed forests. It lies near the upper reaches of the Dnieper River. The climate in the region is temperate continental. The mean monthly temperature of the warmest month (July) is +17.9°C; the mean monthly temperature of the coldest month (January) is –8.5°C. The mean annual precipitation is 610 mm, two thirds of which falls during ice free periods. Sustainable snow cover is formed on average in the beginning of December and breaks during the first days of April.

A cooling pond constructed on the Desna River provides the water supply for the power plant. Its average volume, area and depth are 210×10^6 m^3, 32.2×10^6 m^2 and 6.5 m, respectively. The water exchange constant is about 0.8 a^{-1}.

5.2.2. Ukrainian reactors

Currently there are 13 nuclear power reactors operating in Ukraine at four locations (see Table 5.2); ten are in the Dnieper River basin (see Fig. 3.1). These reactors supply 43–45% of Ukraine's electricity. Following the shutdown of the last of the Chernobyl reactors in December 2000, all operating reactors are PWRs of Russian design.

There are three nuclear power reactors (at the South Ukraine nuclear power plant) in the Bug River basin, which adjoins the Dnieper River basin. The South Ukraine nuclear power plant is included in this discussion because of its possible impact on the Dnieper River basin via airborne releases in the event of a nuclear accident.

Additionally, one 1000 MW(e) nuclear power reactor is being commissioned at Rovno, while another is under construction at Khmelnitski.

5.2.2.1. Zaporozhe nuclear power plant

The Zaporozhe nuclear complex, shown in Fig. 3.4, comprises six 1000 MW reactors, making it one of the largest nuclear power plants in the world. The Kiev Energoproject Institute developed the design. The plant site is situated on the left bank of the Kakhovka reservoir opposite the town of Nikopol. The energy workers' town is Energodar.

The water source for the nuclear power plant is the Kakhovka reservoir. Water is provided by a combination of a cooling pond, cooling towers and a spray evaporation system. The cooling pond has an area of 8.2 km^2 and a volume of 47×10^6 m^3. The cooling pond is connected to the Kakhovka reservoir by entrance and discharge canals 4 km long and 130 m wide (see Fig. 3.4). Water losses are replenished by make-up water drawn from the reservoir. In 1999 the cooling ponds were replenished with 143×10^6 m^3 of water from the reservoir, and 88×10^6 m^3 was discharged back to the reservoir to prevent an accumulation of dissolved salts.

5.2.2.2. Rovno nuclear power plant

The Rovno nuclear power plant is located in the north of the Rovno region, close to the energy workers' town, Kuznetsovsk. It is the only nuclear power plant in Ukraine that employs cooling towers

TABLE 5.2. OPERATING NUCLEAR POWER REACTORS IN UKRAINE

	Gross capacity (MW(e))	Type	Commissioning date
Zaporozhe 1	1000	WWER-1000	10 October 1984
Zaporozhe 2	1000	WWER-1000	2 July 1985
Zaporozhe 3	1000	WWER-1000	10 December 1986
Zaporozhe 4	1000	WWER-1000	24 December 1987
Zaporozhe 5	1000	WWER-1000	31 August 1989
Zaporozhe 6	1000	WWER-1000	19 October 1995
Rovno 1	402	WWER-440	31 December 1980
Rovno 2	416	WWER-440	30 December 1981
Rovno 3	1000	WWER-1000	24 December 1986
Khmelnitski 1	1000	WWER-1000	31 December 1987
South Ukraine 1	1000	WWER-1000	22 December 1982
South Ukraine 2	1000	WWER-1000	6 January 1985
South Ukraine 3	1000	WWER-1000	20 September 1989

as the sole form of cooling. One cooling tower is used for the two smaller units (Rovno 1 and 2), while two are used for the largest unit (Rovno 3).

The Rovno 4 unit has been under construction, with interruptions, since 1986.

The water flow for the reactors is obtained directly from the Styr River without any regulating construction on the river. The average volume of replenishment is 36–38 × 10^6 m^3/a. According to an environmental impact assessment [5.3], the influence of the four reactors on the river flow will be small and the water supply is guaranteed.

5.2.2.3. Khmelnitski nuclear power plant

At present, the Khmelnitski nuclear power plant consists of only one reactor, but another is under construction. The design was developed by the Kiev Energoproject Institute. The site is located on the right bank of the Horyn River in the north-west part of the Khmelnitski region, almost on the boundary with the Rovno region. The energy workers' town is Neteshin.

The water supply for the Khmelnitski nuclear power plant is a specially constructed cooling pond located on a small river, the Gniloy Rog, that is a tributary of the Viliya River, which, in turn, flows into the Horyn River and finally the Pripyat River. The surface area of the cooling pond is 20 km^2 and the working volume is 88 × 10^6 m^3.

The water is replenished from the Horyn River. In order to reduce the negative influence of the Khmelnitski nuclear power plant on the Horyn River, the water intake for replenishment is carried out when the river flow exceeds 6 m^3/s during the period from October until April.

After commissioning of Khmelnitski nuclear power plant unit 2, the reduction of the Horyn River discharge will be about 33 × 10^6 m^3/a, which is equivalent to an average expenditure of 1.05 m^3/s. Investigations performed for the environmental impact assessment for Khmelnitski nuclear power plant unit 2 showed that this value is not large in comparison with the average river flow rate (16.4 m^3/s) [5.3].

5.2.2.4. South Ukraine nuclear power plant

The design of this nuclear power plant was developed by the Kharkov Energoproject Institute. The plant is located on the left bank of the southern Bug River approximately midway between Pervomaisk and Voznesensk. The energy workers' town is Yuzhnoukrainsk.

The water supply for the power plant is provided by a specially constructed cooling pond built on the small Tashlyk River, which flows into the southern Bug River. The cooling pond has an area of 8.6 km^2 and a storage volume of 86 × 10^6 m^3. The pond is quite deep, up to 38 m, and there is a considerable difference in temperature between the lower and upper layers.

Initially it was envisaged that the nuclear power plant would function as a component of an energy complex that included the Tashlyk hydroelectric power station. According to the concept, water from the cooling pond would be discharged through the hydroelectric station. However, the accident at Chernobyl caused a revision of the design. In particular, it was decided not to allow discharge of water from the cooling pond. Due to this decision, the thermal load on the cooling pond was quite high, and the discharge temperature reached 38–40°C. Owing to this restriction, the overall nuclear power plant capacity has been restricted to 1.8 GW.

5.2.3. Ignalina nuclear power plant, Lithuania

There are no nuclear power plants in the Republic of Belarus; however, the Ignalina nuclear power plant is located about three miles from the western border of Belarus. Consequently, the 30 km zone extends into Belarusian territory. The power plant is constructed on the southern side of Lake Drukshiai, 40 km from the town of Ignalina.

There are two nuclear reactors (Ignalina 1 and 2), both Soviet designed RBMK-1500 reactors with a nominal gross power of 1500 MW. These are the largest nuclear power reactors in the world. The safety of the reactors has been a cause of concern in Europe, and a number of international safety studies have been undertaken, resulting in many safety upgrades. In return for funding from the European Union, it has been decided to shut down unit 1 in 2005 and unit 2 in 2009.

Releases to surface waters from the Ignalina nuclear power plant do not enter the Dnieper River basin; however, for about 100 days per year winds from the north-west and west prevail, so that radioactive fallout could reach the Dnieper catchment in the event of an accident.

5.3. SAFETY FEATURES OF NUCLEAR REACTORS

This section gives an overview of the main safety features of the nuclear reactors in the Dnieper River basin.

5.3.1. Russian Federation

Figure 5.1 shows the important features of RBMK type reactors. Instead of a reactor pressure vessel containing the reactor core with the fuel elements and cooling water, the core is made up of either 1693 (first generation) or 1661 (second generation) pressure tubes. This design allows for on-load refuelling and thus high availability. The pressure tubes contain the fuel elements, which are cooled by water flowing through the channels. These channels are contained in a large volume of graphite, which is capable of absorbing and storing large amounts of energy. The water passing through the pressure tubes is heated to a water–steam mixture. The steam is separated from the water in four large steam drums and then passed on to the turbine for electricity production (see Fig. 5.2). This arrangement means that, similar to boiling water reactors, there is no secondary circuit and the water passing through the core also passes through the turbine in the form of steam.

The original design suffered from a substantial positive reactivity coefficient under certain conditions, exacerbated by an insufficient negative reactivity insertion capability, allowing a runaway effect of neutron power. Overpressurization from a simultaneous multiple pressure tube rupture could cause lifting of the reactor cavity cover, leading to rupturing of all the remaining pressure tubes. These two effects are the basic physical phenomena that caused the Chernobyl accident.

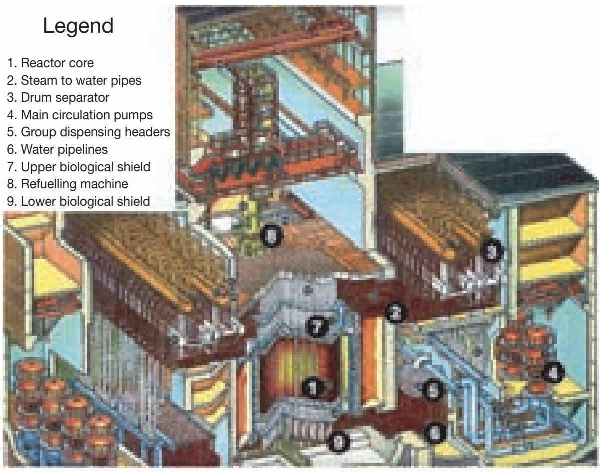

FIG. 5.1. Main features of the RBMK-1000 reactor.

After the Chernobyl accident, the positive reactivity coefficient was reduced in all RBMK reactors, the reactor shutdown system was improved and the venting capacity of the reactor cavity was increased.

Another specific feature of RBMKs is that instead of a containment structure they have a compartment system for the purpose of localizing accident conditions. This feature has a very limited capability in the first generation plants.

The first two units (Kursk 1 and 2) are first generation reactors based on designs developed in the 1960s, while the remainder belong to the second generation, with improved safety features. Since the Chernobyl accident a considerable amount of work has been undertaken to improve the safety of RBMK reactors and to exclude the possibility of an accident like the one at Chernobyl [5.4].

The first generation RBMKs had a very limited range of primary pipe break design basis accidents (DBAs), which was recently extended to cover breaks up to 300 mm. In contrast, it was possible to extend the DBA for second generation RBMKs to a diameter of 900 mm. The accident localization system (ALS) for first generation plants is limited to the reactor cavity, whereas for second generation plants it includes all pressure bearing components up to the steam drums, which are outside of the ALS. Improvements can be made to first generation RBMKs by providing for steam venting through a water bubbler system. Another important difference relates to the capacity of the reactor cavity to cope with rupture of the pressure tubes without lifting the cavity cover. For all plants the venting capacity has now been increased to handle simultaneous rupture of about nine tubes.

As mentioned above, RBMK reactors posses a compartment system instead of a containment structure. Originally, first generation plants would vent steam from pipe ruptures to the atmosphere; this was improved by filtering the steam through a bubbler tank system. Second generation plants were provided by the original design with a bubbler condenser system for condensing and containing steam and radioactivity from DBAs. The limited capacity of first generation RBMK reactors to cope with pipe breaks contributed, together with the positive reactivity feedback under certain conditions, and other factors, to the decision made to limit the power to 70% of the design capacity.

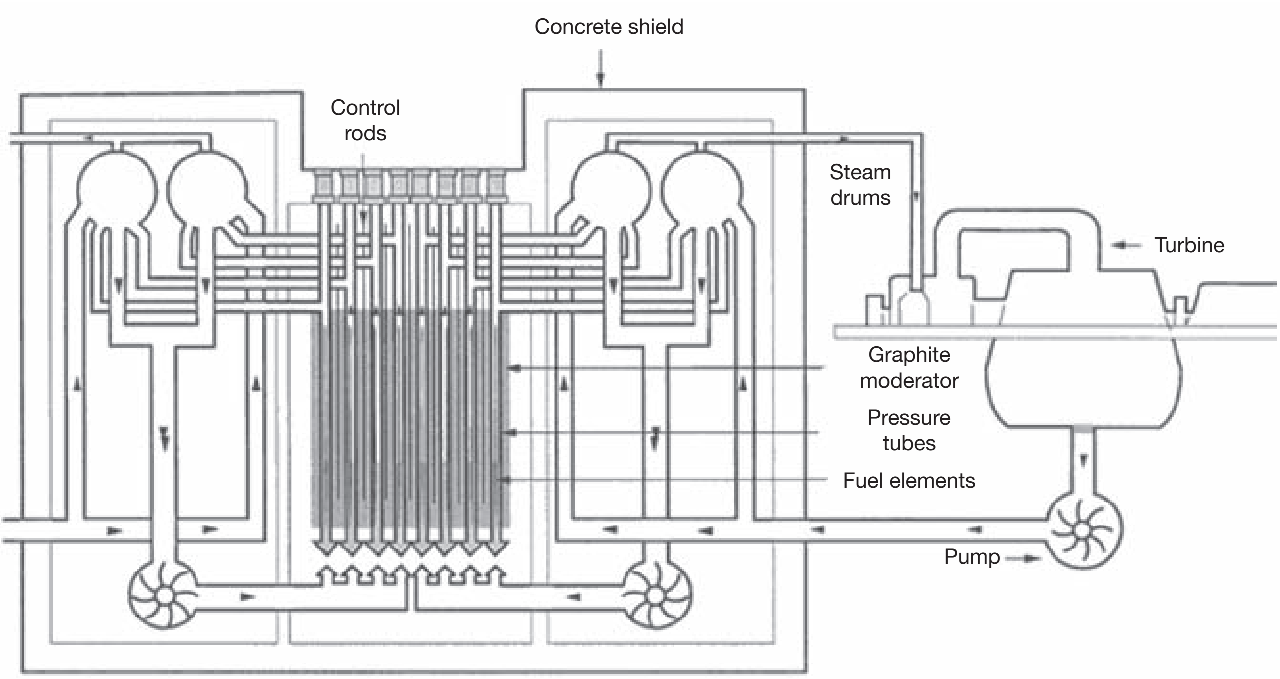

FIG. 5.2. The water/steam flow in RBMK reactors.

5.3.2. Ukraine

All the operational nuclear reactors in Ukraine are WWER (water cooled and water moderated) reactors, which belong to the category of PWRs. This is the most common reactor type in the world, comprising more than 50% of all power reactors. All of the Ukrainian WWER reactors belong to the second generation of Soviet built reactors. Rovno 1 and 2 are WWER-440/213 reactors with a capacity of about 400 MW(e) (see Fig. 5.3), whereas the other reactors belong to the larger WWER-1000 category (see Fig. 5.4) with a capacity of 1000 MW(e). Two reactors, South Ukraine 1 and 2, belong to an earlier version of the reactors called the small series. Both reactors under construction at the Rovno and Khmelnitski sites are of the WWER-1000 series.

The main WWER design criteria are consistent with current international safety practices. The enveloping DBA is the break of a main coolant pipe (diameter of 500 mm for WWER-440, 850 mm for WWER-1000). Safety systems have been designed with a 3 × 100% redundancy; however, separation of trains is not always totally effective. In particular, all steam and feed water pipes at the 28.7 m level in WWER-1000 reactors are installed in parallel. Efforts are under way to improve emergency operating procedures and to develop some accident management guidelines.

Specific design characteristics of WWER reactors are horizontal steam generators (versus the usual vertical steam generators) and a hexagonal design of the fuel elements with the fuel contained in tubes (‘cassettes’). The design of the horizontal steam generators introduces the possibility of collector breaks, of which a large one could lead to a severe accident. The later designs have been modified and manufacturing techniques have been improved to practically exclude the possibility of large primary to secondary circuit breaks (larger than 100 mm diameter equivalent). Safety and relief valves of the primary circuit are being replaced with valves designed for water or water–steam mixtures.

A relatively low power density in the core and large water inventories in the primary and secondary coolant circuits characterize the WWER-440/213 reactors. They have six steam generators and coolant loops that can be individually (but not very reliably) isolated in the event of an emergency. This provides for large safety margins and possibilities for accident management measures in the event of an accident. Without power and coolant water supply, natural circulation of the primary loop can cool the core for more than five hours. All coolant pipes are made of austenitic steel, making pipe breaks very unlikely.

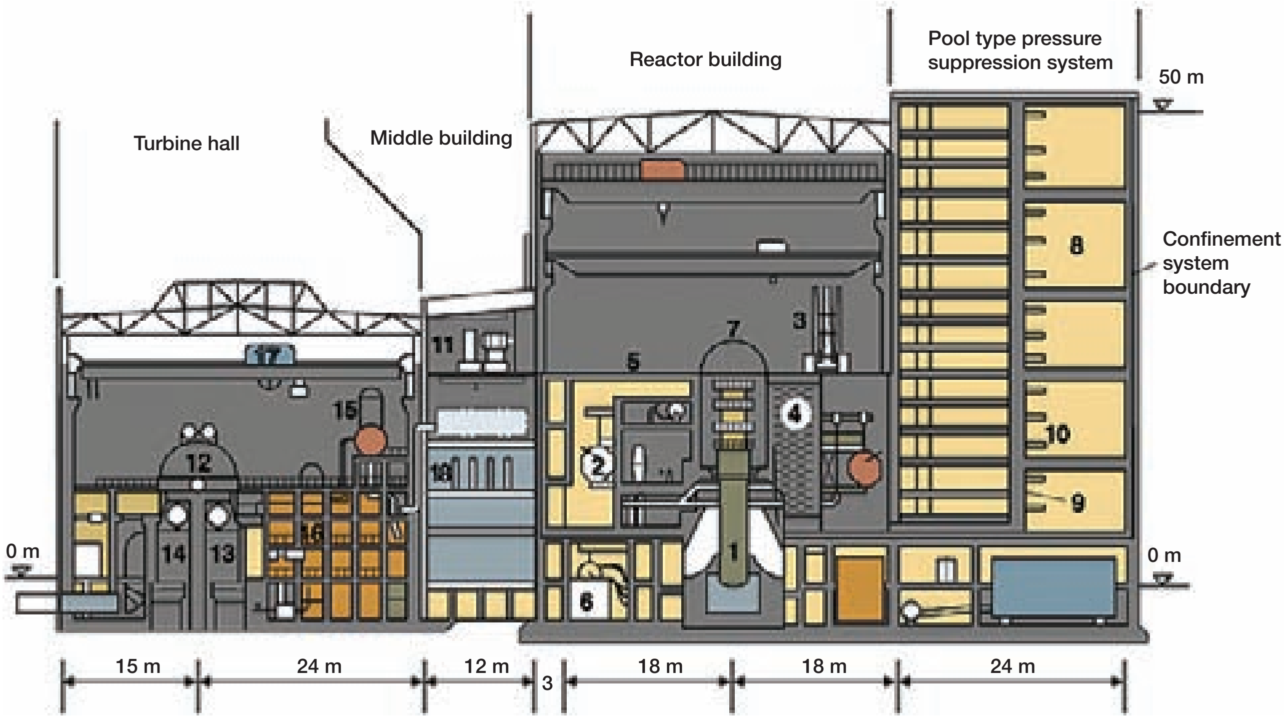

FIG. 5.3. WWER-440 reactor as used at Rovno units 1 and 2. 1: reactor pressure vessel; 2: steam generator; 3: refuelling machine; 4: spent fuel pit; 5: confinement system; 6: make-up feedwater system; 7: protective cover; 8: confinement system; 9: sparging system; 10: check valves; 11: intake air unit; 12: turbine; 13: condenser; 14: turbine block; 15: feedwater tank with degasifier; 16: preheater; 17: turbine hall crane; 18: electrical instrumentation and control compartments.

For the WWER-440/213 reactors, in contrast to standard western PWR designs, there is no containment. Instead they have a compartment structure and a bubbler condenser tower. This tower consists of floors or 'shelves' filled with water (see Fig. 5.3) that can condense the steam and contain radioactivity. Final experiments are under way within the umbrella of the OECD/NEA to experimentally confirm the functioning and physical stability of the bubbler condenser towers.

The larger WWER-1000 reactors are equipped with containments more similar in design to those of western reactors (see Fig. 5.4). The main parameters, such as power density or number of steam generators and water inventory, are also quite similar to the usual PWR design. In comparison to the 'oversized' WWER-440 design, safety margins have as a result been reduced to normal levels and have to be compensated for by the capacity of the safety systems. In order to facilitate transport by rail, reactor pressure vessels were kept rather slim (but long). This poses special requirements when considering the doubling of power between the WWER-213 and WWER-1000 types, in particular for monitoring the neutron flux sustained by the vessel walls and for the loading patterns necessary for low neutron leakage cores.

The standard WWER-1000 has some improvements over the small series reactors, including a stricter separation of redundant trains,

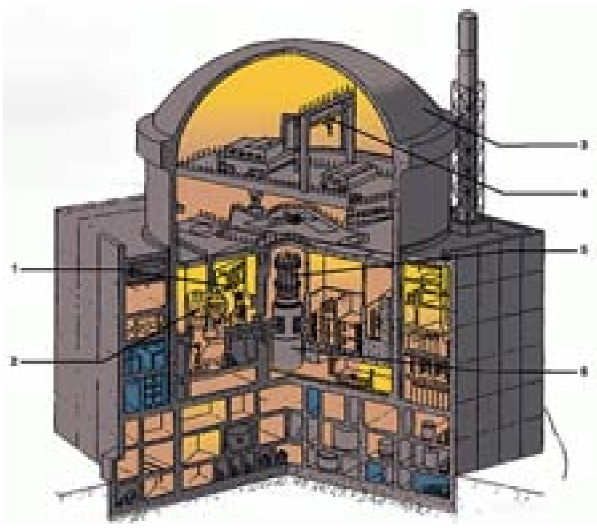

FIG. 5.4. WWER-1000 reactor. 1: horizontal steam generator; 2: reactor coolant pump; 3: containment building; 4: refuelling crane; 5: control rod assemblies; 6: reactor vessel.

improvements in instrumentation and control, extended ranges of high pressure and low pressure injection of the emergency core cooling system and the possibility to switch to the containment sump to allow for feed and bleed operation.

Safety improvement programmes have either already been implemented or are still under way for all reactors. These have significantly improved the level of safety of the reactors but have the potential for further improvement.

5.4. LICENSING STATUS OF NUCLEAR FACILITIES

5.4.1. Russian Federation

In the Russian Federation the law that governs all nuclear activities was enacted in 1995 (Federal Law on the Use of Atomic Energy, 1995, RF FL 170-FZ). It establishes the legal basis and principles for the regulation and licensing of activities related to the use of atomic energy. The law also contains principles for safeguarding health and life and protecting the environment and property. It has provisions concerning:

(a) The safe use of atomic energy;
(b) Free access to information on the use of atomic energy (unless such information constitutes a State secret);
(c) The participation of citizens, commercial enterprises and corporate bodies in the review of State policy and the drafting of legislation relating to the use of atomic energy;
(d) Compensation for damage caused by the effects of radiation.

The Federal Law on the Use of Atomic Energy is complemented by the Federal Law on Environmental Protection (RF FL 2060-1 of 19 December 1991) and by the Federal Law on Radiation Safety of the Population (RF FL 3FZ 09 of 1 January 1996). In line with internationally recognized safety standards, the latter legislation sets out key principles for radiation safety, as well as a mechanism for their implementation. These are:

(i) The standardization of permissible dose limits of radiation for the population at large and for personnel working at nuclear installations;
(ii) The prohibition of all activities using sources of ionizing radiation for which the benefit to humans and society in general does not exceed the risk posed by such activities;
(iii) Ensuring that individual doses and the number of people exposed to ionizing radiation are kept to the lowest possible level, taking into account the social and economic factors involved in the use of atomic energy (as low as reasonably achievable (the ALARA principle)).

The Russian legislation affirms the priority of human health and environmental protection in the context of the operation of nuclear installations and the use of radioactive substances and other sources of ionizing radiation.

The main State regulatory bodies set up to enforce compliance with the legislation, as of 2003, were the:

— Federal Nuclear and Radiation Safety Authority of Russia (Gosatomnadzor);
— Federal Sanitary and Epidemiological Inspectorate (Gossanepidnadzor);
— Federal Mining and Industrial Inspectorate of Russia;
— State fire service.

Gosatomnadzor is the organization that regulates nuclear and radiation safety. It establishes conditions that ensure the protection of workers, the public and the environment from undue harm from radiation. As such, it is charged with the tasks of defining safety principles, standards and criteria, as well as with licensing, inspection and enforcement of all activities related to the use of nuclear energy.

In 1997 Gosatomnadzor updated the General Provisions Governing the Safety of Nuclear Power Stations (OPB-88). This regulation contains objectives, safety goals, basic criteria and principles, and, in some cases, details of engineering and organizational measures needed to meet the nuclear and radiation safety standards.

The concept of defence in depth has been further developed in OPB-88, which requires that:

> "[A] nuclear power plant design and operation shall ensure that exposure of personnel, the public, and the environment to radiation during normal operation or during any abnormal operational occurrences, including design basis accidents, does not result in radiation doses that exceed those

prescribed for personnel and the public, as well as the standards governing releases, discharges, and the content of radioactive substances in the environment. In the case of beyond design basis (BDB) accidents, such exposure should be limited as far as possible."

The permissible personal radiation dose limits and dose limits for the public as a result of releases and discharges of radioactive substances from a nuclear power plant are defined in Russian Radiation Protection Rules NRB-99 (SP 2.6.1.758-99). It is required that the maximum dose for a DBA be less than the intervention levels set for off-site contamination, which at present are 5 mSv individual whole body dose within the first ten days after an accident.

OPB-88 also establishes the requirements for preventing, controlling and mitigating the consequences of BDB and severe accidents. It also includes a probabilistic safety goal for severe core damage of a frequency less than 10^{-5} per reactor year. OPB-88 recommends that every attempt be made to ensure that the estimated frequency of large unacceptable radioactive releases does not exceed 10^{-7} per reactor year. Accident management systems are required to cope with BDB accidents.

The Law on the Use of Atomic Energy, supported by a governmental decree, requires that a licence be obtained for some 35 prescribed activities. These include the siting, construction, commissioning, operation, modification and decommissioning of nuclear power plants. For a licence to be issued by Gosatomnadzor, a given activity should be in compliance with the standards and rules prescribed by the applicable legal and regulatory documents.

The units of the Kursk and Smolensk nuclear power plants have had their safety justification documents submitted to the regulatory body in accordance with the requirements of the licensing process. The current validity of the licences is different, dependent upon the age and design type of the unit. The present practice is that, for first generation units, a licence is granted on an annual basis, while for second generation units the licence is valid for five years.

5.4.2. Ukraine

In Ukraine the overarching law that governs all nuclear activities, the Law on Use of Nuclear Energy and Radiation Safety, No. 39/95, was enacted in 1995. There were subsequent amendments to this law in 1996 and 1997, and since then a significant number of relevant subordinate regulations and regulatory guides have been developed. This legislation establishes the framework for the regulation of activities related to the use of atomic energy and includes provisions for the following:

(a) Setting up agencies to carry out the control and State regulation of safety in the use of nuclear energy in accordance with the law.
(b) Making decisions on the safe siting, planning, construction, operation and decommissioning of uranium ore mining enterprises, nuclear installations and radioactive waste management facilities.
(c) Administration of nuclear installations, ionizing radiation sources, nuclear material and radioactive waste management facilities that are the property of the State.
(d) Protecting the public and the environment from the harmful effects of ionizing radiation.
(e) Preparing measures connected with the accountancy and monitoring of nuclear material and ionizing radiation sources and with the physical protection of nuclear installations, ionizing radiation sources, nuclear material and radioactive waste management facilities.
(f) Defining the procedure for drafting and adopting regulations, rules and standards regarding nuclear and radiation safety.
(g) Defining the types of activities that should be licensed.

The Law on Human Protection Against Ionizing Radiation (dated January 1998) sets out the requirements for the radiation protection of workers and the public. This law is supported by relevant regulations and standards developed by the Ministry of Health.

In January 2000 the Law on Permissible Activity in the Area of Nuclear Energy Utilization established the following principles:

(i) The prioritization of maintenance of nuclear and radiation safety above other interests;
(ii) A varied approach to activities commensurate with the potential nuclear and radiation danger associated with them;

(iii) The independence and objectivity of regulatory bodies and acceptance of their decisions;
(iv) The validity of established criteria, requirements and conditions for safety, having regard for all ecological, economic and social factors;
(v) The responsibility of regulatory bodies to ensure that licensing conditions are observed.

The procedure for licensing was established by the Order for Licensing Various Kinds of Activity in the Field of Nuclear Energy Use, which was approved by the Cabinet of Ministers (No. 1782 on 6 December 2000). The order establishes the conditions of licensing, the list of documents required, the conditions and procedures for renewal, cessation and cancellation of licences, procedures for the registration of the given licences and control over the observance of the licence conditions.

The Ukrainian legislation represents a comprehensive basis for ensuring nuclear and radiation safety, including protection of the population and the environment. It affirms the priority of human health and environmental protection in the context of the operation of nuclear installations and the use of radioactive substances and other sources of ionizing radiation.

The main State regulatory bodies set up to enforce compliance with the legislation are the:

— State Nuclear Regulatory Committee of Ukraine (SNRCU);
— Ministry of Environment and Natural Resources of Ukraine (MENRU);
— Ministry of Health of Ukraine;
— Ministry of Emergencies.

In December 2000 the President of Ukraine issued a decree (1303/2000, Decree on State Regulation of Nuclear and Radiation Safety) that established the SNRCU as the prime independent regulatory body for the safety aspects of nuclear activities. As such, it is charged with the tasks of defining safety principles, standards and criteria, as well as with licensing, inspection and enforcement of all activities related to the use of nuclear energy.

The SNRCU has made use of OPB-88 in setting its objectives, safety goals, basic criteria and principles for nuclear safety. The standards and dose rate limits are set in Norms of Radiation Safety of Ukraine, Supplement: Radiation Protection from Potential Ionizing Radiation Sources (NRBU-97/D-2000). Maximum occupational and public exposure dose limits for the whole body are set at 20 mSv and 1 mSv, respectively. The principle of ALARA is also set down in the law, which follows the latest IAEA and ICRP recommendations.

Within the Law on Permissible Activity in the Area of Nuclear Energy Utilization, enacted in January 2000, the function of issuing licences was assigned to the SNRCU, and a requirement to define and attach conditions to a licence was also given. The scope of the licensing regime in Ukraine covers all significant facilities and activities, including: nuclear power plant design, construction and operation; uranium ore processing; radioactive waste storage and treatment; transport of radioactive material; decommissioning of nuclear facilities; closure of radioactive waste disposal sites; and nuclear power plant operator training.

In accordance with the law mentioned above, the scope and format of the documents that shall be submitted by the licence applicant in order to obtain a licence are to be determined by the SNRCU. It has defined two strategies in relation to its reactor licensing process: one for nuclear power plants under operation and the other for nuclear power plants under construction.

For the reactor units on the four operating nuclear power plant sites, the SNRCU has decided to give site licences, as it is allowed to do under the law. For this purpose the contents of the safety analysis report (SAR) required from the operators were specified in a guide prepared by the SNRCU.

It was recognized by the SNRCU that the process for the completion of comprehensive SARs will take several years, and therefore to speed up the licensing process it was decided to issue licences based on partially developed or basic SARs. All the licences have now been issued; however, they are valid for only one year and have stringent conditions attached, including timescales for the completion of comprehensive SARs. This annual licence renewal procedure will remain until all the plant specific SARs have been submitted by the operators to the SNRCU for regulatory review and assessment. Once satisfied, permanent licences will be granted to the nuclear power plants by the SNRCU. However, one of the conditions attached to these licences will be for the operators to perform a full periodic safety review on a ten year cycle.

For Rovno 4 and Khmelnitski 2, which are currently under construction/commissioning, a full

scope safety assessment based on a SAR containing BDB and severe accident analyses as well as a plant specific probabilistic safety assessment (PSA) is required as a condition for active commissioning of the units.

5.5. SYSTEM FOR ENVIRONMENTAL RADIATION MONITORING IN THE VICINITY OF NUCLEAR POWER PLANTS

5.5.1. Russian Federation

The radiation situation in the 30 km zone of Russian nuclear power plants is monitored by their internal services in accordance with the Procedures for Radiation Monitoring. Included is monitoring of the:

(a) Space–time distribution of gamma radiation dose rate and spatial distribution of annual absorbed dose in the area;
(b) Volumetric activity of radioactive aerosols in the surface atmospheric layer and of the radioactive deposition density;
(c) Radionuclide content in soil, vegetation and local food;
(d) Volumetric activity of radionuclides in water in discharge pipelines, at industrial and municipal sewage sites, in open water bodies, in fish and in other aquatic organisms;
(e) Leakage (if any) to groundwater from liquid waste storage sites and storage facilities containing spent nuclear fuel;
(f) Sources of drinking water supply and the water network used for district heating.

In the 100 km zone around nuclear power plants, regional units of the hydrometeorological services conduct monitoring.

A process is now under way to set up at all Russian nuclear power plants automated systems for radiation monitoring (ASKRO), which are planned to be integrated in future into the unified State automated system for radiation monitoring (EGASKRO) [5.5]. The ASKROs of nuclear power plants incorporate [5.6]:

(i) Stations to measure the radiation dose rate in the sanitary zone and observation zone;
(ii) Facilities for emergency monitoring of releases through the ventilation stacks of nuclear power plants;
(iii) Meteorological stations;
(iv) Central points of data collection from different subsystems engaged in the gathering and primary processing of information from instrumentation;
(v) Central monitoring posts to receive and process information from the central points of all subsystems and its transmission to the information network of nuclear power plants and the emergency centre of Rosenergoatom.

ASKROs are designed to provide [5.5, 5.6]:

— Continuous monitoring of the radiation situation on the site and in the sanitary zone and observation zone;
— Prognosis of the evolution of the radiation situation and doses to the population and personnel in the normal operation of nuclear power plants and in the event of an emergency;
— Information and analytical support to nuclear power plant management, the operating organization and territorial authorities;
— Information to the public about the radiation situation in the observation zone around nuclear power plants through the media and display boards.

The existing monitoring system is primarily geared towards an emergency response in the event of an accident involving an atmospheric release of radioactivity. There is no doubt that this system serves its purpose, and will more so after ASKROs are fully put into operation. On the other hand, monitoring of contamination of surface waters and groundwaters is currently conducted on a monthly or quarterly basis, and it cannot be excluded that leakage of a considerable amount of radioactive substances to surface waters or groundwaters could occur, precluding timely and effective counter-measures.

This possibility is exemplified by the leak from a liquid waste storage facility that occurred at the Novovoronezh nuclear power plant in 1985 [5.7]. By the time the leak was detected, only ^{137}Cs was found at the leak site, whereas ^{60}Co, in the form of a non-sorbable complex, had migrated to groundwater. From 1995 onwards elevated concentrations of ^{60}Co were detected in bottom sediments of the Don

River (up to 5 kBq/kg) as a result of uncontrolled discharge of this radionuclide. In 2000 a significant level of ^{60}Co was measured in soil on the Don River bank near the mouth of the wastewater discharge pipeline of the nuclear power plant (dose rate up to 30 μSv/h). Thus the failure to detect the leak quickly made it impossible to contain it within a localized area. The above example shows that the system of monitoring leaks of radioactive substances to natural waters from nuclear power plant sites needs to be improved.

5.5.2. Ukraine

In the vicinity of the operating Ukrainian nuclear power plants, environmental monitoring is organized as follows:

(a) At the facilities of nuclear power plants and within the 10 km zone, the safety and environmental departments of nuclear power plants monitor releases. The following are monitored: releases from ventilation stacks, air and soil at nuclear power plant sites and in their vicinity, waste water discharge and water intake points, cooling ponds and underground waters.
(b) Within the 30 km zones around nuclear power plants and the zones of potential impact, monitoring is carried out by units of the Hydrometeorological Service of Ukraine and Gossanepidnadzor.
(c) Sampling near water intakes and other water supply facilities and estimation of radioactive contamination levels is the responsibility of Gosvodkhoz. In addition to Gosvodkhoz, surface and underground waters are monitored by other entities, as prescribed by agency protocols and rules. The system for monitoring groundwater contamination levels in Ukraine is described in Ref. [5.8].

5.5.3. Belarus

There are no nuclear power plants in Belarus, but the 100 km zones of four nuclear power plants (Chernobyl, Ignalina, Rovno and Smolensk) in the neighbouring countries extend into the territory of the republic. The RCREM and its network units carry out radiation monitoring in the nuclear power plant impact zones in Belarus. The radiation dose rate is monitored continuously, and radioactive contamination of the air and atmospheric fallout is monitored on a regular basis. The monitoring of surface waters and bottom sediments is conducted, however, only on Lake Drisvyaty in the zone influenced by the Ignalina nuclear power plant.

5.6. RELEASES FROM NUCLEAR REACTORS IN THE DNIEPER RIVER BASIN

5.6.1. Releases from the Kursk and Smolensk nuclear power plants

Gaseous and aerosol releases at the Kursk and Smolensk nuclear power plants are discharged through ventilation stacks with a height of 150 m and through small stacks with a height of 60 m. The gases are detained for a certain time prior to release, to allow for decay of short lived radionuclides, and are then partially cleaned of radioactive aerosols and radio-iodine.

During the whole period of operation of the Smolensk and Kursk nuclear power plants, the permissible rate of radionuclide releases into the atmosphere both of groups of and individual radionuclides as prescribed by the Sanitary Rules on Design and Operation of Nuclear Power Plants (SPAES-68 and SPAES-79) have not been exceeded [5.1, 5.7, 5.9–5.12]. Actual releases have been much lower than the requirements of SPAES-88.

In the latest revision of the Sanitary Rules (SPAES-99), the permissible releases into the atmosphere were further reduced. Table 5.3 compares the actual and permissible releases for the Kursk and Smolensk nuclear power plants for the period 1995–2000. The releases were greatest for the inert radioactive gases (isotopes of xenon, krypton and argon), but well below the permissible limits in all cases.

Discharge of radionuclides from nuclear power plants into surface water occurs via the following wastewaters:

(a) Excess (debalanced) water;
(b) Cooling water from the heat exchange equipment in the reactor compartment;
(c) Industrial and shower sewage water;
(d) Special laundry and shower room water;
(e) Utility sewage water.

During the first years of nuclear power plant operation, the release of radionuclides was attributable mainly to debalanced waters and, thereafter,

TABLE 5.3. ANNUAL GASEOUS AND AEROSOL RELEASES OF RADIONUCLIDES AS A PERCENTAGE OF PERMISSIBLE RELEASES [5.7, 5.13]

	Radionuclide	Permissible release (Bq)	Actual release as per cent of permissible limit					
			1995	1996	1997	1998	1999	2000
Kursk	IRG[a]	3.7×10^{15}	30	32	17	13	14	10
	Iodine-131	9.3×10^{10}	7.5	11	12	8.3	9.1	2.0
	Cobalt-60	2.5×10^{9}	5.2	32	16	8.8	1.9	—
	Strontium-90	2.4×10^{8}	<0.1	<0.1	<0.1	<0.1	<0.1	—
	Caesium-134	1.4×10^{9}	0.86	0.61	3.4	1.6	0.66	—
	Caesium-137	4×10^{9}	0.60	0.93	2.8	1.6	1.3	—
Smolensk	IRG	3.7×10^{15}	27	18	19	17	16	14
	Iodine-131	9.3×10^{10}	6.8	6.0	27	15	5.7	8.9
	Cobalt-60	2.5×10^{9}	4.0	3.0	2.8	2.7	2.3	4.0
	Strontium-90	2.4×10^{8}	6.0	5.0	5.0	4.2	17	17
	Caesium-134	1.4×10^{9}	1.6	0.16	4.8	3.2	1.9	1.2
	Caesium-137	4×10^{9}	2.2	0.78	4.3	3.5	1.8	1.6

[a] IRG: inert radioactive gases.

cooling water and industrial and shower sewage water [5.12]. A typical radionuclide composition of these waters for nuclear power plants of the RBMK type is presented in Table 5.4.

Deviations from the above norms were not observed at the Kursk or Smolensk nuclear power plants. The permissible and actual releases of radionuclides into surface waters during 1998–2000 are presented in Table 4.5. The actual releases are lower than the permissible releases by several orders of magnitude.

5.6.2. Radioactive contamination in the vicinities of the Kursk and Smolensk nuclear power plants

5.6.2.1. Soil

Before the Chernobyl accident, the level of soil contamination in the central regions of the European part of the USSR was, on average, ^{137}Cs = 3.0 kBq/m^2 and ^{90}Sr = 1.9 kBq/m^2. The density of ^{137}Cs contamination in the soil in the vicinity of the Kursk and Smolensk nuclear power plants was determined by the global background, and it was practically the same as in the reference regions (see Table 5.6).

TABLE 5.6. DENSITY OF CONTAMINATION OF SOIL WITH CAESIUM-137 IN THE VICINITY OF THE SMOLENSK AND KURSK NUCLEAR POWER PLANTS [5.16]

	Year	Caesium-137 (kBq/m^2)	
		Nuclear power plant surroundings	Monitored territory
Kursk	1978	2.8 ± 0.1	2.70 ± 0.03
Smolensk	1981	2.8 ± 0.1	2.61 ± 0.02
Smolensk	1983	3.1 ± 0.2	2.61 ± 0.02

TABLE 5.4. TYPICAL RADIONUCLIDE COMPOSITION OF RELEASED WATERS FROM RBMK TYPE NUCLEAR POWER PLANTS [5.12]

	Debalanced waters (Bq/L)		Waters of industrial and shower sewage (Bq/L)		Waters of reactor department (Bq/L)
	Operation year		Operation year		
	1–5	>5	1–5	>5	
Caesium-134	4–15	$(4–7) \times 10^{-3}$	0.04–0.185	1.85×10^{-3}	3.7×10^{-3}
Caesium-137	3.7	$(0.4–4) \times 10^{-3}$	7.4×10^{-2}	—	—
Strontium-90	1.85	$(1.5–2.2) \times 10^{-4}$	$(7–15) \times 10^{-3}$	3.7×10^{-4}	7.4×10^{-3}
Cobalt-60	15–30	$(0.4–1.85) \times 10^{-3}$	7.4×10^{-2}	—	7.4×10^{-3}
Cobalt-58	11–33	3.7×10^{-4}	3.7×10^{-3}	—	1.5×10^{-3}
Argon-41	40–3000	$(0.4–1.85) \times 10^{-3}$	0.4–4	—	3.7×10^{-2}
Manganese-54	2–11	$(0.4–1.1) \times 10^{-3}$	$(0.4–3.7) \times 10^{-2}$	—	7.4×10^{-3}
Iron-59	15–300	$(0.4–1.85) \times 10^{-3}$	15	—	7.4×10^{-3}
Iodine-131	7–15	$(0.4–4) \times 10^{-2}$	—	—	—

TABLE 5.5. PERMITTED AND ACTUAL RELEASES FROM THE KURSK AND SMOLENSK NUCLEAR POWER PLANTS INTO SURFACE WATERS [5.7, 5.11]

	Radionuclide	Permitted release (Bq/a)	Actual release (Bq/a)		
			1998	1999	2000
Kursk	Cobalt-60	3.0×10^{11}	7.0×10^{7}	1.05×10^{8}	2.5×10^{7}
	Strontium-90	3.2×10^{10}	3.6×10^{7}	3.92×10^{7}	1.82×10^{6}
	Caesium-137	2.4×10^{11}	1.2×10^{8}	—	6.0×10^{7}
Smolensk	Cobalt-60	4.81×10^{11}	6.4×10^{5}	4.05×10^{7}	4.09×10^{7}
	Strontium-90	1.81×10^{9}	1.27×10^{6}	2.98×10^{6}	3.7×10^{6}
	Caesium-137	2.85×10^{9}	4.0×10^{6}	5.25×10^{7}	3.03×10^{7}

After 1986 the level of soil contamination with ^{137}Cs in the vicinity of the Smolensk and Kursk nuclear power plants was determined mainly by fallout from Chernobyl (see Section 3). To the north-east of Smolensk, the density of fallout was 18.5–37 kBq/m^2 (0.5–1 Ci/km^2); in other areas the levels reached 37–74 kBq/m^2 (1–2 Ci/km^2). In the south-west direction, the densities of contamination were lower than 18.5 kBq/m^2 (0.5 Ci/km^2).

The Kursk nuclear power plant is located in territory with a general level of contamination of 7.4–18.5 kBq/m^2 (0.2–0.5 Ci/km^2); at a distance of about 10 km to the south-west there is a spot with a higher concentration, viz. 18.5–37 kBq/m^2 (0.5–1 Ci/km^2). According to the assessment in Ref. [5.14], during 16 years of operation of the Kursk nuclear power plant, 0.2 Bq/m^2 of ^{90}Sr and 0.8 Bq/m^2 of ^{137}Cs were deposited in the area of Kurchatov town. This is three to four orders of magnitude lower than the level of contamination as a result of global releases.

It is not possible to discern any statistically significant contribution from releases of the Smolensk and Kursk nuclear power plants into the soil [5.12, 5.14, 5.15]. Firstly, the necessary information on the initial contamination of the regions is absent or insufficiently complete and qualitative. Secondly, the contribution of the nuclear power plants is negligibly low.

5.6.2.2. *Air*

During the whole period of their operation, gaseous and aerosol releases from the Kursk and Smolensk nuclear power plants did not lead to any

TABLE 5.7. CAESIUM RADIONUCLIDE ACTIVITY CONCENTRATION IN SURFACE WATERS IN THE VICINITY OF THE KURSK NUCLEAR POWER PLANT [5.18]

Sampling location	Observation period	Caesium-134 (mBq/L)	Caesium-137 (mBq/L)
Cooling pond	1980–1985, 1987–1993	25	35
	1986	55	63
Seim River	1980–1985, 1987–1993	23[a]	32[a]
	1986	37	72
Reut River	1980–1985, 1987–1993	23[a]	32[a]
	1986	88	140

[a] Median value of concentrations in the Seim and Reut Rivers in 1986.

significant contamination of the air; they were lower than the effective norms. In 1983–1985 the content of ^{137}Cs in the area of the Smolensk nuclear power plant was (1–4) × 10^{-6} Bq/m^3. After the Chernobyl accident it significantly increased, and in 1988–1989 was tens of μBq/m^3 [5.15]. In 2000 the maximum concentration of ^{137}Cs in the area of the Smolensk nuclear power plant equalled 3 × 10^{-5} Bq/m^3. At a distance of 35 km from the nuclear power plant it was approximately the same as at the plant site.

In the vicinity of the Kursk nuclear power plant the content of ^{137}Cs in the air increased by 10^4 times during 1986 and reached (2–4) × 10^{-4} Bq/m^3 [5.14]. In 2000 at the Kursk nuclear power plant site the mean annual content of ^{137}Cs in the air equalled 8 × 10^{-5} Bq/m^3 [5.7]. Releases from the Kursk nuclear power plant were proposed as an explanation for a small increase in the airborne concentration of ^{137}Cs in Kursk city compared with the average over the whole of the Russian Federation [5.11]; however, this may be a result of contamination from the Chernobyl releases.

5.6.2.3. Natural water

The concentrations of radionuclides in the surface waters of the Bryansk region may be used to assess the pre-Chernobyl concentrations in rivers in the territories of the Kursk and Smolensk regions, namely 14–20 mBq/L for ^{90}Sr, 4–8 Bq/L for tritium and 0.2–1.3 mBq/L for ^{137}Cs [5.17]. Before 1986 the content of radionuclides in the surface waters in the area of the Smolensk nuclear power plant did not exceed these ranges. In 1983–1985 the concentrations in this area were 0.4–1.2 mBq/L ^{137}Cs and 1.5–5.6 Bq/L tritium [5.15]. The median value of ^{137}Cs activity in the water of the Smolensk cooling pond during the operational period up until the beginning of the 1990s, excluding 1986, was 0.7 mBq/L [5.18].

Concentrations of ^{137}Cs are a little higher in the Smolensk cooling pond and in the Seim and Reut Rivers in the area of the power plant (see Table 5.7). In 1986 they increased 2.5–3 times, but in 1988 they were back to the pre-Chernobyl level [5.18].

At present, the concentrations of ^{137}Cs in the surface waters in the vicinity of nuclear power plants remain at low levels that do not require intervention, although they are a little higher than the pre-Chernobyl concentrations caused by global releases. In 1999 the activity of ^{137}Cs in the Desna River and the Desnogorsk reservoir was 13 mBq/L [5.11] and in the Seim and Reut Rivers up to 20 mBq/L (see Table 5.8).

Since there were no significant releases of ^{90}Sr from the Chernobyl nuclear power plant in the areas of the Kursk and Smolensk plants, its present concentrations in surface waters are approximately the same as before 1986.

Thus the operation of the Kursk and Smolensk plants has not led to significant releases of radionuclides into the environment. The influence of nuclear power plants on the radioactive contamination of soil, air and natural water becomes apparent mainly at certain times in a few samples, where trace quantities of radionuclides of reactor origin, such as ^{51}Cr, ^{54}Mn and $^{58,60}Co$, are detected. The only detectable influence of the nuclear power plants on the radioactive contamination of the environment is apparently a small increase (compared with the global level) in the ^{137}Cs concentration in surface waters in the vicinity of the Kursk nuclear power plant.

5.6.3. Releases from Ukrainian nuclear power plants

Release of radioactivity from nuclear power plants can occur via either the air or water pathway.

TABLE 5.8. CONCENTRATION OF RADIONUCLIDES IN THE WATER OF INDUSTRIAL AND OPEN WATER BODIES IN THE AREA OF THE KURSK NUCLEAR POWER PLANT IN 1996–2000 [5.1, 5.7, 5.10, 5.11]

Sampling location	Strontium-90 (mBq/L)					Caesium-137 (mBq/L)					Total beta activity (mBq/L)				
	1996	1997	1998	1999	2000	1996	1997	1998	1999	2000	1996	1997	1998	1999	2000
							Cooling pond								
Outlet canal	1.5	8	7.4	8	7	—	—	100	—	—	200	200	250	240	230
Inlet canal	3	8.5	13	7.8	8	—	—	—	—	80	200	200	240	230	220
							Seim River								
ISS[a] release	2.8	3.2	98	5	5	—	20	10	10	—	200	200	280	260	230
Upstream ISS release	4.2	16	12	15	15	—		6	—	—	200	200	250	260	230
Downstream ISS release	1	10	1	11	11	—	10	—	—	—	200	200	220	230	230
							Reut River								
WK[b] release	70	4	9	16	16	50	120	90	70	—	200	200	280	250	220
Upstream WK release	1.6	14	6	12	12	—	20	—	—	—	200	200	290	250	220
Downstream WK release	1.3	9	7	13	13	—	10	10	—	—	200	200	240	250	220

[a] ISS: interim storage site.
[b] WK: wastewater treatment works, Kurchatov.

After cleaning, ventilation air is released to the atmosphere via tall stacks. Gaseous and aerosol releases may also enter the atmosphere via ejectors when there is a leak of coolant from the primary to the secondary circuit. In the turbine condenser, separation of non-condensable gases takes place, which then are exhausted by the ejectors. The gases are exhausted into the outlet canal of the circulating water and then into the cooling ponds.

The permissible release of radioactivity to the environment is determined for each nuclear power plant taking account of the stack height, average meteorological conditions at the site and location of the sanitary and protective zones. Table 5.9 shows these permissible releases for Ukrainian nuclear power plants. Before 2000, ischarges from all nuclear power plants were below the requirements set out in standard SPAS-88.

In 1997 new radiation safety regulations were introduced (NRBU-97) based on the Basic Safety Standards [5.19] and the recommendations of the IAEA. Under these regulations, the permissible release is calculated on the basis of a dose quotient that takes account of all exposure routes to a critical group of the population. For nuclear power plants, the dose limit is 40 μSv/a, which represents 4% of the allowable dose to the general population from all sources (1 mSv/a).

In addition to the permissible limits, more restrictive control levels for releases to air and water are set following discussions with the State Sanitary Supervisory Agency.

TABLE 5.9. PERMISSIBLE RELEASES FROM NUCLEAR POWER PLANTS IN UKRAINE

	Permissible releases (TBq/d)	Long lived radionuclides (MBq/d)	Iodines (MBq/d)
Zaporozhe	148	3330	1480
South Ukraine	55.5	1660	1110
Rovno	34.8	1040	695
Khmelnitski	18.5	555	370

TABLE 5.10. RADIONUCLIDE RELEASES FROM NUCLEAR POWER PLANTS DURING 1997–2001

	Caesium-137 (MBq/a)				Cobalt-60 (MBq/a)			
	Zaporozhe	Rovno	Khmelnitski	South Ukraine	Zaporozhe	Rovno	Khmelnitski	South Ukraine
1997	254	1345	0.7	15.8	40.2	84.0	0.9	28.3
1998	615	3627	0.0	31.4	116	152	11.9	159
1999	213	1220	2.0	65.1	57.5	61.8	0.0	158
2000	157	633	130	47.6	121.8	45.6	0.5	38.7
2001	153	628	39.2	151	63.9	8.2	0.4	223

TABLE 5.11. RADIONUCLIDE RELEASES INTO THE ZAPOROZHE NUCLEAR POWER PLANT COOLING POND (2000)

Effluent source	Released water (10^6 m^3)	Radioactivity (MBq)			
		Caesium-137	Caesium-134	Manganese-54	Cobalt-60
Blowdown from spray ponds	1.36	135	59	52	104
Chemical water cleaning	0.17	22	12	5	17
Total effluents	1.53	157	71	57	121
Control level (MBq/a)	—	930	370	1900	2600
Release index (%)	—	16.9	19.1	3.0	4.7

TABLE 5.12. RADIONUCLIDE RELEASES INTO THE KHMELNITSKI NUCLEAR POWER PLANT COOLING POND (2000)

Effluent source	Released water (10^3 m^3)	Tritium (GBq)	Radioactivity (MBq)				
			Strontium-90	Caesium-137	Caesium-134	Cobalt-60	Manganese-54
Spray ponds	333	5300	2.3	8.8	15.3	0.4	—
Desalting installation	18	—	—	1.3	1.3	—	0.3
Chemical water cleaning	317	430	1.5	2.8	7.7	0.1	—
Total	668	5720	3.8	129.7	24.3	0.5	0.3

The main releases of radioactivity to water occur via primary circuit leaks, blowdown of cooling water systems, drainage from active areas, spent fuel pond operations, decontamination and maintenance operations, and drains from washrooms, showers, etc. Table 5.10 shows the radionuclide releases from all Ukrainian nuclear power plants for the five years from 1997.

Tables 5.11–5.13 show releases to the cooling ponds. In all cases the release rates are only a small fraction of the maximum permissible releases or the control level.

Tables 5.14 and 5.15 show the concentrations of the key radionuclides, ^{137}Cs and ^{90}Sr, in the ponds and receiving waters of Ukrainian nuclear power plants. These data demonstrate that, at least under post-Chernobyl conditions, it is impossible to distinguish the influence of nuclear power plant releases. Actual releases are significantly lower than permissible releases.

TABLE 5.13. RADIONUCLIDE RELEASES INTO THE ROVNO NUCLEAR POWER PLANT COOLING POND (2000)

	Released water (10^6 m^3)	Radioactivity (MBq)						
		Cobalt-60	Caesium-134	Caesium-137	Strontium-90	Silver-110m	Cobalt-58	Manganese-54
Industrial water and shower sewage	15.6	<45.0	327	755	76.6	<90	<73	<63
Domestic sewage	0.2	2.3	6.3	13	0.3	<1	<1	<1
Maximum permissible release	—	63 000	34 000	6	93	190 000	360 000	230 000
Index of maximum permissible release (%)	—	<0.08	0.98	1.30	0.08	<0.05	<0.02	<0.03

TABLE 5.14. CONCENTRATION (Bq/m^3) OF RADIONUCLIDES IN SURFACE WATERS NEAR ZAPOROZHE NUCLEAR POWER PLANT (2000–2001)

	Cooling pond		Kakhovka reservoir		
	2000	2001	Background[a]	2000	2001
Caesium-137	9.3	3.7	2.6	8.9	3.7
Strontium-90	161	74	24.3	113	57

[a] Background refers to measurements taken before reactors were commissioned.

TABLE 5.15. CONCENTRATION (Bq/m^3) OF RADIONUCLIDES IN SURFACE WATERS NEAR SOUTH UKRAINE NUCLEAR POWER PLANT (2000–2001)

	South Bug River		Outlet canals		Treatment pond for domestic sewage	
	2000	2001	2000	2001	2000	2001
Caesium-137	22	22	29	36	31	38
Strontium-90	30	30	21	40	31	38

5.7. MANAGEMENT OF RADIOACTIVE WASTE AND SPENT FUEL

5.7.1. Russian nuclear power plants

The spent fuel from RBMK reactors is currently stored under water at each plant site. The specific activity of the fuel after unloading from the reactor is as high as 10^{18}–10^{19} Bq/t, but after three years of storage it decreases to (2–4) × 10^{16} Bq/t [5.16].

Several thousand tonnes of spent fuel have accumulated from operation of the Kursk and Smolensk reactors. Existing storage facilities are almost full [5.20, 5.21]. To solve this problem, a plan has been developed, viz. Concept of Spent Fuel Management, and approved by Minatom. It prescribes the following successive actions for the period until 2020 [5.20]:

(a) Extension of existing storage facilities;
(b) Construction of interim dry storage facilities using a container type design;
(c) Removal of all the spent fuel from nuclear power plants to the centralized storage facility near Krasnoyarsk.

At present, these actions are carried out in accordance with the Work Programme of Rosenergoatom for Spent Fuel Management, 2002–2005 [5.20]. Extension of the existing storage facilities, currently under way at the Kursk nuclear power plant, will increase storage capacity by 67%. Construction of interim dry storage facilities has also commenced. A metal–concrete container that can be used for both dry storage and transport of RBMK spent fuel has been designed and is currently undergoing trials.

In addition to the spent fuel, tens of thousands of cubic metres of both liquid and solid radioactive waste is stored at the Kursk and Smolensk nuclear power plants. The volume of stored waste is close to the storage capacity, especially for solid waste [5.16]. For this reason, new waste treatment facilities will be established at the nuclear power plants. Such facilities are under construction at the Smolensk plant, while at the Kursk plant they are being designed [5.20].

5.7.2. Ukrainian nuclear power plants

The radioactive waste resulting from the production of nuclear power includes gases, liquids and solids. Very low level gaseous and liquid waste is monitored and discharged to the environment in accordance with the licensing conditions. Liquid and solid waste is treated to reduce volume and then stored at each plant. Although there have been problems with the treatment and storage of radioactive waste and spent fuel at nuclear power plants in Ukraine, there is no evidence of significant radioactive releases to surface waters or groundwaters in the vicinity of the plants.

A brief description of the waste management practices at Ukrainian nuclear power plants within the Dnieper River basin is given below.

5.7.2.1. Zaporozhe nuclear power plant

The management of radioactive waste is carried out within the main facilities of the reactor units and in special buildings designed for the processing and storage of solid radioactive waste.

Liquid radioactive waste is collected at the place of production and transported to a chemical treatment plant, where it is processed to reduce its volume. The resulting liquid is stored and pumped into another treatment process involving deep evaporation to further reduce the volume. The end product of such treatment is a salt concentrate (density about 2000 kg/m^3), which is deposited into 200 L drums. Upon cooling, the liquid solidifies into a salt monolith. The drums are then stored on the site as solid waste.

Solid radioactive waste is collected at the place of production. It is then sorted into combustible and non-combustible waste. The combustible waste is incinerated in an on-site facility. The non-combustible waste is compacted and stored on the site. A programme to minimize waste production is in progress. Table 5.16 shows the downward trend in the production of liquid and solid radioactive waste in recent years.

As of 1 January 2002 the volume of solid and liquid radioactive waste in storage at the Zaporozhe nuclear power plant was approximately 7831 m^3 and 3002 m^3, respectively. The radioactive waste management programme at the plant includes new facilities for transporting, reprocessing and decontaminating liquid radioactive waste.

TABLE 5.16. VOLUME AND ACTIVITY OF RADIOACTIVE WASTE PRODUCED AT THE ZAPOROZHE NUCLEAR POWER PLANT DURING THE PERIOD OF IMPLEMENTATION OF THE WASTE MINIMIZATION PROGRAMME (1998–2001)

	Liquid waste	Solid waste
1998	1695 m^3	487 m^3
	5.9×10^8 Bq	1.4×10^9 Bq
1999	1145 m^3	466 m^3
	1.7×10^{10} Bq	1.2×10^{10} Bq
2000	893 m^3	575 m^3
	1.7×10^{10} Bq	3.0×10^9 Bq
2001	761 m^3	380 m^3
	6.7×10^6 Bq	9.6×10^8 Bq

TABLE 5.17. VOLUME OF RADIOACTIVE WASTE (m^3) PRODUCED AT THE ROVNO NUCLEAR POWER PLANT DURING THE PERIOD OF IMPLEMENTATION OF THE WASTE MINIMIZATION PROGRAMME (1998–2001)

	Liquid waste	Solid waste
1998	1904	280
1999	1860	262
2000	1522	190
2001	1330	110

The Zaporozhe nuclear power plant is unique in Ukraine in that practical measures have been taken to solve the problem of the long term safe storage of spent nuclear fuel. Since 1993 work has been undertaken on the dry storage of spent nuclear fuel. Having analysed the various design options, it was decided to use concrete containers as developed in the USA. A positive feature of this design is its low cost.

5.7.2.2. Rovno nuclear power plant

The radioactive waste management system at the Rovno nuclear power plant is similar to that at the Zaporozhe nuclear power plant. Liquid radioactive waste processing at the Rovno nuclear power plant includes pretreatment, evaporation and bituminization. The procedure for solid radioactive waste treatment includes sorting the waste followed by on-site storage. Table 5.17 shows the reduction in waste volumes with time due to implementation of the waste minimization programme at the Rovno nuclear power plant.

Waste minimization initiatives have included improvement of existing systems and installation of a bituminization plant and a facility to immobilize evaporated salts in a bitumen matrix. There are plans for a new facility for sorting, drying and compacting solid waste, and another for evaporation of liquid radioactive waste to dryness. At the beginning of 2002 the accumulated volumes of radioactive waste were estimated as 3838 m^3 of solid waste and 6216 m^3 of liquid waste.

The previous waste management programme expired in 2001 and a new programme is being developed that will take into account the operation of the fourth reactor at the Rovno nuclear power plant.

The safe storage of spent fuel remains an important issue at the Rovno nuclear power plant as at other sites in Ukraine. Previously the spent fuel was exported to the Russian Federation. The design of a temporary storage facility for spent fuel is currently under development.

5.7.2.3. Khmelnitski nuclear power plant

Waste management operations at the Khmelnitski nuclear power plant include sorting, purification and evaporation of liquid waste to form a salt mixture. The conditioned waste is stored on the site.

A radioactive waste management programme was implemented from 1998 to 2001. Table 5.18

TABLE 5.18. VOLUME OF RADIOACTIVE WASTE (m^3) PRODUCED AT THE KHMELNITSKI NUCLEAR POWER PLANT DURING THE PERIOD OF IMPLEMENTATION OF THE WASTE MINIMIZATION PROGRAMME (1998–2001)

	Liquid waste	Solid waste
1998	140	196
1999	114	184
2000	158	204
2001	98	175

shows the trend in waste volumes over this period. The lowest waste volumes were achieved in the final year of the programme. The National Nuclear Regulatory Body of Ukraine has approved the waste management action plan for 2002.

At the beginning of 2002 the accumulated volumes of radioactive waste were estimated as 3363 m^3 of solid waste and 530 m^3 of liquid waste.

The capacity of storage facilities at the Khmelnitski nuclear power plant is currently stretched; for example, five of the six tanks in use for storage of the highest category solid radioactive waste are full. New facilities for the temporary storage of spent fuel are under development.

5.8. OVERVIEW OF SAFETY ANALYSES PERFORMED FOR NUCLEAR REACTORS

5.8.1. Russian Federation

The first efforts to assess the safety of the Smolensk and Kursk nuclear power plants were made during the phase of preparing the environmental impact assessment. The environmental impact assessment analyses all impacts of significance, including releases of radioactive substances during normal operation and in the event of design and BDB accidents.

Since 1990 all industrial facilities, including nuclear power plants, have been obliged to have an environmental 'passport' approved by the USSR Goscompriroda or, after the collapse of the USSR, the Russian Ministry of Natural Resources (Minpriroda). The environmental passport includes, inter alia, a brief description of the facility and its location, data on actual (including emergency) and maximum permissible discharges and releases to the environment (all media), and information on water treatment facilities and quantities and methods of waste storage. When modifications are made to technology, equipment, standards, etc., appropriate changes are made in the environmental passport.

As part of the regulatory licensing regime described above, the operators of nuclear facilities must also provide a written SAR in order to justify construction, operation or continuation of operations. The scope and content of these submissions are outlined in a regulatory guide issued by Gosatomnadzor. This guide has been recently amended and the current requirements on the content and format of the SARs in the Russian Federation are in line with best international practice.

Over the last few years a programme of SAR production/enhancement has taken place to the point where the expectation is that a fully developed safety report or justification for each reactor unit will be provided, the content and scope of which should meet Gosatomnadzor requirements and international standards.

Specifically, for the first generation RBMK plants, which did not have a modern SAR, an 'in-depth safety assessment' (IDSA) was required, primarily within the scope of the European Bank for Reconstruction and Development (EBRD) activities in support of nuclear safety improvements in eastern Europe. The aim of the IDSA is to provide the operator and the regulator with a comprehensive analysis on which safety decisions, such as continued plant operation and the need for further plant safety upgrades, can be based. Most of the IDSAs have now been completed, or are nearing completion for the older designs of nuclear power plant.

As mentioned in Section 5.3.1, at the Kursk nuclear power plant two of the reactor units are of the first generation and two are of the second generation. An IDSA was completed for unit 1 in 2000. This was the first IDSA for an RBMK in the Russian Federation. The accident analyses performed within the scope of this assessment justified the new design basis for the plant, which has been extended to cover primary pipe breaks up to 300 mm. A number of BDB and severe accidents have also been considered, and measures to improve accident management have been elaborated. The impact on safety of all safety improvement measures implemented at the site has been evaluated. The report has been reviewed by the regulatory body and amended to take account of its comments. In the preparation of the IDSA report for Kursk nuclear power plant unit 2, the relevant experience gained at Kursk 1 is being taken into account.

The first version of the PSA for Kursk 1, which considers internal initiators during normal power operation, has also been recently completed. The preliminary results show that the expected core damage frequency might be in the range of 6.0×10^{-5}, but it is understood that the study needs to be revised and completed before taking any safety related decisions.

The unit 2 IDSA is planned for completion by the end of 2003. Units 3 and 4 have a basic SAR.

TABLE 5.19. ESTIMATES OF EXTERNAL RADIATION DOSES TO THE CRITICAL POPULATION GROUP FOR DESIGN AND BEYOND DESIGN BASIS ACCIDENTS AT THE FIFTH UNIT OF THE KURSK NUCLEAR POWER PLANT

	Radiation dose for the whole body (mSv/a)	
	From plume	From soil surface
Design	0.15	0.08
BDB	0.65	0.24

However, work is planned to enhance the scope of the safety analyses for these units to also include a PSA by the end of 2005.

At the Smolensk nuclear power plant the three units are of the second generation and have had basic SARs for some years. However, as for Kursk units 3 and 4, a programme is in place to enhance the safety analyses to include a PSA by the end of 2005.

In the meantime, all nuclear power plants annually submit a report on operational safety to Gosatomnadzor. The scope of these reports is set out in guidelines jointly produced by Gosatomnadzor and Minatom. The annual assessments check on plant physical condition, report on progress with modification programmes, review operational experience feedback and identify any additional measures to improve operational safety in the forthcoming year.

In Ref. [5.22] the dose rates to the critical population group resulting from design and BDB accidents at the fifth unit of the Kursk nuclear power plant (then under construction) are estimated. The critical group was the residents of the western edge of the town of Kurchatov, lying 3 km from the plant. The derived estimates are presented in Tables 5.19 and 5.20. The doses to the critical population group do not necessitate any special protection measures, even in the event of a BDB accident.

The report of ISTC Project 503 [5.23] provides a review of models for the transport of radionuclides in the accident confinement systems (ACSs) and their release to the environment. Analysis of ACSs was performed for units 1–3 of the Smolensk nuclear power plant. Assessments have been made for releases of radionuclides from ACSs to the environment under different scenarios of accident evolution, involving rupture of the pressure header in the event of loss of tightness in 10% and 100% of fuel elements.

5.8.2. Ukraine

For each of the nuclear plants in Ukraine, a basic SAR (hereafter referred to as a safety substantiation report) exists. These reports now form the basis on which the SNRCU grants annual permits for continued operation of the units. The safety substantiation report includes an analysis of a number of anticipated operational occurrences and DBAs that have been considered in the justification of plant design safety and in development of the design operating limits and conditions. This substantiation report stipulates the fulfilment of the safety standards and codes that are effective at the time of development of the document.

TABLE 5.20. ESTIMATES OF DOSES TO THE CRITICAL POPULATION GROUP VIA INHALATION FOR DESIGN AND BEYOND DESIGN BASIS ACCIDENTS AT THE FIFTH UNIT OF THE KURSK NUCLEAR POWER PLANT

	Radiation dose for organs (mSv/a)		
	Gonads	Lungs	Thyroid
Design	0.10	0.11	18
BDB	0.28	3	21

Over the past few years Energoatom and the nuclear power plants have devoted considerable effort to reassessing the safety of the units in operation in order to comply with the SNRCU's requirements for the development of comprehensive SARs. A programme has been established for the gradual completion of the work and submission to the SNRCU of all the documents needed to obtain a permanent licence in accordance with the new regulatory body licensing policy.

The strategy of the safety reassessment is focused on combining a periodic safety review by the end of a specified date with an IDSA using modern analysis techniques (such as probabilistic safety analysis and BDB accident analysis). This safety reassessment is being undertaken now for three reference units, representing each of the three types of reactor in operation. These are:

(a) Zaporozhe unit 5, WWER-1000 (B-320), large series;
(b) South Ukraine unit 1, WWER-1000 (B-302), small series;
(c) Rovno unit 1, WWER-440 (B-213).

In accordance with the SNRCU's regulation, at the first stage of a safety reassessment the analysis should contain an extended (supplementary to the original design) safety substantiation report, additional material on safety analysis related to the evaluation of operational safety and ageing mechanisms and a new design basis analysis and probabilistic safety analyses at level 1 for internal initiators at nominal power. Based on the results of these analyses, the SNRCU will take a decision as to whether to grant a permanent licence for each of the plants and will set up the priorities for further nuclear power plant safety improvements.

During the second stage of the safety reassessment, the PSA analysis at level 1 should be complemented with analyses for external initiators and a low power and shutdown PSA. It is planned also to perform level 2 PSAs and BDB accident analyses, which will allow completion of the evaluation and preparation of comprehensive SARs in accordance with best international practice.

The first part of the safety reassessment for South Ukraine 1 and Rovno 1 has recently been completed and submitted to the regulatory body. The work for completion of that for Zaporozhe 5 is also at an advanced stage. Similar analyses will be performed for the remaining units; however, it is understood that their scope will be limited to consideration of the differences between the reference plant and each individual plant.

The results of the first versions of the PSA level 1 studies for the South Ukraine 1, Zaporozhe 5 and Rovno 1 units are in line with the results for similar types of nuclear power plant in other countries, and the estimated core damage frequency is reported to be 1.5×10^{-4}, 4.5×10^{-5} and 8.1×10^{-5}, respectively. The iterative process adopted by the regulatory body for the review of these studies is scheduled for completion by the end of 2002.

The second part of the safety reassessment for the reference plants is expected to be ongoing until the end of 2003/2004. Once completed, results from severe accident analyses and PSA level 2 studies can serve as a basis for improvement of the accident management guidelines and emergency preparedness for the nuclear power plants in the Dnieper River basin.

For future construction work and commissioning of the new units at Khmelnitski and Rovno, the preparation of a comprehensive SAR, in accordance with best international practice, is envisaged.

5.9. STATUS OF THE IMPLEMENTATION OF SAFETY IMPROVEMENT PROGRAMMES FOR NUCLEAR FACILITIES

5.9.1. Russian Federation

After the Chernobyl accident an improvement programme began for the RBMK reactors. The most urgent safety improvements required for the first generation RBMKs were completed in 1986 to exclude the possibility of another accident like that at Chernobyl [5.4, 5.24]. There are six RBMK units in total: Leningrad units 1 and 2, Kursk units 1 and 2 and Chernobyl units 1 and 2 (now closed down). Some further general improvements have been completed but others remain to be implemented. The first stage of modernization took place in the 1990s. The second stage of modernization is ongoing.

The urgent measures were carried out to improve both the inherent behaviour of the reactor and operational safety. In particular, the following measures were implemented:

(a) Increased enrichment of the fuel and increased neutron absorbers;

(b) Reduction of the positive void effect by improving reliability of the water supply of the control and protection system (CPS) cooling circuit and reducing the water volume within the core part of the CPS circuit;
(c) Improvement of the efficiency and reliability of the CPS by modifying the design of the control rods, increasing the worth and the speed of the shutdown system, and improvement of the monitoring of the operational reactivity margin (ORM);
(d) Monitoring of the margin of the main cooling pump cavitations;
(e) Implementation of improved in-service inspection of pipes and components;
(f) Improvement of operational documentation.

Following the urgent upgrading programme, the first stage of modernization was performed in the middle and late 1990s; some of it is still ongoing. Where necessary this included replacement of the fuel channels to avoid closure of the gap between the channels and the surrounding graphite. In particular, the following measures were taken:

(a) Enhancment of the pressure boundary integrity by:
  (i) Replacement of some reactor coolant circuit pressure components;
  (ii) Increased in-service inspection of the main coolant components.
(b) Improvement of the load bearing capability of the building structure by improving the reactor cavity venting system (simultaneous rupture of about nine fuel channels).
(c) Enhancement of the core structure and control and shutdown systems:
  (i) Introduction of uranium–erbium fuel;
  (ii) Introduction of 12 additional CPS manual rods as a shutdown system backup;
  (iii) Replacement of CPS drives and flux distribution monitoring (high frequency sensors);
  (iv) Interlock systems to prevent unauthorized withdrawal of CPS rods.
(d) Improvement of emergency core cooling:
  (i) Two additional emergency feedwater pumps for the emergency core cooling system (ECCS-1) (first generation nuclear power plants);
  (ii) Possibility of emergency makeup of the main cooling circuit by service and fire fighting water.
(e) Installation of a temporary emergency control panel (as a preliminary solution for the emergency control room).

At present, the safety of nuclear installations in the Russian Federation is being improved in accordance with the programme of development of atomic energy in the Russian Federation in 1998–2005 and to 2010 (Decree of the Government of the Russian Federation of 21 July 1998) and the federal targeted programme on nuclear and radiation safety in the Russian Federation (Decree of the Government of the Russian Federation 149 of 22 February 2000). Within the last programme, in 2000–2001, a number of research institutions and other organizations further developed the scientific, normative, methodological and organizational framework. It is envisaged that in the second stage (2002–2003) all subunits of the programme will be performed in a consistent way. In the final stage (2004–2006) the key tasks will be implemented and future activities will be identified. Specifically, the section on nuclear installations and facilities of radiation hazard provides for the following activities:

(a) Improving the quality of maintenance and repair of the equipment of nuclear power plants;
(b) Setting up systems for warning and mitigation of emergencies at nuclear power plants and other nuclear installations, including emergency centres and consulting and research centres;
(c) Enhancing the logistical and organizational base of the emergency rescue units of Minatom to improve preparedness for emergencies;
(d) Conducting research and design activities to improve the nuclear and radiation safety of fuel cycle activities in the nuclear industry using fast breeder reactors;
(e) Development and adoption of guidelines and training aids, including full scale simulators in training centres at nuclear power plants;
(f) Updating technologies for handling radioactive waste and spent nuclear fuel;
(g) Setting up disposal sites and storage facilities for radioactive waste and spent nuclear fuel.

A second stage of modernization is being undertaken in order to bring the state of RBMKs into compliance with the current requirements. Where applicable this includes:

(a) Integrated instrumentation for monitoring, control and protection of the reactor with two redundant and diverse trains.
(b) ECCS with two redundant trains, one upgraded and one new (ECCS-2).
(c) A physically separated and protected emergency building to house an emergency control room (from where reactor shutdown and core cooling can be controlled).
(d) Completion of the ACOTT leak detection system with three diverse types of sensor train (one measure of the leak before break concept, which should compensate for the limited cooling and load bearing capability, since the first generation of nuclear power plants can not sustain pipe ruptures larger than 300 mm).
(e) Introduction of a confinement safety system activated at fuel channel rupture.
(f) Introduction of a reactor protection trip signal caused by a group distributor header (GDH) flow rate decrease.
(g) Implementation/replacement of GDH check valves.
(h) Installation of a modern operational information support system (SKALA);
(i) Introduction of an automated radiation monitoring system (ASKRO).
(j) Upgrade of the service water system.
(k) Introduction of a bypass pipe between the reactor coolant pump pressure header and the ECCS.
(l) Upgrade of the drum separators.
(m) Upgrade of the AC/DC emergency power supply.
(n) Upgrade of fire protection, for example replacement of flammable turbine hall roof lagging.
(o) Improvement in the area of operational safety by restructuring of the nuclear power plant management and improvements in training, including simulator training.

Further planned improvements will take into account operational experience feedback and recommendations of the updated SAR and plant specific PSA.

Emphasis will be given to further enhancements at all levels of the defence in depth safety concept, in order to compensate for the absence of a full containment (especially for nuclear power plants of the first generation). Furthermore, work will include the enhancement of emergency operating procedures (and development of a symptom based emergency operating procedure (EOP) and accident management guidelines) and the introduction of a systematic ageing management programme.

The additional planned improvements will be influenced by any decision on possible life extension of the reactors to more than 30 years, which was the original design life.

Table 5.21 summarizes the current status of implementation of the main safety upgrades for the Russian reactors. The table has been prepared based on the available information and may not be fully up to date.

A series of actions are also under way to further protect the public and operating personnel at nuclear power plants. These measures are especially important for the Kursk and Smolensk nuclear power plants, as the personnel exposures at plants with RBMK reactors are twice as high as at other Russian nuclear power plants. The personnel exposure levels will be reduced through the following initiatives:

(a) Organizational actions including study and application of the ALARA concept;
(b) Measures to improve the radiation situation;
(c) Measures to reduce the time spent by personnel in ionizing radiation fields.

A comparative analysis of personnel exposure at the Kursk and Smolensk nuclear power plants over many years indicates that organizational improvements only are possible at the Kursk nuclear power plant, whereas at the Smolensk nuclear power plant technical changes are needed. Some technical changes are proceeding, in spite of limited funding. In particular, a series of remote automated instruments has been developed for maintaining the RBMK-1000 reactors operating at the Kursk and Smolensk nuclear power plants.

One of the important activities within the federal law section Protection of the Population, Rehabilitation of Contaminated Areas and Monitoring of the Radiation Situation is technical and organizational support for the federal automated system for monitoring the radiation situation (ASKRO) (see Section 5.5.1). At present, there are 14 stations for automated monitoring of the dose rate around the Smolensk nuclear power plant and 11 stations around the Kursk nuclear power plant. The ASKRO for the Kursk nuclear power plant began operation on a test basis in 2002.

TABLE 5.21. SUMMARY OF THE STATUS OF THE MAIN SAFETY UPGRADES FOR THE KURSK AND SMOLENSK NUCLEAR POWER PLANTS

Improvement measure	Kursk				Smolensk		
	1	2	3	4	1	2	3
New fuel (enrichment, erbium as burnable absorber)	P	P	P	P	—	—	—
CPS channel and cooling modifications	Y	—	—	—	—	—	—
Modification of control rods and speed of insertion	Y	Y	Y	Y	Y	Y	Y
Interlock to prevent unauthorized control rod withdrawal	Y	—	[a]	[a]	Y	Y	Y
Monitoring of ORM	Y	Y	Y	Y	Y	Y	Y
Addition of fast acting shutdown system	Y	Y	Y	Y	Y	Y	Y
Redundant, diverse and physically separated shutdown system	Y	—	—	—	—	—	—
Reactor protection signal caused by GDH flow rate decrease	Y	—	—	—	—	—	—
Replacement of fuel channels (channel–graphite gaps)	Y	Y	P/2002	P/2003	P/2002	P/2006	P/2010
Capacity of reactor cavity venting system (simultaneous rupture of about nine channels)	Y	—	Y	Y	Y	Y	Y
Bubble condenser for ALS (first generation)	Y	—	Included in the original design				
Inspection of intergranular stress corrosion of lower water lines	Y	Y	Y	Y	Y	Y	Y
Upgrading of existing ECCS	Y	—	Included in the original design				
Redundant and physically separated ECCS	Y	—	Included in the original design				
Steam drum modification to increase water inventory for emergency cooling	Y	—	Water volume is enlarged by design				
Implementation of check valve in group distribution headers	Y	2002	Y	Y	Y	Y	Y
Emergency control room	Y	—	[a]	[a]	[a]	[a]	[a]
Upgrade of AC/DC emergency power supply	Y	—	[a]	[a]	[a]	[a]	[a]
SKALA-micro (modernized operational information support system)	Y	—	—	—	—	—	—
ACOTT leak detection system (leak before break concept)	Y	—	[a]	[a]	[a]	[a]	[a]
Introduction of ASKRO automated radiation monitoring system	Y	—	—	—	—	—	—
Significant upgrading of fire protection	Y	P	P	P	P	P	P

TABLE 5.21. SUMMARY OF THE STATUS OF THE MAIN SAFETY UPGRADES FOR THE KURSK AND SMOLENSK NUCLEAR POWER PLANTS (cont.)

Improvement measure	Kursk				Smolensk		
	1	2	3	4	1	2	3
Improvement in operator training and licensing	Y	Y	Y	Y	Y	Y	Y
Full scope simulator	—	—	Y	Y	Y	Y	Y
Status of IDSA	P	—	TOB	TOB	TOB	TOB	TOB
Plant specific PSA	June 2003	—	—	—	—	—	—
Issue and expiry date of the operational licence	October 2000– October 2003	April 2002– April 2003	November 1999– November 2003	November 1999– November 2003	January 1999– December 2003	February 1999– January 2004	January 2002– April 2007

[a] Information on the implementation status not publicly available.
Y: Implemented.
P: Partly implemented.
TOB: Technical substantiation of safety (basic SAR).
—: No.

5.9.2. Ukraine

A design review of the second generation WWER reactors did not identify any safety deficiencies of the highest significance (as, for example, were found for the first generation reactors). Safety improvements, however, have been made to these plants in relation to:

(a) Control rod insertion reliability;
(b) Prevention of containment sump filter clogging (to ensure recirculation of the ECCS in the event of a loss of coolant accident (LOCA));
(c) Reliability of overpressure protection devices;
(d) Capacity of accumulator batteries.

There are several other issues that require resolution, and measures to address these are still under way. These issues include, inter alia, the following:

(i) Quality and reliability of individual safety related equipment (e.g. instrumentation and control);
(ii) Reactor pressure vessel embrittlement;
(iii) Steam generator integrity (protection against primary to secondary leaks);
(iv) Vulnerability with regard to hazardous systems interactions, including protection against common cause failures (e.g. high energy pipe breaks, fire and internal flooding);
(v) Monitoring for vibration and water leaks;
(vi) Control room design in conjunction with accident monitoring equipment;
(vii) Installation of a safety parameter display system in order to provide the most relevant information on critical safety parameters under accident conditions.

At present, an international IDSA process is under way to optimize improvement programmes. Further analyses are being carried out in relation to:

— Design criteria of containment integrity assessment for simultaneous occurrence of a large break LOCA and an earthquake;
— Periodicity of and methods for containment integrity and tightness tests;
— Stability of reactor pressure vessel internals in the event of a large break LOCA;
— Estimated frequency and size of large steam generator collector leaks and the possible impact on pipes and supports of dynamic loads;
— Total loss of service water (input and results from PSAs);
— Extreme natural phenomena and an aircraft crash;
— Integrity of the suction line of the ECCS.

Feedback of operating experience is a major contributory factor to the development of improved plant safety. The most important sources for feedback of experience are abnormal occurrences and deficiencies revealed during operation, as well as experience gained from maintenance and inspection activities.

Table 5.22 summarizes the current status of implementation of the main safety upgrades for Ukrainian reactors. The table has been prepared based on the available information and may not be fully up to date.

5.9.3. Emergency preparedness and response

The Chernobyl accident demonstrated the need for the development and constant maintenance of systems for emergency preparedness and response.

The systems for emergency preparedness and response in the Ukrainian and Russian nuclear power plants are based on IAEA recommendations [5.25–5.27] (i.e. they include a set of technical and organizational measures). The State Committee of Nuclear Regulation of Ukraine and Goskomnadzor in the Russian Federation control the levels of a nuclear power plant's emergency preparedness. Special procedures define the interaction of the nuclear power plant's emergency units with the regional branches of the Ministries of Emergencies in the Russian Federation and Ukraine for population protection in the event of an emergency. Specialized drills and exercises for the emergency units of nuclear power plants and their interaction with the emergency units of other institutions are performed on a regular basis. Information crisis centres with various levels of equipment and telecommunications exist at the SCNRU, Goskomatomnadzor, the Ministries of Emergencies of Ukraine and the Russian Federation, Energoatom in Ukraine and Rosenergoatom.

In Ukraine all measures for emergency preparedness and response are integrated into the Uniform State System for Prevention and Response to Man-induced and Natural Emergencies (USSE). In 2001 a plan of response to State level emergencies was developed by the Ministry of Emergencies and approved by Resolution No. 1567 of the Cabinet of Ministers of Ukraine [5.28]. The plan specifies the performance of work to mitigate the consequences of any human-made or natural emergency, the responsibilities of the various control authorities and the required financial, material and other resources. The development of a specific plan for nuclear and radiation accidents was approved by Resolution No. 122 of the Cabinet of Ministers of Ukraine. The plan will be developed taking into account recommendations of the IAEA [5.29].

The technical bases for emergency response are monitoring systems around nuclear power plants. Each plant has its own system of automatic control of radioactive contamination in the 30 km zone (ASKRO) as well as systems for monitoring releases from the stacks. In Ukraine, with the support of the European Commission, and within the framework of the Technical Assistance to Commonwealth of Independent States (TACIS) programme, the early warning system GAMMA-1 was developed around the Zaporozhe and Rovno nuclear power plants. The information from GAMMA-1 is transmitted to the emergency centres of the Ministry of the Environment of Ukraine and Ministry of Emergencies of Ukraine, with duplication to the SCNRU.

Each nuclear power plant uses computer codes for the simulation of atmospheric dispersion of radionuclides after atmospheric releases. A real time, on-line decision support system (RECASS) was developed by SPA Typhoon and is under implementation now for the Kursk and Smolensk nuclear power plants. In Ukraine a real time, on-line decision support system for off-site nuclear emergency management (RODOS) was implemented in 2002. It was customized for the Zaporozhe nuclear power plant site and linked with GAMMA-1 and the system of real time meteorological forecasting. In Belarus, RODOS has been used in the off-line mode to simulate fallout on Belarusian territory from an accidental release from the Ignalina nuclear power plant.

Strengthening of the system of emergency response in all countries requires further development of the automatic monitoring (early warning) systems around each nuclear power plant and further development of the real time decision support system for off-site emergency management. The decision support system should include modules for forecasting post-accident contamination of water bodies after accident fallout or direct releases into water. The system for information exchange between nuclear power plant emergency units and regional authorities should be improved.

TABLE 5.22. SUMMARY OF THE STATUS OF THE MAIN SAFETY UPGRADES FOR UKRAINIAN NUCLEAR POWER PLANTS

Improvement measure	Zaporozhe						South Ukraine			Khmelnitski	Rovno		
	1	2	3	4	5	6	1	2	3	1	3	1	2
Control rod insertion reliability	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	n.a.	n.a.
Prevention of sump filter clogging	—	—	—	—	—	—	P	—	P	—	—	P	P
Reliability of overpressure protection devices	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Equipment qualification (e.g. instrumentation and control)	A programme for equipment qualification has been prepared by Energoatom; work to be implemented in the near future for each of the units												
Reactor pressure vessel embrittlement (monitoring, measures)	P	P	P	P	P	P	P	P	P	P	P	n.a.	n.a.
Heating system	—	—	—	—	—	—	P	P	P	Y	Y	Y	Y
Steam generator integrity	P	P	P	P	P	P	P	P	P	P	P	P	P
28.8 m (14.7 m for WWER-440) platform; vulnerability with regard to hazardous systems interactions; high energy pipe breaks	Safety analyses are in progress to evaluate the necessity of additional plant upgrades												
Modification of feedwater supply system	P	P	P	P	P	P	P	Y	—	—	Y	P	P
Upgrade of emergency power supply	Y	P	P	P	P	P	P	P	P	P	P	P	P
Significant upgrading of fire protection	Y	Y	Y	Y	Y	Y	P	P	P	P	Y	P	P
Leak detection system (leak before break concept)	—	—	—	—	—	—	—	—	—	—	P	—	P
Introduction of automated radiation monitoring system	P	P	P	P	P	P	P	P	P	P	P	P	P
Installation of a safety parameter display system (SPDS)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ageing management (fatigue monitoring)	P	P	P	P	P	P	P	P	P	P	P	P	P
Symptom based EOP	—	—	P	—	P	—	P	—	—	—	P	—	—
Full scope simulator	Y	P	—	—	—	—	Y	—	Y	Y	Y	P	—
Severe accident guidelines	—	—	—	—	—	P	P	—	—	P	P	—	—
Status of safety reassessment													
First stage	—	—	—	—	P	—	Y	—	—	—	—	Y	—
Second stage	—	—	—	—	2004	—	2004	—	—	—	—	2005	—
Plant specific PSA	—	—	—	—	Y	—	Y	—	P	P	Y	Y	—
Issue and expiry date of the operational licence	Issued on an annual basis												

Y: Implemented.
P: Partly implemented.
n/a: Not applicable.
—: No.

5.10. CONCLUSIONS

(a) The Russian and Ukrainian legislation affirms the priority of human health and environmental protection in the context of the operation of nuclear installations.

(b) A legislative and regulatory basis established in both the Russian Federation and Ukraine ensures that all nuclear power plants operate with a valid licence. A legal mechanism exists for regulatory body review and assessment of plant safety and renewal of plant licences on a regular basis.

(c) In the Dnieper Basin within the Russian Federation there are two nuclear power plants in operation. They comprise seven reactor units of the RBMK type. Following the Chernobyl accident, modernization programmes have been put in place that have significantly increased the safety of these reactors.

(d) In Ukraine there are 13 WWER units in operation, of which ten are in the Dnieper River basin. These reactors belong to the common PWR type. Significant improvements have been made to these reactors and are ongoing.

(e) During normal operation the radioactive emissions from the reactors in the Dnieper River basin represent a small fraction of the authorized discharge limits. The contribution of these emissions to the atmospheric radioactive burden and to the aquatic environment are negligible for the Dnieper River basin.

(f) For potential severe accidents, a set of intervention criteria that are consistent with the Basic Safety Standards [5.19] and the relevant ICRP recommendations [5.30] has been established by the countries of the region.

(g) Over the past few years considerable effort has been made to complete the IDSA for reference units, covering all types of the reactors operating in the river basin. This assessment includes analyses of DBAs and BDB and severe accidents, as well as PSAs. These studies have been performed in accordance with current international practice.

5.11. RECOMMENDATIONS

(a) Rules and regulations governing the safety of the operation of nuclear power plants should be further developed with a view to harmonizing them within the Dnieper River basin region, consistent with international practice and the standards of the IAEA.

(b) Cooperation and information exchange between regulatory organizations should be strengthened to make use of the experience gained in implementing the safety upgrading programmes and lessons learned from operating experience.

(c) The scope of SARs for each of the nuclear power plants should be in compliance with the national requirements and be consistent with the IAEA safety standards and current international practices. The experience gained in developing the assessments for the reference units should serve in future as a sound basis for these reports. It would be desirable to exchange information on the results.

(d) Comprehensive, plant specific PSAs should be finalized for all nuclear power plants in the region and subjected to thorough regulatory review. This would provide the basis to use them for identifying priorities for safety improvements and risk informed decision making. The countries could benefit from participation in the activities organized by international organizations such as the IAEA on comparison of PSA studies for similar reactors.

(e) To improve preparedness for a possible nuclear accident, technical measures (early warning systems, decision support systems), institutional measures (logistics) and links between nuclear power plants and regional administrative units should be improved.

(f) Plans established for safety improvements should be carried out as a matter of high priority. Exchange of experience in implementing safety improvement programmes for similar plants will help to harmonize the level of safety in the region and minimize the potential for radioactive releases from operational nuclear power plants.

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6. URANIUM MINING AND ORE PROCESSING

6.1. SCOPE

This section reviews the environmental impact of uranium mining and ore processing in Ukraine. Particular attention is given to the management of mill tailings, releases from current and former plants, and data available on contamination of water bodies within the Dnieper River basin. Radiation exposure of the public via water-borne pathways is discussed in Section 8 and uranium facilities are assessed as radiological hot spots in Section 9.

6.2. OVERVIEW OF URANIUM MINING AND PROCESSING IN THE DNIEPER RIVER BASIN

As noted in Section 3, the only uranium mining and ore processing in the Dnieper River basin is in Ukraine. Uranium exploration started in 1944 and led to the discovery of the Pervomayskaya deposit in 1945 and the Zheltorechenskoye deposit in 1946. Other ore bodies were subsequently discovered within the boundaries of the Kirovograd, Dnipropetrovsk and Nikolaev regions. Figure 6.1 shows the 21 uranium deposits discovered in Ukraine [6.1]. The largest deposits are Severinskoye, Michurinskoye and Vatutinskoye.

Uranium was first produced in Ukraine at the Prydniprovsky chemical plant, which was part of a large industrial complex on the shores of the Dnieper River in Dniprodzerzhinsk. From 1948 until its closure in 1991, about 42×10^6 t of uranium tailings and other radioactive waste was generated.

The Zhovti Vody hydrometallurgical plant has processed ores from southern Ukraine since 1959. It is located at a former iron ore production site near the centre of Ukraine's main uranium province and is operated by the Eastern Mining and Concentrating Mill (VostGOK). The design capacity of the mill is 1×10^6 t of ore per year, but in recent years it has been operating at about 50% capacity. Currently, most of the production comes from the Ingulsky mine developed on the Michurinskoye deposit. There is also a small amount of production from the Smolino mine developed on the Vatutinskoye deposit. Ore from the Ingulsky and Smolino mines is hauled to the mill at Zhovti Vody by dedicated trains [6.2].

There are proposals to mine the Severinskoye deposit, which has reserves of 64 000 t U at an average grade of 0.1%. Doubling of the capacity of the Zhovti Vody plant to 2000 t U/a is also envisaged [6.2].

Three ore bodies, Bratskoye, Devladovo and Safonovskoye, have been exploited by the in situ leaching method. This involves injection of sulphuric acid and a small amount of nitric acid into the ore body and pumping the uranium bearing solution to the surface, where it is recovered. This avoids the problems of solid waste management but, with unfavourable conditions, can result in contamination of groundwater.

The following sections discuss the source terms arising from the uranium mines and mills in southern Ukraine.

FIG. 6.1. Uranium ore deposits and uranium processing operations in Ukraine [6.1]. 1: Vatutinskoye; 2: Severinskoye; 3: Michurinskoye; 4: Zheltorechenskoye; 5: Pervomayskoye; 6: Lozovatskoye; 7: Kalinovskoye; 8: Yuzhnoye; 9: Nikolokozelskoye; 10: Nikolayevskoye; 11: Berekskoye; 12: Krasnooskolskoye; 13: Adamovskoye; 14: Sadovokonstantinovskoye; 15: Bratskoye; 16: Safonovskoye; 17: Devladovo; 18: Novogurievskoye; 19: Surskoye; 20: Chervonoyarskoye; 21: Markovskoye.

6.3. SYSTEMS FOR MONITORING POLLUTION FROM THE URANIUM INDUSTRY

In Ukraine monitoring of the environment around uranium mines and mills is based on standards developed in the 1970s. Measurements of radioactive pollution arising from liquid discharges (e.g. mine, drainage and tailings pond water) to non-stagnant receiving waters are carried out twice yearly in spring and autumn. The location of the sampling points depends on specific conditions, but typically sampling is carried out at the following locations:

(a) Above the site of release of liquid waste;
(b) At the site of runoff water release;
(c) Two to four points downstream of the release site (at the sites of possible water use, in the region of settlements, etc.).

Water samples are analysed for uranium, ^{226}Ra and total alpha activity. The concentrations of other radionuclides (^{230}Th, ^{210}Po and ^{210}Pb) are determined if the uranium and/or total alpha activities are above the permissible levels.

Radiation–sanitary monitoring at closed and decommissioned uranium facilities is carried out every three years. Reoriented uranium facilities (i.e. those that formerly processed uranium but now have different functions) are monitored every five years. Measurements are made of the radiochemical composition of drainage water and of the water bodies that receive the water.

After cessation of uranium processing, waste storage/disposal facilities are the responsibility of new enterprises that are controlled by a specially established commission that has the power to evaluate and control the condition of the waste management facilities. The commission is composed of specialists, local authorities and representatives of regulatory bodies.

In accordance with the 1996 government document Provisions of the State Monitoring of Waters, monitoring of the quality of surface and underground waters of the Dnipropetrovsk region is performed by specified State and regional laboratories. These laboratories perform measurements of the content of artificial radionuclides in the environment, namely ^{90}Sr and ^{137}Cs, and of total beta and total alpha activity in drinking water and in the surface waters of the Dniprodzerzhinsk (lower part), Dnieper and Kakhovka (upper part) reservoirs and the tributaries of the Dnieper–Samara, Orel and Ingulets Rivers. The sampling is performed several times a month, and the reports are sent monthly to the higher regional authorities.

The Sanitary and Epidemiological Station No. 8 and the Laboratory for Radiation Control of Industrial Enterprises ‘barrier’ monitor the tailings at the Prydniprovsky chemical plant site and within the sanitary and protective zones. These laboratories mainly perform routine measurements; there is no interpretation of the data. Since the actual levels of contaminants in water do not exceed the sanitary norms permitting unrestricted water use, no attention is paid to assessments of low levels of contamination [6.3–6.6].

The regional administration supports scientific and research work on the ecological and toxicological state of surface waters of the region where ecological hazards are greatest. The administration also develops recommendations on minimization of any negative impacts (particularly from tailings at the former Prydniprovsky chemical plant site — Dniprovske D and Sukhachevskoye C).

Following a government decision in 1999, a field programme was developed to improve the radiological condition of uranium facilities and the environment in which they are located. The aim of the programme is to implement State policy on radioactive waste management in uranium processing in the region. The main aspects of this programme are:

(i) Closure, restoration and temporary shutdown of uranium facilities, where appropriate;
(ii) Development and optimization of regional radiation monitoring;
(iii) Reduction of the harmful impact of uranium facilities on the environment and human health.

The following tasks are envisaged within the framework of this programme:

— Identification of the negative impact of uranium facilities on the environment;
— Assessment of the contamination of the ground, water and air;
— Calculation of the dose rate to people living in areas affected by uranium facilities;
— Determination of the required expenditures for closure, redirection and temporary shutdown of uranium facilities;

— Determination of the expenditure needed for reduction of the harmful impact of uranium facilities on the environment;
— Determination of the expenditure needed for performance of radiation monitoring and public awareness.

During the first phase of the field programme, the tasks and priorities were defined, and the administrative, legislative and financial requirements for their realization elaborated. However, this programme is mainly focused on the problem of technological reconstruction and cleanup of the contaminated areas. Owing to a lack of funds, implementation of the various tasks has been postponed and instead efforts are being focused on monitoring programmes and research related to environmental impact assessment of the former uranium reprocessing plants, tailings and uranium ore mining, as well as the scientific justification of the future regional SAP.

All investigations on the effects of tailings and former sites of underground leaching on the state of surface and underground waters in the regions of their location are provided by the specified State and regional laboratories. At present, there is no routine monitoring of water released from the decommissioned Pervomayskaya deposit; as a result, it has not been considered in estimates of current or potential radiation exposure of the local population.

The above analysis shows that there is an adequately developed infrastructure for radiation and radioecological monitoring within the zone of influence of the uranium industry. At the same time, the envisaged programme has not been fully implemented because of funding problems. Accordingly, the majority of available data is of an episodic, non-systematic nature and does not facilitate an understanding of the temporal trends in environmental data or an assessment of the effects on aquatic ecosystems.

6.4. SOURCES OF POTENTIAL CONTAMINATION AT THE ZHOVTI VODY SITE

The mining and processing of uranium ores at Zhovti Vody has negatively affected the environment as well as the sanitary state of the town since the start of operations in the 1950s [6.7–6.10]. The mining of uranium ores ceased in 1990, but mining of iron ore at the Novaya mine is still in progress.

Figure 6.2 shows the layout of the major mining operations and the location of waste. The main sources of radioactive contamination are the three tailings sites:

(a) Tailings KBZh;
(b) Tailings Sch;
(c) Tailings R.

6.4.1. Tailings KBZh

Tailings KBZh are located 2 km from the northern boundary of the town (see Fig. 6.2) on the dividing plateau between the Zheltaya and Zelenaya Rivers. The closest settlements are Zhovti Vody, 2 km to the south, Zeleny Gai in the south-west and Veselo Ivanovka, 1.7 km to the east in the valley of the Zheltaya River. The site is an old iron ore quarry, consisting of a little pit with a depth of 10–15 m and large pit with a depth of 60–65 m. No measures have been taken to minimize seepage from the tailings area.

Tailings were deposited at this site from 1964 until 1982 by the method of hydropouring. At present, most of the tailings surface is covered with 0.4 m of clay to prevent dispersion of tailings dust. The remainder is a small pond that serves as emergency storage for the mill. The area of tailings is 54.8 ha and the total mass of 19×10^6 t of tailings occupies a volume of 12.4×10^6 m^3. The tailings water has a pH of pH7.1, a ^{238}U concentration of 0.43 Bq/L, a ^{226}Ra concentration of 0.96 Bq/L and a total dissolved solids content of 7680 mg/L. These values can be compared with the action levels (^{238}U + ^{234}U = 1 Bq/L, ^{226}Ra = 1 Bq/L) and with the permissible concentrations (PC^{ingest}) of 10 Bq/L for ^{238}U and 1 Bq/L for ^{226}Ra in drinking water (as per Ref. [6.4]).

Restoration of the KBZh site began in 1991 but is still incomplete because of financial problems. The project plan envisages the following covering layers: 0.4 m of loamy clay (which is already in place), 0.4 m of rock, 3.5 m of packed loamy clay and 0.4 m of black soil [6.8, 6.9, 6.11].

6.4.2. Tailings Sch

The tailings impoundment Sch is located 1.5 km to the south of the town within the limits of the Scherbakovskaya gully. It consists of two sections, old and new, separated by a dyke (see

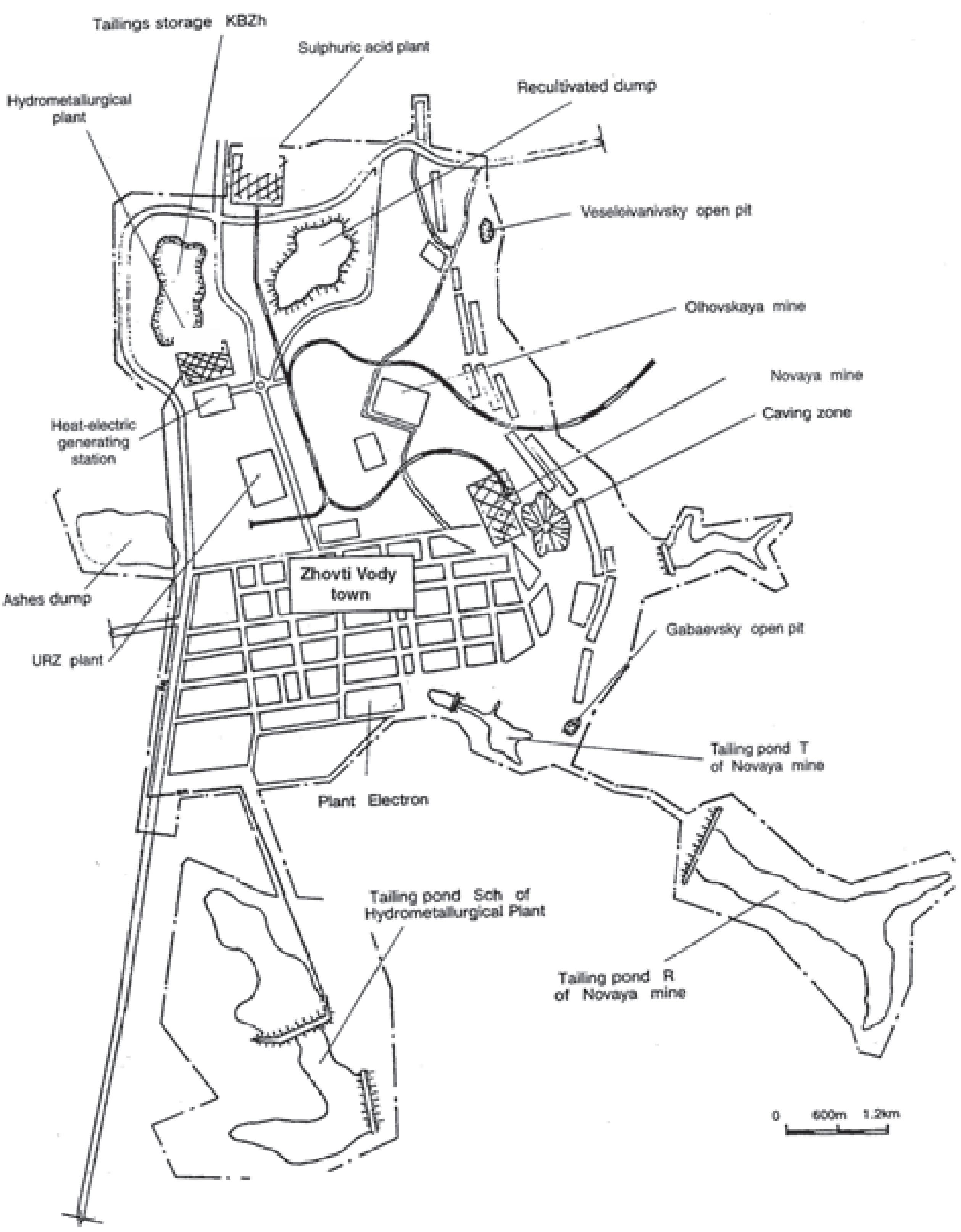

FIG. 6.2. Diagram of Zhovti Vody showing mines and tailings sites [6.8].

Fig. 6.2). The old section, which is 1.6 km long and 0.6 km wide (at the dyke), has an area of 98.4 ha and a useful volume of about 5.5×10^6 m^3. This section was operated from 1959 until 1980 and is now used for reserve storage only. The new section of the tailings is located in the western lower part of the gully. It has an area of 152 ha and a total mass of 34×10^6 t of tailings, which occupies a volume of 25×10^6 m^3. This area was commissioned in 1979 and is still operating. The radiochemical compositions of the liquid and solid phases are given in Tables 6.1 and 6.2, respectively.

Table 6.2 shows depletion in ^{230}Th compared with the equilibrium value at secular equilibrium (compare the specific activities of ^{230}Th with ^{226}Ra and ^{210}Pb). This can be explained as follows: samples were taken from superficial layers of the solid tailings ‘mud’, whereas ^{230}Th is partially leached and tends to migrate to the deeper layers of the tailings. To obtain more accurate estimates of the total activity of the radionuclides, a more representative sampling programme needs to be implemented. The ‘beaches’ of tailings Sch produce dust, which is a source of radioactive contamination of the air in the southern part of the surrounding settlements during summer.

6.4.3. Tailings R

Tailings R are located on the left slope of the valley of the Zheltaya River in the Razberi gully. The closest settlements are Zhovti Vody and Marianovka, situated 1.5 km to the west and southwest, respectively, and Udachny and Zaporozhets, situated 0.4 km to the east. The area of the tailings pond is 230 ha. This was originally a storage pond for iron ore milling sludge but was also used as a settling mine for uranium mine drainage waters. The solids retention system was constructed without seepage controls; however, the natural material that forms the dyke is loamy and clayey earth.

Table 6.3 gives the chemical and radiochemical composition of the liquid phase, maximum permissible concentrations (MPCs) for chemicals and PC^{ingest} for radionuclides in drinking water according to the Radiation Safety Standard of Ukraine [6.4].

The contaminated water seeps into the Zheltaya River. In some cases the seepage waters exceed the maximum permissible levels for chlorides, sulphates and even for ^{210}Po in drinking water. There is a need to assess their long term impact on the environment.

TABLE 6.1. RADIOCHEMICAL COMPOSITION OF THE LIQUIDS IN TAILINGS SCH [6.12]

	Volumetric activity (Bq/L)			
	Uranium-238	Radium-226	Lead-210	Polonium-210
Dyke water	0.74	2.6	1.2	0.4
Tailings water	2.2	8.1	0.8	0.5
PC^{ingest}	10.0	1.0	0.5	0.2

TABLE 6.2. RADIOCHEMICAL COMPOSITION OF THE SOLIDS IN TAILINGS SCH

Year of deposition	Radionuclides and their activity (Bq/kg)				
	Lead-210	Radium-226	Thorium-230	Thorium-232	Uranium-238
1992	5 760	7 010	4730	18	1980
2000	10 360	12 255	4860	32	1490
2001	5 910	7 840	3265	54	1045
2002	6 175	7 270	2400	35	1770

TABLE 6.3. COMPOSITION OF CONTAMINATED WATERS OF TAILINGS R

Sampling place	pH	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	NH_4^+ (mg/L)	Fe_{total} (mg/L)	U_{total} (mg/L)	Radium-226 (Bq/L)	Polonium-210 (Bq/L)
Tailings									
New	9.3	360	943	1.0	3.8	0.6	0.13	0.33	0.24
Old	9.3	220	815	1.15	n.d.	0.1	0.1	0.10	0.02
Release to Zheltaya River									
Tailings water	9.25	320	944	0.75	0.45	0.18	0.4	0.02	0.11
Mine water	8.35	1130	457	0.65	n.d.	0.1	0.04	0.12	0.006
MPC and PC^{ingest} according to Ref. [6.4]	—	350	500	10	—	—	0.8	1.0	0.2

n.d.: Not detected.

6.5. ASSESSMENT OF THE SOURCES OF CONTAMINATION OF NATURAL WATERS IN THE ZHOVTI VODY AREA

The water basin within the limits of Zhovti Vody town is the Zheltaya River, which is a left tributary of the Ingulets River. At present, its bed is silted, and only a small channel is cleared. The treated mine waters from the Novaya mine are discharged into it.

The length of the river is 61 km and the area of the watershed is 490 km^2. The average slope of the river is 0.00175. The average annual drainage is 1.24 L·km^{-2}·s^{-1}. The average velocity of the current is 0.1–0.2 m/s; during flooding it increases to 0.5 m/s. Melting snow is the main contributor to flow and is responsible for two thirds of the annual drainage; rain and groundwaters are of secondary importance. For most of the year, the river bed is dry, forming chains of separated stretches, and, at some locations, the river is parched for up to 10 months. Downstream of the wastewater outlet from the uranium mill, the water has elevated levels of total dissolved solids (TDS). Table 6.4 presents the results of the chemical analysis of the river water at the town of Zhovti Vody.

There are clean water bodies within the town: in the north-eastern section there is a municipal beach, in the south-eastern section there is a beach and pond used by children, and in the eastern part there is a reservoir, Vodobud, used at present as a reserve water body for the drinking water supply. Table 6.5 gives the results of radiochemical analysis of water samples of the Zheltaya River, starting from the source and finishing with the exit of the river beyond the limits of the town.

The results confirm contamination of the Zheltaya River with uranium from the milling operation. In the area of Netesovka the concentration of uranium in the water exceeds the concentration at the source of the river by a factor of 80. Even at a distance of more than 10 km, in the area of Annovka, high activities of natural radionuclides are apparent (Table 6.6), exceeding by ten times the activity of these radionuclides in the Saksagan and Ingulets Rivers.

Some dose estimates arising from water consumption for the most conservative scenario of water use from the Zheltaya River have been calculated for the residents of Annovka: see Section 8.4.2.

The results in Ref. [6.12] and the dose calculations presented in Section 8.4.2 show that the conservatively estimated annual doses from consumption of river water may exceed the constraint value of 0.05 mSv established in Ref. [6.4] for water use in areas of uranium mining and milling. These assessments draw attention to the problem and indicate the need for more extensive monitoring and remedial works to reduce releases of radioactive substances into the river.

TABLE 6.4. CHEMICAL COMPOSITION OF THE WATER FROM THE ZHELTAYA RIVER AT ZHOVTI VODY (1995)

	April 1995	May 1995	June 1995
pH	7.65	8.2	8.2
Hardness (meq/L)	11.8	14	21.6
Ca + Mg (mg/L)	189	280	343
Na + K (mg/L)	104	264	360
CO_3 (mg/L)	—	40	—
HCO_3 (mg/L)	415	346	354
Chlorine (mg/L)	142	177	247
SO_4 (mg/L)	256	650	432
NH_4 (mg/L)	0.08	1	0.26
NO_3 (mg/L)	n.d.	n.d.	0.17
NO_2 (mg/L)	—	1.5	0.02
TDS (mg/L)	1106	1757	1380

n.d.: Not detected.

TABLE 6.5. CONCENTRATION OF NATURAL RADIONUCLIDES IN WATER FROM THE ZHELTAYA RIVER (1999)

Sampling site	Total uranium (Bq/L)	Radium-226 (Bq/L)
Zheltaya River (source)	0.08	0.013
Veselo Ivanovka reservoir	0.08	0.015
Vodobud reservoir	0.07	0.047
Stream from Vodobud reservoir	0.04	0.011
Zheltaya River (Marianovka)	2.14	0.010
Zheltaya River (Netesovka)	5.9	0.013
PC^{ingest} [6.4]	10.0	1.0

TABLE 6.6. CONCENTRATION OF NATURAL RADIONUCLIDES IN THE INGULETS, SAKSAGAN AND ZHELTAYA RIVERS (MAY–JUNE 2002)

Sampling place	Activity (mBq/L)					$^{234}U/^{238}U$
	Uranium-238	Uranium-234	Lead-210	Radium-226	Polonium-210	
Zheltaya River in Annovka in May	1020 ± 100	1160 ± 115	<11	8 ± 3	20 ± 3	1.13
Zheltaya River in Annovka in June	1400 ± 90	1600 ± 130	—	—	—	1.14
Drinking water in Zhovti Vody	36 ± 5	58 ± 6	<11	5 ± 2	2.4 ± 0.5	1.61
Ingulets River in Aleksandria	35 ± 5	54 ± 6	<11	16 ± 5	0.4 ± 0.1	1.54
Ingulets River (Iskra reservoir)	31 ± 5	48 ± 6	<11	13 ± 3	0.5 ± 0.2	1.54
Saksagan River (Kress reservoir)	55 ± 6	77 ± 7	<11	7 ± 4	1.1 ± 0.5	1.40
PC^{ingest} [6.4]	10 000	10 000	500	1000	200	

6.6. EFFECT OF IN SITU LEACHING OF URANIUM ON CONTAMINATION OF NATURAL WATERS

6.6.1. Devladovo site

One of the former in situ leaching sites, Devladovo (see Fig. 6.1, position 17), is situated at the interfluve of the Saksagan and Kamenka Rivers. Exploitation of the deposit was completed by 1984 and the affected lands were recultivated and transferred to general land tenure [6.7, 6.13]. During decommissioning, the underground waters were found to be contaminated with naturally occurring radionuclides. The legislation then in place did not envisage restoration of the underground waters to their initial state. Until 1990, the mine water ponds remained on the Devladovo site.

The ore deposits were leached within the Buchak water bearing horizon. This horizon occupies a significant portion of the deposit; its groundwaters discharge to the Dnieper Ternovskaya valley. At present, this horizon of underground waters is contaminated with residual acid solutions containing natural radionuclides. The water-containing rocks are coal and carbon free sands up to 15 m thick. The underground water flux of this horizon is pressurized; the water pressure is 28–40 m and flow is in the direction of east to west, with slopes of the piezometric surface of 0.0015–0.0028. The valley of the Kamenka River supplies the water horizon under natural conditions. The release takes place into the Saksagan River.

The underground waters of the Buchak water bearing horizon have naturally elevated concentrations of sulphates and high TDS and, for that reason, were not used for drinking water prior to the development of the ore body. Table 6.7 gives data on the background concentrations of uranium series members taken from the horizons beyond the boundary of the impact area.

The main source of contamination of the underground waters was the leaching solutions, with typical concentrations of 10 g/L sulphuric acid and 2 g/L nitric acid. During the period of operation, 200 000 t of sulphate ion (as sulphuric acid) and 18 600 t of nitrate (as nitric acid) were pumped into the horizon. The extent of the artificial contamination from leaching covers the whole area of the former site in the direction of underground water movement from east to west in the monitored area.

The major contributors to radioactive contamination are U_{total}, ^{210}Pb and ^{210}Po. The measured concentrations are within the following ranges: U_{total} from 2.5 to 885 Bq/L, ^{210}Pb from 0.2 to 15 Bq/L and ^{210}Po from 0.02 to 0.7 Bq/L.

6.6.2. Forecast of the long term potential contamination of the Saksagan River

In 1997, with the assistance of COGEMA–SGN (France) and under the TACIS programme, modelling studies were undertaken to forecast the future hydrological and radiological situation near the Devladovo site [6.14]. The task was to forecast the uranium concentrations for the next 1000 years, assuming that the object of contamination would be the Saksagan River, which is 13.5 km from the Devladovo site and the main regional source of water supply.

Two sources of contamination were considered:

(a) Pond water on the surface, contaminating the Quaternary water bearing horizon;
(b) Residual solutions from underground leaching, contaminating the Buchak water bearing horizon [6.13].

Simulation of outflow of pollutants from the waste storage pond for times in excess of 1000 years showed that, with a high probability (80%), contamination would reach the Saksagan River with concentrations exceeding the current sanitary standards [6.3–6.6]. The predicted concentrations 1000 years from now are given in Table 6.8 [6.14].

These estimates, made on the basis of measurements and simulation, show that there is no problem with current contamination of the surface water in the region. However, there is a high probability that contamination above current sanitary standards will occur from several hundred to one thousand years in the future, when polluted water containing uranium series nuclides reaches the Saksagan River. Accordingly, the movement of these contaminated groundwaters should be monitored within the framework of long term environmental programmes.

One of the priority tasks is to create an ongoing operating system for external radio-ecological monitoring of the environment (water, soil, vegetation, air, food products) in the regions of the former and present uranium facilities to assess the developing situation and to justify possible

TABLE 6.7. BACKGROUND CONCENTRATION IN UNDERGROUND WATERS OF THE BUCHAK HORIZON (FOR 1998) AT LOCATIONS BEYOND THE IMPACTED AREAS [6.13]

Well No.	SO_4^{2-} (mg/L)	TDS (mg/L)	Concentration (Bq/L)				
			Uranium-238	Radium-226	Thorium-230	Lead-210	Polonium-210
1	619	2580	1.23	—	—	—	—
2	350	1542	0.65	—	—	—	—
3	440	1245	1.95	0.27	0.22	0.56	0.11
5	584	1836	0.59	0.02	0.02	0.37	0.04
6	498	2274	0.79	0.14	0.34	1.11	0.08
14	814	2199	0.79	—	—	—	—
33	526	2344	0.69	—	—	—	—
34	718	1836	0.79	0.15	0.06	0.22	0.04
98-2	4023	8062	0.59	—	—	—	—
B-58	3353	5513	0	0.10	0.09	1.37	0.15
B-59	297	598	0.84	0.28	0.02	0.59	0.07
B-61	661	2686	1.77	0.01	0.60	0.51	0.04
B-64	533	2818	0	—	—	—	—
B-69	638	2942	0.98	0.07	0.02	0.22	0.06
B-78	718	2242	1.28	0.10	0.09	1.07	0.09
B-97	627	2145	0.42	—	—	—	—
B-99	709	2428	0.59	0.24	0.07	0.67	0.07
MPC and PC^{ingest}	500	1000	10	1	0.7	0.5	0.2

TABLE 6.8. ESTIMATED RADIONUCLIDE CONCENTRATION (Bq/L) WITHIN THE GROUND-WATER OF THE QUATERNARY HORIZON PREDICTED FOR 1000 YEARS FROM NOW

	Close zone of Devladovo site	Zone of observational control
Uranium-238	2.7	1.5
Radium-226	1.1	0.53
Thorium-230	0.33	0.13
Lead-210	0.86	0.53
Polonium-210	0.11	0.06

remedial measures. It is very important to coordinate the work of the present system of radioecological monitoring by external agencies.

6.7. IMPACT OF THE FORMER PERVOMAYSKAYA URANIUM MINING OPERATION ON RADIOACTIVE CONTAMINATION OF NATURAL WATERS

The first uranium mining enterprise in the Ukraine was the exploitation of the Pervomayskaya uranium ore deposit located at Krivoy Rog [6.1, 6.15, 6.16]. In the late 1960s uranium mining was stopped, but mining of iron ore at the Objedinyonnaya mine continued. In early 1998 iron ore mining finally ceased and decommissioning was begun. The total area of the mining enterprise to be rehabilitated is 68.5 ha. Uranium mining contaminated the environment due to ore dispersal, leaching of natural radionuclides from the ore, uncontrolled waste use for other purposes and dust contamination.

Within the area of the enterprise a stream flows through the Gryadkovataya narrows, which enters the Saksagan River. To estimate pollution in the stream, samples were taken after rainfall. One of the samples was taken upstream of the industrial site; the other was taken downstream. The results of the analysis are given in Table 6.9. These results confirm pollution of surface waters by natural radionuclides.

At present, water from the former Pervomayskaya mine is pumped to the tailings pond of the joint stock company SevGOK, located 7 km from the mine. Table 6.10 shows the concentration of natural radionuclides in mine water and tailings water [6.17].

Both the mine water and the tailings water exceed the natural background levels. The main contributors to dose are ^{238}U, ^{234}U and ^{226}Ra. However, the current situation does not create a significant risk to the residents of Krivoy Rog, since estimates of annual effective exposure, even for the most conservative scenarios of water consumption, do not exceed 0.01–0.03 mSv/a. Nevertheless, despite the relatively low level of current population exposure, the situation should be regularly monitored at the local and regional level.

TABLE 6.9. RADIONUCLIDE CONCENTRATION IN WATER SAMPLES FROM THE STREAM THROUGH THE GRYADKOVATAYA NARROWS AND THE SAKSAGAN RIVER

Site of water sampling	Radioactivity (Bq/L)				
	Total alpha	Uranium-238	Radium-226	Lead-210	Polonium-210
Upstream of industrial site	<0.4	0.033 ± 0.002	0.045 ± 0.011	<0.012	0.007 ± 0.0014
Downstream of industrial site	2.3 ± 1.0	1.2 ± 0.3	0.09 ± 0.018	<0.011	0.002 ± 0.0006
Saksagan River (background)	0.32 ± 0.025	0.03 ± 0.004	0.015 ± 0.003	0.004 ± 0.001	0.001 ± 0.0003

TABLE 6.10. AVERAGE CONCENTRATION (Bq/L) OF RADIONUCLIDES IN MINE WATER FROM THE PERVOMAYSKAYA MINE AND WATER FROM THE SevGOK TAILINGS

	Mine water from Pervomayskaya			SevGOK tailings	
	1998	Oct. 2001	Nov. 2001	Oct. 2001	Nov. 2001
Uranium-238	n.d.	0.05	0.14	0.04	0.12
Uranium-234	n.d.	0.15	0.25	0.34	0.19
Thorium-230	0.16	<0.001	<0.001	<0.001	<0.001
Radium-226	0.27	0.028	0.029	0.018	1.32
Lead-210	0.34	<0.01	0.03	<0.01	<0.01
Polonium-210	0.14	<0.001	<0.001	<0.001	<0.001

n.d.: Not detected.

6.8. RADIOACTIVE WASTE FROM FORMER URANIUM PROCESSING IN DNIPRODZERZHINSK

According to the National Reports on the State of the Environment in Ukraine (1994–2001), the Dnipropetrovsk region is one of the most unfavourable in terms of contamination of air, adjacent catchment areas and water bodies. One of the reasons for this situation is the large concentration of industrial enterprises, which include chemical, coke and metallurgical plants. These enterprises have severely affected the environment and human health in the region.

One of the metallurgical facilities was the former Prydniprovsky chemical plant, at which uranium ores were processed from 1948 until 1991. It is located on a large industrial site within the territory of the city of Dniprodzerzhinsk in the Dnipropetrovsk region. During operation of the Prydniprovsky chemical plant, nine tailings dumps were created, containing about 42×10^6 t of radioactive waste with a total activity of 3.2×10^{15} Bq (86 000 Ci). Some of the radioactive waste is located within the territory of the industrial zone of Dniprodzerzhinsk, while other waste is stored about 14 km to the south-east (see Fig. 6.3).

The city of Dniprodzerzhinsk is a large industrial centre; the population at the beginning of 2000 was 276 500 people. The residential area covers 41% of the municipal territory and the industrial and communal areas cover 18%. The enterprises located on the right bank area of the town are grouped into industrial zones.

In addition to imported ores, the Prydniprovsky chemical plant processed uranium bearing sludges obtained from cast iron smelting of iron ores from the Krivoy Rog region. In the early 1990s the Prydniprovsky chemical plant was split into several separate enterprises, and processing of uranium was stopped.

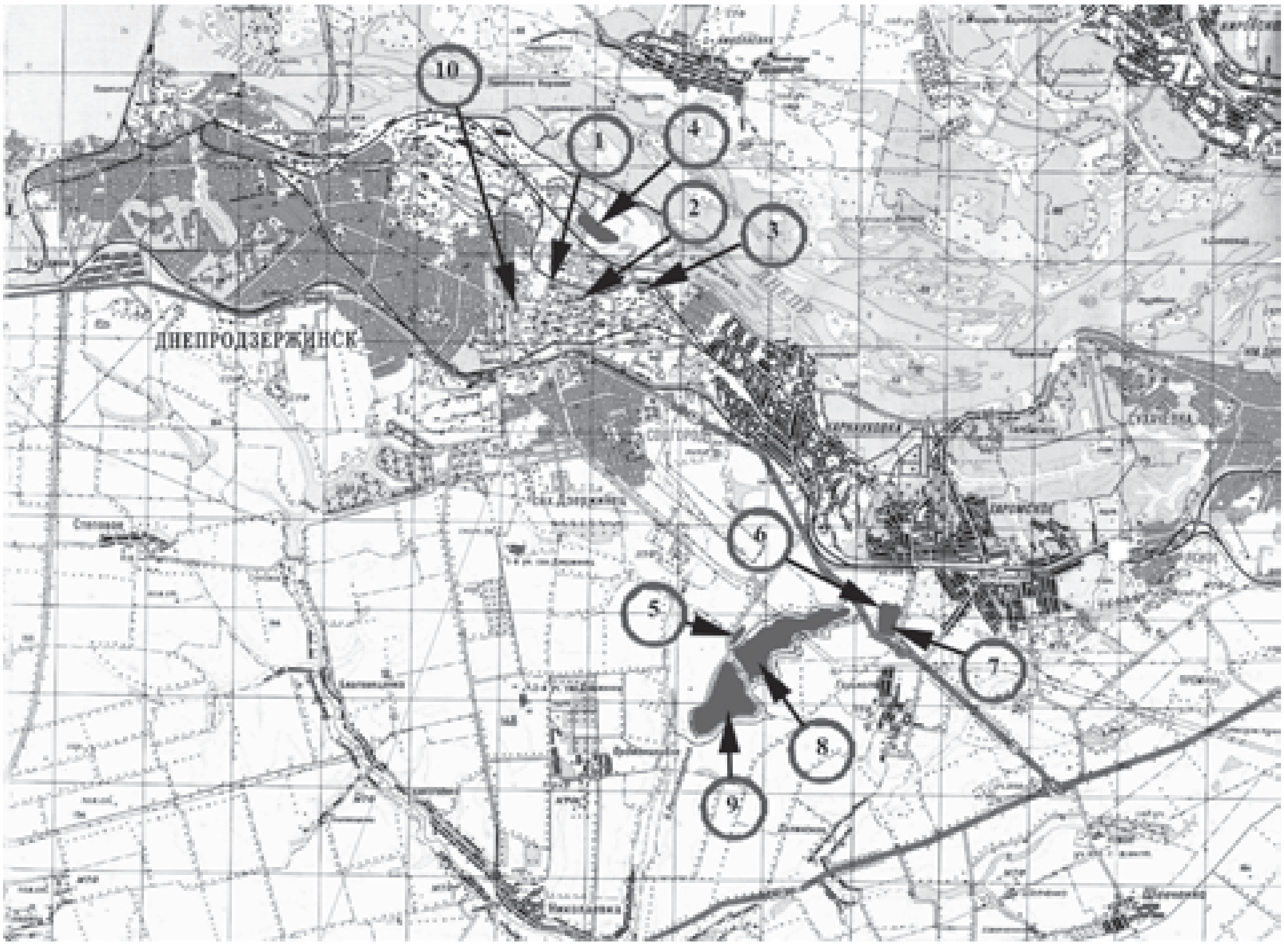

FIG. 6.3. Location of radioactive waste in the Dniprodzerzhinsk region [6.18] (see text for identification of numbered positions).

Information on the main radioactive waste storage areas is given in Table 6.11. Initially, tailings were stored in nearby clay gullies and open pits, which are unsuitable for the long term storage of radioactive waste. Tailings were deposited on the industrial site at Zapadnoye and Centralny Yar (which operated from the early 1950s). The tailings D (Dniprovske) site, which operated from 1954 to 1968, was established on the floodlands of the Dnieper River. In the period from 1968 to 1993, radioactive waste was stored in the specially constructed sections I and II of tailings C, which is located to the south of Dniprodzerzhinsk city (see Fig. 6.3).

The deposited tailings and other radioactive material are a source of current and future contamination of:

(a) The atmosphere, via radioactive dust and aerosols, and radon and its progeny;
(b) Watercourses, including the Dnieper River itself, through seepage and migration of radionuclides and chemical components of the waste;
(c) Watercourses and land, if erosion or catastrophic failure of the radioactive waste storage systems were to occur.

The sources of radioactive waste and radioactive contamination are briefly described in the following sections.

6.8.1. Tailings Zapadnoye

The radioactive waste on this site was deposited by both hydropouring and piling methods between 1949 and 1954. The radioactive waste volume is about 350 000 m^3 (0.77×10^6 t). The total activity of the stored waste is 180 TBq [6.11, 6.16, 6.18].

The tailings are located on 6 ha of land in the south-western part of the industrial site within a fenced area with earthen dykes in a spent clay open pit (see position 1 in Fig. 6.3). In terms of geomorphology, the tailings are situated within the boundaries of the floodland terrace of the Dnieper River. The general slope of the surface is from the south to the north. The hydrogeological conditions are characterized by the development of an alluvial water bearing horizon, with the depth of deposition being 12–22 m. In the north-western section, the alluvial horizon reaches the bottom of the tailings.

The surface of the tailings is partially covered with loess and loamy sands along with construction and domestic waste with a thickness of up to 2.5 m. The exposure rate of gamma radiation[1] within the waste is mostly within the range 100–2000 μR/h; on the surface it is mostly 20–40 μR/h, but on the uncovered surface it is up to 100–2200 μR/h. The thickness of contamination of the ground beneath the foundation of the tailings varies from 0.2 to 5.4 m. For this zone, exposure rates of 30–100 μR/h are typical.

The concentration of ^{226}Ra in the waste varies from 789 to 1.72×10^6 Bq/kg (the latter over a very limited area), ^{238}U from 952 to 3200 Bq/kg and ^{230}Th from 9800 to 32 000 Bq/kg [6.16]. The ^{222}Rn flux from the surface of the tailings impoundment,

[1] Exposure to gamma radiation is sometimes measured in units of roentgen (R) or microroentgen (μR). The SI equivalent is the coulomb per kilogram. One coulomb per kilogram is equivalent to 3881 R.

TABLE 6.11. CHARACTERISTICS OF THE MAIN STORAGE AREAS FOR RADIOACTIVE WASTE FROM THE PRYDNIPROVSKY CHEMICAL PLANT (PRELIMINARY ASSESSMENT IN 2001)

	Operational period	Area (ha)	Radioactive waste mass (10^6 t)	Radioactive waste volume (10^6 m^3)	Total activity (TBq)
Zapadnoye	1949–1954	6.0	0.77	0.35	180
Centralny Yar	1951–1954	2.4	0.22	0.10	104
Yugo-Vostochnoye	1956–1980	3.6	0.33	0.15	67
C, section I	1968–1983	90	19.0	8.6	710
C, section II	1983–1992	70	9.6	4.4	270
Base C	1960–1991	25	0.3	0.15	440
D	1954–1968	73	12.0	5.9	1400

where covered by a protective layer, is around 0.32 to 1.5 Bq·m^{-2}·s^{-1}, whereas radon exhalation background levels are only around 9 to 18 mBq·m^{-2}·s^{-1} [6.19]. Annual emission of radon to the atmosphere is estimated to be 0.75 TBq.

6.8.2. Tailings Centralny Yar

The radioactive waste on this site was deposited by both hydropouring and piling methods between 1951 and 1954. In total, 100 000 m^3 (0.22 × 10^6 t) of radioactive waste with a total activity of 104 TBq was deposited.

The tailings are located on 2.4 ha of land in the south-central part of the former Prydniprovsky chemical plant and within the recreation zone of the town (see position 2 in Fig. 6.3). The site is situated in a sandy gully running from the south to the north and within the floodland terraces of the Dnieper River.

The hydrological conditions are characterized by seasonal fluctuations of the alluvial water bearing horizon. The surface of the tailings is covered with loess and loamy sands from construction waste (thickness is 1.5–6.5 m). The exposure rate within the waste varies from 15 to 30 μR/h (in the southern part of the tailings) to more than 10 000 μR/h. On the surface of the tailings the exposure rate varies from 20 to 1000 μR/h. The radon flux from the surface of the tailings varies from 0.24 to 2.57 Bq·m^{-2}·s^{-1}. The annual emission of radon to air is 0.6 TBq.

There are no data on possible migration of radionuclides via underground waters into the drainage network.

6.8.3. Tailings Yugo-Vostochnoye

The radioactive waste on this site was emplaced by the piling method between 1956 and 1980. The radioactive waste volume is about 150 000 m^3 (330 000 t). The total activity of the stored waste is 67 TBq [6.11, 6.18, 6.19].

The site is located on 3.6 ha of land in the south-eastern part of the industrial site of the former Prydniprovsky chemical plant within the boundaries of a large gully and on the floodland terraces of the Dnieper River (see position 3 in Fig. 6.3).

The site contains piled material comprising heterogeneous industrial waste such as sludges, metal, construction and domestic waste (concrete, stone, wood, gravel, etc.) and loamy sands with a total thickness of 0.5–3.0 m beyond the limits and up to 19.2 m within the limits of the waste dump. Thus the site is highly porous and subject to high rates of seepage. The rocks beneath the tailings are overlain by loess, loamy sands and clay sands ranging in thickness from 7.5 to 27.5 m, and alluvial sands 20 m thick. The subsurface hydrological conditions are similar to those at Centralny Yar.

The exposure rate within the waste varies from 60 to more than 6000 μR/h; on the surface it ranges from 30 to more than 3000 μR/h. The radon flux from the surface of the tailings varies from 0.11 to 1 Bq·m^{-2}·s^{-1}. Annual emissions of radon are estimated to be 0.9 TBq.

6.8.4. Tailings Dniprovske (D)

Tailings D is a much larger and more significant tailings dump than those discussed above. It was deposited by hydropouring between 1954 and 1968. It contains about 5.8 × 10^6 m^3 (12 × 10^6 t) of radioactive waste. The total activity of the stored waste is about 1400 TBq (40 000 Ci).

The tailings are located on the right side of the Dniprovske reservoir at a distance of 0.8 to 1.2 km and on the floodplain of the river. The Konoplyanka River flows near the south and west boundaries of the tailings (Fig. 6.3, position 4, and Fig. 6.4). On the north side there are settling ponds of the Dniprodzerzhinsk coke chemical plant. Bulk waste from the Dniprodzerzhinsk metallurgical combine is located on the eastern and northern boundaries, between the tailings and the reservoir. The geological section beneath the foundation of the tailings is composed of alluvial deposits with a total thickness from 3.0 to 15.5 m, located on an uneven surface of crystalline rock. The alluvial layer

FIG. 6.4. Tailings D, showing the slope to the Konoplyanka River (right) and waste from the coke chemical plant in the distance.

consists of humus silty clay sands and loamy sands with a thickness of 0.1–3.3 m distributed over much of the natural surface, and sands 3.0–15.3 m thick.

The tailings impoundment was constructed by building a closed contour of protective dam walls of 6–11.8 m in height. The length of the dam perimeter is 4 km. The absolute elevation of the dam crest before 1959 was 57.5 m, but after further construction it reached 61.3–64.2 m. It was constructed on alluvial sands and loamy sands. The fencing dam is a regular embankment built by the dry method with compacting. There are no seepage control features either in the dam walls or the floor.

The tailings consist mainly of sandy material (fine and dusty), seldom of loamy sands and clay sands, and are covered with a layer of phosphogypsum (a waste product from the production of phosphate fertilizers) with a thickness of 1–5 m near the dam walls and up to 19 m in the central and eastern part of the bowl.

The exposure rate of gamma radiation within the tailings is mainly within the range 200–600 μR/h; in some places it reaches 1000–4500 μR/h [6.19]. The exposure rate on the surface of the tailings is 10–40 μR/h; at the more contaminated areas in the north-western part of the bowl it is 40–74 μR/h. The total volume of solid waste is 22×10^6 t (including phosphogypsum). The concentration of ^{226}Ra in the waste varies from 4400 to 52 000 Bq/kg, ^{238}U from 125 to 3500 Bq/kg, ^{230}Th from 3000 to 62 000 Bq/kg and ^{210}Pb from 4100 to 50 000 Bq/kg. The radon flux from the surface of the tailings covered by a thick layer of phosphogypsum is 1–26 $mBq \cdot m^{-2} \cdot s^{-1}$. The tailings deposits are partly saturated with water. The maximum recorded elevation of the level of the artificial horizon of tailings waters is 61.0 m, indicating a substantial increase since 1975, when the level was recorded at 52.0–54.5 m. The main reason for the high artificial horizon is percolation of water from the north-eastern settling ponds of the Dniprodzerzhinsk coke chemical plant.

The hydrological conditions are characterized by the availability of the artificial horizon of tailings within the dam and an alluvial water bearing horizon underneath. As a result of persistent inflow and hydrostatic pressure within the tailings, radionuclide migration into the environment is occurring. The radionuclides move into the alluvial water bearing horizon, rivers and eventually the Dnieper River. Estimates of the average annual release of radionuclides to the Dnieper River via groundwater and surface flow via the Konoplyanka River are given in Table 6.12. Future releases are difficult to predict based on present knowledge. Comprehensive geotechnical studies need to be undertaken to determine the long term stability of the tailings and to model the release of radionuclides to the Konoplyanka and Dnieper Rivers.

During 2000–2001 releases from both plants (the Dniprodzerzhinsk coke chemical plant and the Dniprodzerzhinsk metallurgical combine) were suspended. Fifty monitoring wells have been drilled and equipped within the tailings area and in the sanitary protection zone.

Tailings D are considered as a possible hot spot because of the large amount of radioactivity, the long half-life of the main radionuclides, the proximity to the Dniprovske reservoir, the evidence of current seepage and the possibility of catastrophic failure of the impoundment. Section 9.4 provides more information on tailings D (see especially Fig. 9.32).

TABLE 6.12. AVERAGED ANNUAL RADIONUCLIDE RELEASE TO THE DNIEPER RIVER FROM TAILINGS D

	Annual release (GBq)	
	Surface flow via the Konoplyanka River	Via groundwater fluxes
Uranium-238	55	0.2
Thorium-230	5.5	0.03
Radium-226	19	0.03
Lead-210	44	0.15
Polonium-210	8.8	0.01

6.8.5. Base C

Base C is located 14 km to the south-east of the Prydniprovsky chemical plant (see position 7 in Fig. 6.3) and within a fenced area of 720 m × 470 m (an area of 33 ha); temporary storage of uranium raw material took place here between 1960 and 1991. The main facilities at the site were bunkers and open areas for ore storage, and the railway access to them. The storage area is 25 ha.

Base C is contaminated with radioactivity, the main source of contamination being earlier stored uranium ore and some residual material (spillage along the railway, radioactive scrap metal, ore pieces, etc.), which is stored in bunkers. The bunkers are reinforced open iron tanks banked with earthen dykes to heights of 2.5–4.5 m.

The exposure rate of gamma radiation of the remaining ore is from 300 to more than 3000 μR/h. The contained solid radioactive waste in base C has a total activity of 440 TBq. The radioactive waste volume is 150 000 m^3 (0.3×10^6 t). The exposure rate on the surface of the storage area does not exceed 4700 μR/h. The radon flux from the surface is typically 1.25–7.26 $Bq \cdot m^{-2} \cdot s^{-1}$, with a maximum of 21 $Bq \cdot m^{-2} \cdot s^{-1}$. Annual radon emissions are 23 TBq.

The hydrological conditions are characterized by the availability of a water bearing horizon in the loess deposits, which are located at depths of 16–18 m (absolute elevations are 142.0–146.5 m above sea level) and the water bearing horizon in Neogene deposits at depths of more than 90 m. The underground water flows to the west and south-west in the direction of the gully where tailings C are situated.

6.8.6. Tailings C

The tailings C impoundment is located 14 km to the south-east of the Prydniprovsky chemical plant in the Rassolovataya gully, which empties into the valley of the Sukhaya Suhra River. It consists of two sections separated by a raised road. Tailings and other waste were pumped as a slurry to the site from the Prydniprovsky chemical plant by a pipeline. The Dnieper River is about 4 km from the site.

The first (I) section of the tailings dam (see position 8 in Fig. 6.3) was operated from 1968 to 1983. It contains about 19×10^6 t of radioactive waste that occupies a volume of 8.6×10^6 m^3 and a total area of about 90 ha. The area has about 14 ha of dry beaches; the rest is covered with water. The concentration of ^{226}Ra in the waste varies from 560 to 13 500 Bq/kg, ^{238}U from 170 to 880 Bq/kg, ^{230}Th from 350 to 83 000 Bq/kg and ^{210}Pb from 500 to 14 400 Bq/kg.

The total radioactivity in this section is about 710 TBq (19 000 Ci). The maximum exposure rate is 1200 μR/h. The radon flux from the surface is 0.03–1.48 $Bq \cdot m^{-2} \cdot s^{-1}$. Annual radon emissions from the tailings surface are 19 TBq. The site has yet to be rehabilitated.

The second (II) section, covering the lower part of the gully, is formed by a dam crossing the gully (see position 9 in Fig. 6.3). It was commissioned in 1983 and is still used for disposal of non-radioactive waste (e.g. phosphogypsum). It contains 9.6×10^6 t of radioactive waste occupying a volume of about 5.5×10^6 m^3. The total area is 70 ha, of which about 50 ha is covered with water.

The total activity is about 270 TBq (7000 Ci). The exposure rate at the surface is low due to deposition of non-radioactive material on top of the uranium tailings. The content of the natural radionuclides in the sludge waters are: uranium from 0.4 to 2 Bq/L; ^{226}Ra from 0.05 to 0.24 Bq/L; ^{230}Th from 0.05 to 0.10 Bq/L; ^{210}Pb from 0.35 to 5 Bq/L; and ^{210}Po from 0.04 to 0.09 Bq/L. This section of tailings C is fully engineered with clay and polyethylene barriers to minimize seepage.

6.8.7. Other contaminated areas

Other contaminated areas include [6.18]:

(a) A lanthanide dump area near the tailings C site (see position 5 in Fig. 6.3), which contains 0.86 TBq of radioactive waste.
(b) A blast furnace waste storage area (see position 6 in Fig. 6.3) near the base C site, containing 11 TBq of radioactive waste.
(c) Contamination of industrial areas and equipment within former plants (Prydniprovsky chemical plant and Dneproazot) that handled radioactive material.
(d) The Lazo site within the city area (see position 10 in Fig. 6.3). The contamination originated from the Dneproazot complex; further study is required to establish the extent of the contamination.
(e) Some limited areas, including living areas, within the city, with exposure rates from 100–1000 μR/h. These resulted from the use of building materials (e.g. blast furnace slag) with elevated levels of radioactive elements.

6.9. ASSESSMENT OF THE IMPACT OF WASTE FROM THE PRYDNIPROVSKY CHEMICAL PLANT

The main water body within the observation zone of the Prydniprovsky chemical plant is the Dnieper River. As noted previously, a small tributary of the Dnieper, the Konoplyanka River, flows past sections of tailings D (see Fig 6.4). In the observation zone of tailings C are several artificial water bodies (ponds at Taromskoye, Ordzhonikidze and Ptitsefabrika) and a temporary watercourse in the Rassolovataya gully.

The Dnieper River is about 1 km from tailings D, 2.6 km from tailings Zapadnoye and Centralny Yar, 1.8 km from tailings Yugo-Vostochnoye and 4.2–4.4 km from tailings C and base C.

Elevated levels of barium, titanium, manganese, nickel, lanthanum, lithium, lead, strontium and zirconium are observed downstream of the radioactive waste sites, reaching the MPCs for drinking water in some cases (e.g. manganese and lanthanum). Moreover, periodically the levels of sulphates, nitrates, ammonium, phenol, oil products and TDS in the Dnieper River exceed the MPC for drinking water.

The main reasons for chemical pollution of the Dnieper River are the discharge of untreated waters by the industrial enterprises (totalling 270×10^6 m^3/a), surface discharge (rain and snow melting waters) from the territory of the industrial and residential area (approximately 3×10^6 m^3/a) and releases into the Dnieper River of polluted underground waters. The chemical composition of the river water is characterized by a variety of contaminating species (sulphate, nitrate and iron) with TDS of 1.0–1.3 g/L.

The concentrations of monitored radionuclides, ^{238}U and ^{226}Ra, in the Dnieper River are significantly lower than the permissible concentrations established in Ref. [6.4] for drinking water; however, there is a tendency for an increase in concentration downstream of the Konoplyanka River inlet (e.g. in Karnaukhovka).

The main sources of radionuclide input into the Dnieper River are seepage of contaminated groundwaters (mainly under tailings D), surface discharge from the contaminated areas of the industrial site and the discharge of the Konoplyanka River, where the highest concentrations of radionuclides are recorded (see Table 6.13).

It is noteworthy that, in 1995, the Chief State Inspectorate of Gosatomnadzor of Ukraine reported: “In a series of wells within the plant area, high levels of contamination of the underground waters with ^{226}Ra were registered and, in some wells, high levels of dissolved uranium were found (up to 2.4 mg/L). The aureole of contamination of the underground waters with natural radionuclides spread beyond the limits of tailings D in the direction of the Dniprovske reservoir. The content

TABLE 6.13. RADIONUCLIDE CONCENTRATION IN THE DNIEPER AND KONOPLYANKA RIVERS BASED UPON THE RESULTS OF SAMPLING FROM 1992–1999

		Radionuclide	Concentration (Bq/L)		
			Min.	Max.	Averaged
Dnieper River	Dniprodzerzhinsk reservoir	U_{total}	0.017	0.098	0.046
		Radium-226	0.006	0.030	0.014
	Dniprovske reservoir upstream of the Konoplyanka River inlet	U_{total}	0.017	0.116	0.055
		Radium-226	0.004	0.041	0.015
	Dniprovske reservoir, Karnaukhovka, downstream of the Konoplyanka River inlet	U_{total}	0.017	0.261	0.060
		Radium-226	0.003	0.063	0.014
Konoplyanka River		U_{total}	0.034	0.770	0.112
		Radium-226	0.004	0.163	0.120
PC^{ingest} [6.4]		U_{total}	10.0		
		Radium-226	1.0		

of ^{226}Ra exceeded the background values in the region by three to ten times. The maximum concentrations of this radionuclide were registered in wells drilled in the bank of the reservoir."

The Konoplyanka River flows from 50–100 m to the south of tailings D and 0.6–1.0 km to the north of tailings Zapadnoye, Centralny Yar and Yugo-Vostochnoye. Figure 6.5 shows that the concentration of uranium in the Konoplyanka River is consistently higher than in the Dnieper River. Periodically in the Konoplyanka River, MPCs in drinking water are exceeded for sulphates, nitrates, iron, ammonium, hardness, TDS (up to 1.4 g/L), oil products and a series of metal ions, viz. barium (to 1.8 times), lead (to 22 times), titanium (to four times), manganese (to 22 times), lanthanum (to four times) and zinc (to two times).

The regional laboratories studied water samples from the Konoplyanka and Dnieper Rivers during different seasons. The sampling locations are shown in Fig. 6.3 and the results in Tables 6.14 and 6.15. The results show that the activity of natural radionuclides in the Konoplyanka River is typically 2–20 times those in the Dnieper River.

The recent monitoring study by the Dnipropetrovsk National University determined the uranium concentrations in four rivers in the Dniprodzerzhinsk area during the spring to autumn of 2001. The concentration of uranium in the Dniprovske reservoir in its upper and lower sections varied from 20 to 50 Bq/m^3 during spring and autumn and from 120 to 200 Bq/m^3 during summer.

Table 6.16 shows the radioactivity of naturally occurring radionuclides in bottom sediments. This shows that the concentrations of radionuclides in the Konoplyanka River are typically 1.5–100 times those of similar sediments in the Dniprovske reservoir. The highest concentrations are registered in the silty sediments of the Konoplyanka River (samples 7 and 8), where their values exceed by two to five times the concentrations in the sandy deposits (sample 6).

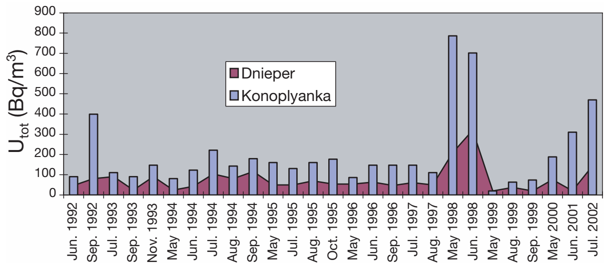

FIG. 6.5. Concentration of total uranium (^{238}U + ^{234}U) in the Dnieper and Konoplyanka Rivers. Note irregular sampling intervals [6.19].

TABLE 6.14. RADIONUCLIDE CONCENTRATION IN WATER SAMPLES FROM THE KONOPLYANKA AND DNIEPER RIVERS (JUNE 2001)

Sample No.	Sampling place	Concentration of natural radionuclides (mBq/L)					Total alpha activity (mBq/L)	Total beta activity (mBq/L)
		Radium-226	Lead-210	Polonium-210	Uranium-238	Uranium-234		
1	Dniprodzerzhinsk reservoir	7 ± 2	11 ± 6	3.3 ± 1	5 ± 2	10 ± 3	24 ± 16	97 ± 67
3	Konoplyanka River mouth	5 ± 2	16 ± 5	1.3 ± 0.3	140 ± 15	160 ± 15	240 ± 140	290 ± 170
4	Dnieper River	7 ± 2	11 ± 6	4.5 ± 1.2	38 ± 4	44 ± 4	40 ± 20	260 ± 120
5	Dnieper River	3 ± 2	13 ± 5	8.8 ± 2.2	23 ± 3	20 ± 3	220 ± 110	370 ± 180
6	Konoplyanka River	29 ± 7	12 ± 5	1.1 ± 0.5	58 ± 3	62 ± 3	130 ± 70	<0.1
7	Konoplyanka River	20 ± 6	18 ± 6	1.5 ± 0.6	147 ± 15	163 ± 15	350 ± 180	240 ± 150
8	Konoplyanka River (granite open pit)	14 ± 5	19 ± 7	0.2 ± 0.1	201 ± 15	192 ± 15	450 ± 180	410 ± 200
9	Konoplyanka River	14 ± 5	14 ± 5	3.3 ± 1	24	27	<180	<0.27
10	Dnieper River	7 ± 2	11 ± 6	3.3 ± 1	9 ± 3	11 ± 3	<80	260 ± 170
	PC^{ingest} [6.4]	1000	500	200	10 000		100	1000

TABLE 6.15. CONCENTRATION OF RADIONUCLIDES IN WATER OF THE KONOPLYANKA AND DNIEPER RIVERS (NOVEMBER 2001)

Sample No.[a]	Sampling place	Concentration of natural radionuclides (mBq/L)					Total alpha activity (mBq/L)	Total beta activity (mBq/L)
		Radium-226	Lead-210	Polonium-210	Uranium-238	Uranium-234		
1	Dniprodzerzhinsk reservoir	35 ± 7	<11	0.2 ± 0.1	13 ± 2	17 ± 2	350 ± 110	320 ± 140
3	Konoplyanka River mouth	34 ± 7	<11	0.5 ± 0.2	115 ± 15	118 ± 5	300 ± 110	590 ± 230
4	Dnieper River	51 ± 12	<11	1 ± 0.5	19 ± 2	17 ± 2	450 ± 160	290 ± 140
5	Dnieper River	41 ± 10	<11	0.8 ± 0.3	7 ± 2	14 ± 2	230 ± 110	<300
6	Konoplyanka River	28 ± 5	12 ± 5	5 ± 1.2	44 ± 11	49 ± 11	250 ± 120	<300
7	Konoplyanka River	11 ± 5	<11	3.8 ± 1	110 ± 15	130 ± 15	1600 ± 500	1070 ± 320
8	Konoplyanka River (granite open pit)	10 ± 5	<11	3.4 ± 0.8	16 ± 8	21 ± 8	1290 ± 300	760 ± 280
9	Konoplyanka River	23 ± 5	11 ± 5	1.8 ± 0.6	46	45	750 ± 250	<300
10	Dnieper River	24 ± 7	<11	1.7 ± 0.4	13 ± 2	11 ± 2	710 ± 2502	<300
	PC^{ingest} [6.4]	1000	500	200	10 000	10 000	100	1000

[a] The same as shown in Table 6.14.

TABLE 6.16. CONCENTRATION OF RADIONUCLIDES IN BOTTOM SEDIMENTS (Bq/kg)[a]

Sample[b]	Sampling place	Potassium-40	Caesium-137	Lead-210	Radium-226	Thorium-232	Uranium-238
1 (sand)	Dniprodzerzhinsk reservoir	38 ± 2	3.1 ± 0.2	3.4 ± 1.4	2.7 ± 0.2	3.7 ± 0.3	3.0 ± 1.2
3 (sand)	Konoplyanka River mouth	106 ± 5	1.7 ± 0.1	12 ± 2	5.2 ± 0.2	7.1 ± 0.3	4.9 ± 1.6
4 (sand)	Dnieper River	93 ± 4	1.9 ± 0.1	9.0 ± 1.5	3.6 ± 0.2	7.1 ± 0.4	4.3 ± 1.5
5 (sand)	Dnieper River	181 ± 8	6.2 ± 0.3	30 ± 5	11 ± 0.4	13 ± 0.6	7.9 ± 3.0
6 (sand)	Konoplyanka River	153 ± 8	27 ± 1	65 ± 8	49 ± 1.9	26 ± 2	43 ± 13
7 (silt)	Konoplyanka River	164 ± 12	9.0 ± 0.7	152 ± 15	130 ± 4	35 ± 2	116 ± 30
8 (silt)	Konoplyanka River (granite open pit)	301 ± 16	32 ± 2	330 ± 26	109 ± 3	114 ± 4	134 ± 34
9 (sand)	Konoplyanka River	113 ± 5	14 ± 1	19 ± 2	12.3 ± 0.3	5.6 ± 0.3	5.2 ± 1.6
10 (sand)	Dnieper River	86 ± 4	5.5 ± 0.3	21 ± 3	6.8 ± 0.3	6.8 ± 0.4	4.3 ± 1.8

[a] Same sample as in Table 6.15.
[b] In the soils of Ukraine the average content of natural radionuclides is: U_{total} = 30–45 Bq/kg, ^{226}Ra = 14–25 Bq/kg.

According to data obtained in spring to autumn 2001, the concentrations of uranium in the bottom sediments of the Dniprovske reservoir were within the range 0.8–5.3 mg/kg (20–134 Bq/kg). The highest levels of uranium in the Dniprovske reservoir occur in the silt–sandy sediments at the site located below the discharges of the Petrovsky metallurgical plant. The values are 5.3–11.5 mg/kg, which is comparable with the levels observed in the clayey bottom sediments of the Konoplyanka River. However, there is no increase in concentration of uranium in the water at this site, suggesting that uranium is present in an insoluble form.

The above results and assessments indicate that drainage from tailings D is having an effect on the aquatic ecosystem of the river tributaries to the Dnieper reservoirs and, in particular, the Konoplyanka River. Unfortunately, there are few reliable data on the accumulation of natural radionuclides in the aquatic species of the rivers and reservoirs of this region. Radioecological monitoring of the accumulation of radionuclides in

the phytoplankton, benthic organisms and fish of the rivers and reservoirs should be part of any future radioecological studies in this region.

6.10. PLANS FOR FUTURE RESTORATION OF RADIOACTIVE WASTE SITES

Currently, because of economic problems, there are no restoration activities. However, under the State Programme for Improving Radioactive Safety of Nuclear Industry Facilities in Ukraine, the government has set out a new programme comprising several tasks [6.2], including:

(a) The complete restoration of the tailings impoundment KBZh at Zhovti Vody and restoration of the waste dumps of the Ingulsky and Smolino mines.
(b) Carrying out restoration of the Prydniprovsky chemical plant uranium site, including tailings D and C section I.
(c) The development of an environmental monitoring system for the Zhovti Vody and Prydniprovsky chemical plant sites. The planned system includes analysis of air, soil, surface and groundwater, vegetation, etc.
(d) The development of new regulations for the operation and restoration of the uranium tailings in accordance with existing international recommendations.
(e) The development and support of a comprehensive research programme.

6.11. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made in respect of radioactive contamination arising from former and current uranium processing operations in Ukraine:

(a) Uranium mining and milling in Ukraine has had a negative impact on the environment. The most serious problem is caused by about 100×10^6 t of accumulated tailings and other radioactive waste from past and current operations.
(b) Most of the tailings dumps have not been properly rehabilitated and will pose a long term problem unless they are properly stabilized. Tailings D at Dniprodzerzhinsk is considered to have the greatest potential for pollution of the environment because of its proximity to the Dnieper River, the evidence of current seepage and the possibility of catastrophic failure of the impoundment.
(c) There is a paucity of data on the levels of radionuclides in the vicinity of uranium mines and mills and radioactive waste impoundments. Consequently, it is not possible to estimate the current or future dose rates from these sources with any degree of accuracy.
(d) An ongoing system for radioecological monitoring of the environment (water, soil, vegetation, air and food products) in the affected regions (Zhovti Vody, mining areas and Dniprodzerzhinsk) needs to be established. This should involve provision of appropriate equipment and coordination of the efforts of the external monitoring organizations. It is advisable to involve the scientific institutes of the Academy of Science of Ukraine in this activity.
(e) The pollution resulting from past and present operations in the Dniprodzerzhinsk industrial complex needs to be considered holistically in order to understand their respective contribution to pollution of the Dnieper River basin and the effects of interactions between the major waste storage areas. Essentially, there needs to be an overall plan for the site, which will include rehabilitation of sites along with possible further industrial development.
(f) Rehabilitation of the non-operational uranium tailings impoundments at Zhovti Vody and Dniprodzerzhinsk needs to be completed in order to ensure that they provide long term containment.
(g) In any rehabilitation plan, particular attention should be given to tailings D and the Konoplyanka River, which is acting as a conduit for the transfer of pollutants from the tailings impoundment into the Dnieper River.
(h) The situation in the region of tailings C and adjacent to it needs regular control, and the decisions on further use should be taken with regard to IAEA recommendations and on the basis of cost–benefit analysis.
(i) Current and future operations need to be carried out in accordance with an environmental plan that includes funding provisions to ensure progressive rehabilitation of closed mines, dumps and other facilities.

(j) It is necessary to urgently start the development of modern standards on protection of the environment, radiation safety and monitoring in the zone of influence of the uranium sites, consistent with the requirements of Ukrainian laws, Ref. [6.4] and recommendations by international organizations such as the IAEA.

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7. OTHER RADIOLOGICAL SOURCES WITHIN THE DNIEPER RIVER BASIN

Sections 4–6 give information on and assessments of radiological sources associated with Chernobyl affected areas, nuclear power plants and uranium mining and processing. This section briefly considers other sources, which include:

(a) Research reactors and associated facilities;
(b) Sources resulting from medical and industrial uses of radioisotopes;
(c) Contaminated waste of Chernobyl origin that has been buried;
(d) Radioactive waste storage/disposal facilities.

Military sources are not considered because of the absence of reliable information. Spent fuel and radioactive waste produced by nuclear power plants are discussed in Section 5.7.

7.1. RESEARCH REACTORS

There are two research reactors in Ukraine, the 10 MW(th) WWR-M reactor at the Kiev Institute for Nuclear Research of NASU and the 200 kW(th) IR-100 reactor at the Sevastopol Institute for Nuclear Power and Industry. The IR-100 reactor, originally used for training nuclear submarine operators, was shut down in 1995.

The WWR-M reactor went critical in 1960 and was used for research into nuclear physics, radioisotope production and radiobiology in the former USSR and then Ukraine. The reactor has undergone a number of upgrades to improve performance and safety, including the following:

(a) Installation of a modern system for physical protection;
(b) Installation of a new computer system for accounting of nuclear material;
(c) Installation of a new system for fire protection;
(d) Installation and connection of two diesel engines for emergency power;
(e) Improvements to the control and safety systems;
(f) Installation of a facility for processing liquid radioactive waste.

The reactor is temporarily shut down.

Belarus operated a 4 MW(th) research reactor (IRT-M Minsk) at the Sosny Institute nuclear complex from 1962 to 1988. There are plans to decommission the reactor. The spent fuel from the reactor will be stored in the Ecores State facility (see Section 7.4.2).

There are no research reactors within the Russian section of the Dnieper River basin.

The research reactors within the Dnieper River basin do not have any impact on the surrounding environment or the Dnieper River system. The decommissioning of these reactors will generate a significant quantity of radioactive waste.

7.2. MEDICAL AND INDUSTRIAL USES OF RADIOISOTOPES

Radioisotopes are widely used in medicine and industry within Belarus, the Russian Federation and Ukraine.

In Ukraine all users of radioisotopes need to be licensed by the competent authority (Ministry of Environmental Protection and Safety) in accordance with the Law on Nuclear Energy Utilization and Radiation Safety. There are about 8000 users and 100 000 ionizing radiation sources in Ukraine. An inventory of these sources is in preparation.

In Belarus about 600 firms and companies use radioactive material and radioactive sources of varying intensity in medicine, industry and research; they include 60 laboratories that use open radioactive sources for research purposes. The total number of officially registered shielded sealed radiation sources located on the premises of users is about 6500. The most significant sources are used in research, industry and radiotherapy irradiators, which are located as follows: 29 in the Minsk region; 11 in the Brest region; five in the Gomel region; three in the Vitebsk region; three in the Grodno region; and five in the Mogilev region.

In the Russian part of the Dnieper River basin several hundred firms and companies (primarily medical) use radioactive material and ionizing radiation sources; none of these (except the Kursk

and Smolensk nuclear power plants) is included in the official list of nuclear and radiation facilities of increased hazard established by Resolution No. 707 of the Government of the Russian Federation (2 October 2001).

Radioisotopes used in diagnostic medicine generally have short half-lives and have no impact on the general public or the environment. Radiation sources used in industry or radiotherapy are often highly radioactive and can pose a localized problem if not properly handled or secured.

In Belarus, Promatomnadzor is responsible for the issuing of permits and licences for all activities involving ionizing radiation sources where the total activity of sources being used exceeds 3.7×10^{10} Bq (1 Ci). Promatomnadzor inspects radiation sources to ensure that they are used and stored safely.

Disused radiation sources are a potential source of exposure if not properly managed. They are often very intense sources of radiation and, in the past, poor management has resulted in high exposures of individuals in several countries. Regulatory authorities need to maintain a register of sources and ensure that they are properly licensed and managed.

7.3. BURIED WASTE OF CHERNOBYL ORIGIN

7.3.1. Storage and disposal sites in Ukraine

Soon after the Chernobyl accident, radioactive waste storage and disposal sites were established within the 10 km exclusion zone. The contaminated items dumped in these sites included soil, wood, equipment, structures and other debris. The burial operations were carried out to reduce radiation levels near the Chernobyl nuclear power plant and to prevent dispersion by wind and water. There were two types of site: interim radioactive storage sites (IRSSs), which were regarded as temporary holding areas, and radioactive disposal sites (RDSs), which were considered to be permanent. The burial activities were not well documented at the time, but beginning in 1990 a programme was undertaken to estimate inventories [7.1]. The sites were classified into various sectors depending on their location. Table 7.1 shows the sector area, inventory and dose rate in the monitored zone. Figure 7.1 shows the location of these sites in the near zone of the Chernobyl nuclear power plant. Further information on the geology and other characteristics of each site is given in Ref. [7.1].

TABLE 7.1. CHARACTERISTICS OF RADIOACTIVE WASTE BURIAL SITES WITHIN THE 10 km CHERNOBYL EXCLUSION ZONE IN 1996 [7.1]

Storage/disposal site	Sector area (ha)	Waste volume (m^3)	Activity (Bq)	Dose rate (μGy/h)
Stroybaza IRSS	125	2.9×10^5	1.1×10^{15}	10–30 000
Ryzhii Les IRSS	400	5.0×10^5	4.8×10^{14}	30–10 000
Yanov Station IRSS	128	3.0×10^4	3.7×10^{13}	25–8000
Pripyat IRSS	70	1.6×10^4	2.6×10^{13}	10–600
Neftebaza IRSS	42	2.2×10^4	6.2×10^{13}	20–500
Peschanoe Plato IRSS	88	1.0×10^5	3.7×10^{13}	20–600
Kopachi IRSS	125	1.1×10^5	3.3×10^{13}	10–300
Chistogalovka IRSS	6	—	3.7×10^{12}	2–500
Buriakovka RDS	14	—	2.4×10^{15}	3–280
Podlesny RDS	6	—	2.5×10^{15}	20–400
Kompleksny RDS	2	—	1.3×10^{15}	7–600

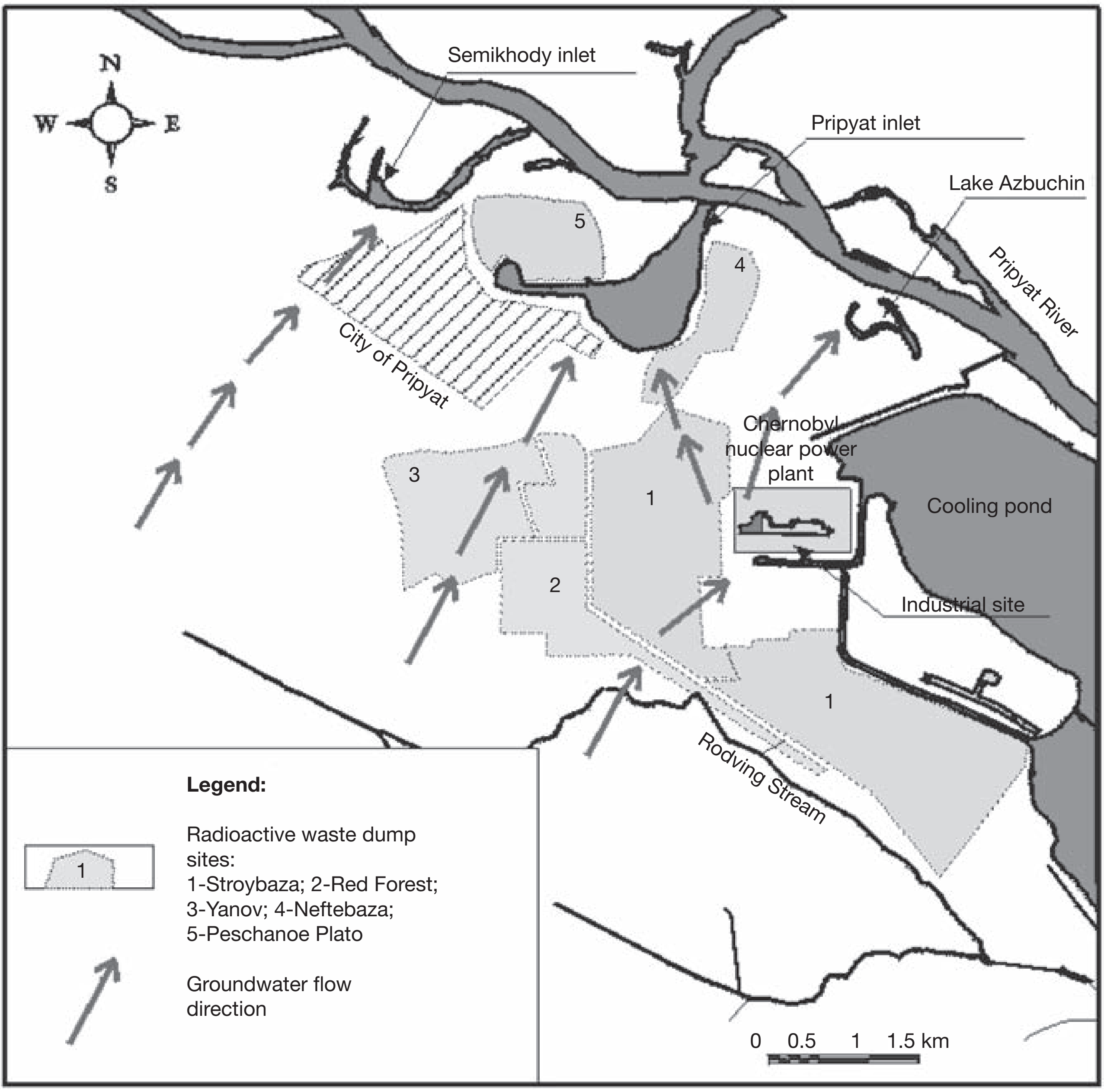

FIG. 7.1. Waste storage sites in the near zone of the Chernobyl nuclear power plant.

The most likely mechanism for release of radioactivity from these burial sites is via leaching of radionuclides from the waste and their subsequent transport by groundwater into rivers and streams (mainly the Pripyat River) and then into the Dnieper River basin. The release of radionuclides from burial sites via leaching and groundwater migration is discussed in Section 4.

7.3.2. Waste from decommissioning of Chernobyl nuclear facilities

The last operating Chernobyl reactor (unit 3) was shut down on 15 December 2000. Ukrainian Government Resolution No. 399 of 25 April 2001 established a special State enterprise, known as ‘Chernobyl nuclear power plant’, with the task of

safely decommissioning the reactor units, providing a new safe confinement for unit 4 and providing radioactive waste management facilities for the resulting waste.

The radioactive waste produced as a result of current activities is taken from the industrial site and buried at the specially constructed Buriakovka radioactive waste storage site (see Table 7.1).

Over 19 000 m^3 of liquid radioactive waste has been collected at the Chernobyl nuclear power plant site. The liquid storage facilities are currently about half full. New facilities are under construction for the safe processing of liquid and solid waste, including a special waste management plant, VECTOR, for incineration and packaging of solid radioactive waste.

7.3.3. Chernobyl contaminated waste in Belarus

After the Chernobyl accident about a quarter of the territory of Belarus was contaminated with radionuclides. In the first years after the Chernobyl accident, decontamination activities generated a large amount of radioactive waste within the Gomel and Mogilev regions. The decontamination waste included removed soil, roofing of buildings, planks, waste from stockbreeding farms, etc. Waste was brought into interim storage sites arranged near the places of the decontamination operations.

The interim storage sites used during the initial stages of decontamination were created without appropriate control by administrative bodies or scientific support. Hydrogeological conditions were not considered and waste was frequently deposited in the water areas of bogs, on the catchments of the Pripyat and Sozh Rivers, and along natural watercourses that drain into these rivers.

In 1990 a special State programme was undertaken to estimate the inventory and assess the situation at the sites. The location of 92 decontamination waste disposal sites (DWDSs) was specified, 27 in the zone of the Pripyat fallout trace (near field zone) and 65 in the zone of the Sozh trace (far field zone). Figure 7.2 shows their location. The regional breakdown was 85 in the Gomel region, four in the Mogilev region and three in the Brest region. Thirteen are in the exclusion zone and three of them are within the Polessye State Radioecological Reserve. Table 7.2 shows a breakdown of the conditions at the disposal sites and Table 7.3 gives the waste characteristics. The total area of the near surface disposal sites is 6.5×10^5 m^2 and the inventory at all sites is estimated as follows:

(a) ^{137}Cs: 2.4×10^{12} Bq.
(b) ^{90}Sr: 2.5×10^{11} Bq.
(c) $^{239,240}Pu$: 3.4×10^{9} Bq.

In order to study the possible contamination of groundwater from leaching of radionuclides from the disposal sites, 11 of the largest DWDSs were studied by the Institute of Radioecological Problems and the Belarusian Hydrogeological Expedition. The sites studied covered the spectrum of natural conditions and engineered environments. For each chosen DWDS, soils, the subsurface ground, surface waters and groundwaters were monitored.

To estimate the possible influence of the disposal sites on the environment, the conditions of operation of the 24 largest and least satisfactory repositories were analysed: 16 sites located in a zone of the Pripyat trace and eight sites in a zone of the Sozh trace. The results are summarized in Table 7.4. Measurements and modelling studies showed that ^{137}Cs does not move significantly beyond the boundaries of the site. Strontium is more mobile, but the zone of influence where the ^{90}Sr concentration is above the national permissible level (NPL) for water of 370 Bq/m^3 extends only 100–300 m beyond the site.

Thus it is concluded that radioactive waste of Chernobyl origin in the Belarusian part of the Dnieper River basin can only locally contribute to radioactive contamination of groundwater. There is no significant risk of surface water contamination due to radionuclide runoff from the radioactive waste depositories. Nevertheless, studies have shown that a number of measures should be undertaken in the future to put the repositories in order, to establish a groundwater monitoring system around the repositories and to continue specification of the radioactive waste inventory, especially at those sites that are located at sites of potential irrigation, ravines, gullies and other forms of relief where surface drainage forms and underground drainage takes place. Specifically, in the near future, it will be necessary to:

(i) Carry out a classification of sites depending on the level of potential danger and to decide on the control and monitoring of the most dangerous repositories;

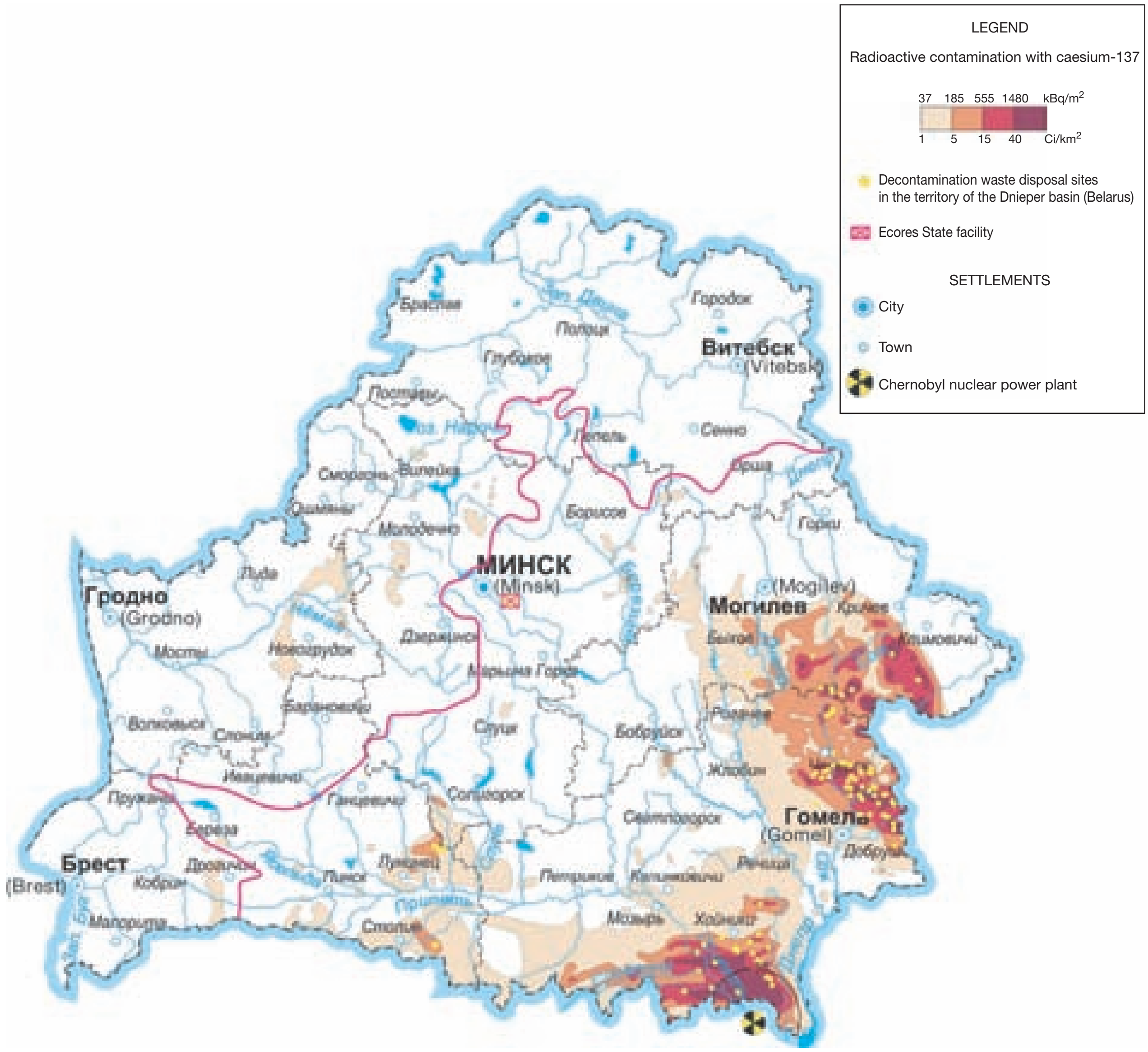

FIG. 7.2. Location of sites (circles — see legend) of buried Chernobyl radioactive waste in Belarus.

(ii) Carry out inspections and inventory measurements on sites within the exclusion zone in Belarus;
(iii) Solve questions of water use and land use around disposal sites.

7.3.4. Disposal sites in the Russian Federation

After the Chernobyl accident several dozen radioactive waste disposal sites were established in the Russian part of the Dnieper River basin (Bryansk region). The main content of the sites is contaminated earth and radioactive waste produced as a result of decontamination activities. The waste was disposed of in trenches or earth embankments without engineered barriers. Caesium-137 is the dominant radionuclide in the buried waste. Both the specific and total radioactivity of waste localized in the Russian part of the Dnieper River basin are significantly lower than those in the Ukrainian and Belarusian parts. The total volume, radioactivity and distribution of waste within administrative districts of the Bryansk region are given in Table 7.5.

TABLE 7.2. CONDITION OF DECONTAMINATION WASTE DISPOSAL SITES IN BELARUS: NUMBER OF SITES ACCORDING TO LOCATION [7.2]

Condition	Pripyat River basin	Sozh River basin
Number in each region	27	65
In the exclusion zone	13	—
In the resettled zone	14	65
Design conditions		
With an artificial barrier of clay or concrete	4	7
With a natural barrier (i.e. with an unsaturated (vadose) zone beneath the repository base)	17	23
Site characteristics		
In quarries	6	21
In foundation pits	10	12
In trenches	7	10
In holes	1	3
In gullies	—	3
Surface repositories of heap type	3	16
Adverse conditions of operation		
Can be flooded by rising groundwater	6	35
Can be swamped by surface water	—	3

TABLE 7.3. CHARACTERISTICS OF WASTE IN WASTE DISPOSAL SITES IN BELARUS [7.2]

Characteristic	Pripyat River basin		Sozh River basin	
	Caesium-137	Strontium-90	Caesium-137	Strontium-90
Activity in DWDSs (kBq)				
Maximum	450×10^6	150×10^6	200×10^6	2.9×10^6
Minimum	0.18×10^6	0.012×10^6	11×10^3	1×10^3
Specific activity (kBq/kg)				
Maximum	244.2	42.0	111.0	1.5
Minimum	0.3	0.02	0.5	0.001
Volume of waste in DWDSs (m^3)				
Maximum	41 000		18 400	
Minimum	180		71	
Contamination of the territory around DWDSs (kBq/m^2)				
Maximum	8440	634	3125	78
Minimum	210	4	210	1.0

7.4. STORAGE/DISPOSAL OF RADIOACTIVE WASTE FROM NON-POWER APPLICATIONS

7.4.1. Ukraine

In Ukraine all activities related to radioactive waste management from non-power applications are carried out by the RADON State enterprise, which operates facilities at six regional locations: Kiev, Donetsk, Odessa, Kharkiv, Dnipropetrovsk and Lviv. The total activity of accumulated radioactive waste in these storage sites is about 27 PBq (mainly tritium, ^{241}Am, ^{137}Cs, ^{60}Co, ^{192}Ir, ^{239}Pu and ^{226}Ra). Just two facilities, Kiev and Dnipropetrovsk, are located in the Dnieper River basin.

TABLE 7.4. CONDITIONS AND CONSERVATIVE ESTIMATES OF RADIONUCLIDE MIGRATION FROM THE LARGEST AND LEAST SATISFACTORY DECONTAMINATION WASTE DISPOSAL SITES IN BELARUS [7.2, 7.3]

Characteristic	Pripyat River basin		Sozh River basin	
	Caesium-137	Strontium-90	Caesium-137	Strontium-90
Activity in DWDSs (GBq)				
Maximum	271	67	37	1.1
Minimum	1.5	0.14	1.6	0.02
Area occupied by decontamination waste (m^2)				
Maximum	59.8×10^3		2.5×10^3	
Minimum	0.6×10^3		0.11×10^3	
Average thickness of protective barrier (m)				
Maximum	4.7		0	
Minimum	0		0	
Maximum activity in groundwaters (Bq/m^3)				
Directly beneath repository	$0–1 \times 10^5$	$200–75\,000 \times 10^4$	$37–1300 \times 10^5$	$480–7000 \times 10^3$
At a distance of 100 m from repository	~0	$0–1 \times 10^4$	~0	0.15–900
Zone of influence at which $C_w \leq C_{w,NPL}$ (m)	100–330		100–180	
Period of potential hazard of repositories (a)	245–370		290–360	

TABLE 7.5. CHARACTERISTICS OF CHERNOBYL ORIGIN WASTE IN DISPOSAL SITES WITHIN THE BRYANSK REGION (DATA FROM THE FRENCH–GERMAN INITIATIVE ON CHERNOBYL)

	Total waste volume (10^3 m^3)	Total ^{137}Cs activity (10^9 Bq)	
		Best estimate	Range
Krasnogorsk	32.4	31.5	20–40
Novozybkov	18.9	111.5	50–130
Zlynka	2.3	29.1	10–30
Gordeevka	21.4	30.9	20–40
Klintsy	8.6	1.9	0.3–2

RADON is responsible for the collection, transport, storage and burial of low and intermediate level radioactive waste and spent sources from all domestic enterprises, establishments and organizations, except for enterprises involved in power production.

The majority of RADON repositories are located close to big cities, so there is potential for human intrusion. Moreover, many sources were disposed of nearly 30 years ago under non-ideal conditions, and there is some risk of mechanical damage to encapsulated sources.

At the Kiev RADON facility, solid and liquid waste is stored in underground iron reinforced concrete reservoirs. These tanks are located on the outskirts of Kiev between the villages of Pyrogiv and Chapayivka in the Vita River valley. The bases of the tanks are above the groundwater horizon; nevertheless, infiltrating waters can transport leakage to the river.

Tritium waste was buried at the Kiev site in the 1960s to 1980s as solids (such as lithium–aluminium hydride), liquids (tritiated water with activities between 1.85–18.5 TBq/L) and gases.

Tritium has escaped from these tanks by evaporation and diffusion through the walls of the concrete tanks. In the mid-1990s a high concentration of tritium (viz. 1.5–5 × 10^5 Bq/kg) was detected in the vadose zone at the Kiev site. The concentration in some wells has reached 6–7 × 10^5 Bq/L. Contaminated underground waters from the site flow towards the Vita River. The concentration of tritium in the river during 1995–1997 was found to be higher than the natural background, but significantly lower than PC^{ingest} for drinking water (30 000 Bq/L) in the National Radiation Safety Standard [7.4].

There is about 550 TBq of stored radioactive waste (mainly tritium, ^{137}Cs, ^{60}Co, ^{90}Sr, ^{239}Pu and ^{210}Po) at the Dnipropetrovsk RADON site. There is no evidence of release of tritium or other radionuclides from this site or of radioactive contamination of any waterways in the region.

Another issue is management of spent ionizing sources of high activity (greater than 37 TBq (1000 Ci)) containing ^{60}Co or ^{90}Sr. There are over 1000 such sources; however, they are strictly controlled at the special waste storage sites of RADON and do not pose a significant risk to the Dnieper River basin.

At some RADON sites the quantity of waste in storage is approaching the capacity of the facility and new facilities will need to be constructed in the near future.

Since independence, the regulatory authority of Ukraine requires preparation of a SAR for operation of a nuclear facility, including radioactive storage/disposal facilities. SARs are under development for RADON facilities.

7.4.2. Belarus

In Belarus, low and intermediate level waste is generated by small enterprises. This is placed in near surface repositories of the Ecores State facility. Originally this facility was built for the storage and disposal of waste generated by the research reactor (at the Sosny Institute), but it was later opened up to other sources of radioactive waste.

The legislative basis for the operation of Ecores are the Norms of Radiation Safety (NRB-2000), the Sanitary Rules for Radioactive Waste Management, 1985, and the Basic Sanitary Rules of Radiation Safety (OSP-2002), which were developed on the basis of the relevant laws of Belarus.

The Ecores State facility contains two closed trenches and two repositories being filled with radioactive waste. It is located in a wooded region near Minsk (Sosny settlement, Minsk region). The minimum distance to the Sloust River is 2 km, the nearest pond is at 1.6 km distance. Table 7.6 gives the hydrogeological conditions at one of the Ecores disposal repositories.

An assessment of the conditions of solid radioactive waste storage at the Ecores repositories shows [7.3, 7.5]:

(a) The content in the filled vaults is a conglomerate of different material (plastic, glass, metal, rags) contaminated with both short lived and long lived radioisotopes;
(b) A closed vault contains irradiated fuel (about 2 kg U) from the Sosny research reactor;
(c) Radioactive waste including long lived alpha emitters such as ^{239}Pu, ^{241}Am and ^{226}Ra is disposed of in vaults with the rest of the waste;
(d) Some of the solid radioactive waste is combustible material;
(e) Significant amounts of radioactive waste are directly stored in concrete vaults without containerization, which excludes a second barrier to radionuclide migration beyond the boundaries of the vaults.

TABLE 7.6. HYDROGEOLOGICAL CONDITIONS OF ONE OF THE ECORES REPOSITORIES

Characteristic	Values
Thickness of vadose zone	28.0–42.0 m
Hydraulic gradient of the groundwater flow	~0.001 m/m
Thickness of aquifer	~20 m
Annual amplitude of the groundwater table fluctuations	0.9–1.0 m
Host rocks of vadose zone and aquifer	In general, mid-sands; inserts, small and large sands

An analysis of the operating conditions of the Ecores repositories indicates that waste is being stored in violation of international recommendations for the safe storage of radioactive waste. Furthermore, an assessment of the potential hazard from the repositories has shown that, within the sanitary protection zone, it is possible that the permissible concentration in the groundwater could be exceeded in the future for the following radioisotopes [7.3]:

(a) Carbon-14, ^{16}Cl, ^{60}Co, ^{90}Sr, ^{239}Pu, ^{226}Ra and ^{232}Th, as a result of migration of radioactive waste from the closed trenches;
(b) Tritium, ^{90}Sr, ^{238}U, ^{239}Pu and ^{226}Ra, as a result of migration from radioactive waste in repositories that are in the process of being filled.

Conservative modelling shows that, within the sanitary protection zone, the maximum permissible individual dose (1 mSv/a) may be temporarily exceeded by a factor of ten to 1000 due to supply of drinking water contaminated with radionuclides. Beyond the boundaries of the sanitary protection zone this is possible within 2000 to 20 000 years because of ^{239}Pu, ^{226}Ra and ^{232}Th seepage from the repositories. Within a period of 20 to 1000 years the most hazardous radionuclides are ^{14}C, ^{36}Cl, ^{90}Sr, ^{238}U and tritium, because they are weakly absorbed by the geological medium. Their high migration ability can result in contamination of the lower aquifer, used for municipal water supply. The radionuclides ^{239}Pu, ^{241}Am, ^{226}Ra and ^{232}Th are hazardous for future generations as long lived radiotoxic isotopes that can contaminate the aquifer with hazardous concentrations in the distant future.

The need to upgrade the Ecores facility was recognized immediately after a new regulatory regime was established in Belarus. In 1997 the joint efforts of several ministries were responsible for launching a national project for the reconstruction of Ecores.

The following factors were important in the decision to reconstruct the facility:

(a) The Ecores repositories had been operated in violation of the international safety requirements for a radioactive waste facility;
(b) The present repositories of the Ecores facility are almost completely full, threatening the normal functioning of institutions and enterprises where radioactive sources are being used;
(c) Safety assessment studies have shown that there is a real threat of radioactive contamination of aquifers used for drinking water, due to leakage of radionuclides from the waste;
(d) The population of the nearest settlements was concerned about possible negative health impacts in the future.

It should be noted that these concerns are for the local population living in the immediate vicinity of the facility. However, the repository is remote from the Dnieper River and any environmental impact in the future will be localized.

The reconstruction of the Ecores facility will include the following:

(a) Construction of an additional repository with a capacity of 3000 m^3 that allows material from the old repositories to be relocated in the new facility.
(b) Design for long term storage rather than disposal. This means that waste must be retrievable and properly conditioned, packaged and labelled.
(c) New plant and equipment for treatment and packaging of waste, including compaction and cementation of waste.
(d) Improvements in bore hole design for spent sealed radioactive sources.

In reconstructing the Ecores facility, a number of issues have still to be resolved. These include [7.5]:

(a) Technical procedures for the safe retrieval and sorting of waste from the existing repositories;
(b) Long term safety considerations;
(c) Public acceptance of relatively high levels of alpha emitters in a near surface facility;
(d) Ensuring the safety of existing RADON wells.

Reconstruction of Ecores is in progress. The rate of progress will be dependent on the availability of funding.

7.5. CONCLUSIONS

(a) There are no operating nuclear research reactors within the Dnieper River basin. The decommissioning of three non-operating

reactors will generate significant amounts of radioactive waste.

(b) Medical and industrial uses of radioisotopes do not pose significant risks to the population of the Dnieper River basin. Radioactive sources with high radioactivity could be a source of local exposure. Regulatory authorities should ensure that these sources are properly licensed and managed.

(c) There are many disposal or temporary storage sites for Chernobyl waste in Belarus, the Russian Federation and Ukraine. There is a need to continue to monitor and characterize the most hazardous of these sites; however, their impact appears to be quite localized and they do not represent a major source of contamination of surface waters.

(d) There are two RADON type waste storage facilities at Kiev and Dnipropetrovsk in the Ukrainian section of the Dnieper River basin. Further safety assessments need to be undertaken to assess their environmental impact.

(e) The Ecores State facility near Minsk does not comply with international standards for the storage or disposal of radioactive waste. This facility is a potential source of radioactive contamination of the local population, but not the Dnieper River basin as a whole. There are plans to reconstruct this facility to modern standards, although this is dependent on the availability of funds.

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8. ASSESSMENT OF HUMAN EXPOSURE TO RADIATION WITHIN THE DNIEPER RIVER BASIN

Radioactivity in the environment or released during an accident can result in human exposure. This section is an assessment of the levels and effects of human exposure to radiation from sources within the Dnieper River basin.

8.1. OVERVIEW OF RADIATION DOSES AND ASSOCIATED HEALTH EFFECTS

This section gives a brief overview of the principles of radiation protection. It is based on the reports of the ICRP, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the Basic Safety Standards [8.1] and an overview of radiation protection principles [8.2].

8.1.1. Doses of ionizing radiation

Alpha, beta and gamma radiation interact with matter by causing ionization (i.e. removal of electrons from atoms or molecules). In living matter, the process of ionization may damage human cells, causing death to some and modifying others. Exposure to ionizing radiation is measured in terms of absorbed dose. The unit of absorbed dose is the gray (Gy), which is a joule per kilogram (J/kg).

The biological effects of radiation to a particular organ depend on the absorbed dose and the type of radiation. The term 'equivalent' dose is used as a measure of biological damage to a particular organ. Another term, the 'effective dose', is used to take account of the overall health risk due to any combination of radiations affecting any organ of the body. The unit of both equivalent dose and effective dose is the sievert. One sievert is a rather large dose and so the millisievert (mSv) is commonly used to describe normal exposures.

To evaluate the effects of exposing a defined population group, the sum of all doses received by the members of that group may be calculated. This is termed the 'collective dose' (in units of man-Sv). It is sometimes used as a basis for decision making when comparing the cost effectiveness of options (countermeasures) to reduce radiation exposure of a population.

Living organisms are continually exposed to ionizing radiation from natural sources, which include cosmic rays and terrestrial radionuclides (such as ^{40}K, ^{238}U, ^{232}Th and their progeny, including ^{222}Rn (radon)). Table 8.1 shows the average annual dose and typical range worldwide from natural sources. Data on the mean annual background exposure in Ukraine, which is fairly typical of the Dnieper River basin, are given in Section 8.4.

In addition to natural sources, radiation exposure occurs as a result of human activities. Table 8.2 shows the annual individual effective doses in 2000 on a worldwide basis. Diagnostic medical exposure is the largest non-natural source of radiation. The residual global effects of the Chernobyl accident are now very small but, of course, are higher in the Dnieper River basin.

8.1.2. Radiobiological effects and health risks

When ionizing radiation passes through living tissue it may interact with critical areas of the cell (such as the DNA), causing direct damage. More frequently, ionization will result in the formation of free radicals, which may then react with other molecules within the cell. This may result in deactivation of chemical mechanisms or lead to interaction with genetic material [8.4]. In most cases the organism can repair cellular damage. At high

TABLE 8.1. RADIATION DOSES FROM NATURAL SOURCES [8.3]

	Worldwide average annual effective dose (mSv)	Typical range (mSv)
External exposure		
Cosmic rays	0.4	0.3–1.0
Terrestrial gamma rays	0.5	0.3–0.6
Internal exposure		
Inhalation (mainly radon)	1.2	0.2–10
Ingestion	0.3	0.2–0.8
Total	2.4	1–10

TABLE 8.2. EFFECTIVE DOSE IN 2000 FROM NATURAL AND HUMAN SOURCES [8.3]

	Worldwide average annual per caput effective dose (mSv)	Range or trend in exposure
Natural background	2.4	Typically ranges from 1 to 10 mSv
Diagnostic medical examinations	0.4	Ranges from 0.04 to 1 mSv at the lowest and highest levels of health care
Atmospheric nuclear testing	0.005	Decreased from a maximum of 0.15 mSv in 1963; higher in the northern hemisphere
Chernobyl accident	0.002	Decreased from a maximum of 0.04 mSv in 1986 (in the northern hemisphere); higher at locations nearer the accident site
Nuclear power production	0.0002	Increased with expansion of nuclear programmes, but decreased with improved practice

dose rates, cells have less time to recover and the probability of repair is lower.

The biological effects of radiation are classified as either deterministic or stochastic. Deterministic effects are those that are found to occur only above some threshold of dose (typically about 1 Sv or more), when large numbers of cells are killed. Stochastic effects occur when a cell is modified rather than killed. In such cases, the cell resulting from the reproduction of a modified, but viable, somatic cell may result in cancer after a latency period of from a few years to several decades.

Knowledge of the effects of radiation exposure on human health comes from epidemiological[1] studies of the survivors of the atomic bombs dropped on Hiroshima and Nagasaki, from radiation accidents, from groups exposed to relatively high doses in radiotherapy, from occupational exposures and from experiments with animals. Molecular radiobiology is now contributing to an understanding of the mechanisms of radiation damage.

It is known that radiation doses above about 100 mSv received in a short period lead to an increased risk of cancer later in life. The risk factor for fatal cancer averaged over all ages and cancer types is about 1% for every 100 mSv of dose.

For radiation doses below 100 mSv the evidence of harm is not clear cut. At the levels of dose typically received by the public, there is little or no direct evidence of adverse health effects. However, no threshold dose for stochastic effects has been demonstrated. Given the scientific uncertainty, radiation authorities have considered it prudent to assume no threshold. This is termed the ‘linear, no threshold hypothesis’.

The evidence for the relationship between fatal cancer and dose is derived mostly from relatively high doses and dose rates. Owing to the time dependence of cellular repair mechanisms, the observed figures need to be reduced for application to low doses and low dose rates. Although the precise figure is uncertain, the ICRP recommends, on the basis of available evidence, that the risk factor should be reduced by a factor of two. On this basis, the risk factor for a fatal cancer averaged over all ages is 5%/Sv of dose.

The risk factors for radiation exposure are subject to continuous review as more evidence becomes available. In its latest publication [8.3], UNSCEAR estimates the lifetime risk for solid cancer mortality from an acute exposure of 1 Sv to be 9% for men and 13% for women. It recommends that these estimates be reduced by 50% for chronic exposures, with an uncertainty factor of two, higher or lower. For leukaemia, the lifetime risk is estimated to be 1% for an acute dose of 1 Sv. The available data suggest a non-linear response, so that the risk is reduced by 20-fold for a tenfold reduction in acute exposure (to 100 mSv).

Although deterministic effects did occur in the initial phase of the Chernobyl accident, any current and future exposures of the population of the Dnieper River basin are likely to be chronic, low dose rate exposures. On this basis, the risk coefficient is taken as 5%/Sv of dose, as recommended by the ICRP.

Hereditary effects in human populations due to radiation have not been demonstrated, even in the children of the survivors of the atomic bombings in Japan [8.3]. However, radiation has been shown to cause hereditary defects in plants and animals,

[1] Epidemiological data are now being gathered and assessed from the Chernobyl accident.

and it can be assumed that humans are unlikely to be exceptions to the rule. UNSCEAR has concluded that the hereditary risk is 0.3–0.5%/Gy to the first generation following exposure [8.3]. This is about one tenth of the risk to the direct recipient of the radiation of a fatal cancer.

8.1.3. International system of radiation protection

Having regard for the detrimental effects of radiation, the ICRP has recommended a system of radiation protection for 'practices' (human activities that give rise to additional controlled exposures) based on three principles [8.2]:

(a) Justification of exposure. A practice that involves exposures or potential exposures should only be adopted if it is likely to produce sufficient benefit to the individual or society to outweigh the detriment or harm to health it may cause.
(b) Optimization of protection. The magnitude of individual exposures, the number of people exposed and the likelihood of exposures should be kept as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle).
(c) Limitation of individual dose. The exposure of individuals should be subject to dose limits. Table 8.3 gives the dose limits recommended by the ICRP. These limits are designed to ensure that deterministic effects are avoided and that the risk of stochastic effects is acceptably low.

TABLE 8.3. ICRP RECOMMENDED DOSE LIMITS [8.5]

Application	Dose limit	
	Occupational	Public
Effective dose	20 mSv/a, averaged over five years	1 mSv/a
Annual equivalent dose to		
The lens of the eye	150 mSv	15 mSv
The skin	500 mSv	50 mSv
The hands and feet	500 mSv	—

The Statute of the IAEA gives it a responsibility to develop international standards for safety in radiation protection. The IAEA has adopted the ICRP recommendation in preparing the Basic Safety Standards [8.1]. In turn, many countries (including Belarus, the Russian Federation and Ukraine) have adopted these limits for regulatory control purposes. The BSS gives numerical tables for converting intake of radionuclides to dose, in order that doses may be assessed and compared with dose limits, and so that radiation protection can be optimized.

The dose limits in Table 8.3 apply to controlled practices. Human activities that seek to reduce existing radiation exposures or the likelihood of exposure, and which are not part of a controlled practice, are termed 'interventions'. In the case of interventions, the circumstances giving rise to exposure and the likelihood of exposure already exist and so dose reduction can only be achieved by means of remedial actions (countermeasures). In the context of this assessment, situations that may require intervention include the state of the Chernobyl shelter, cooling pond and Pripyat floodplain or the uranium tailings from past operations (as at Dniprodzerzhinsk). On the other hand, controlled practices would include the operation of nuclear reactors and uranium processing plants.

The ICRP has recently provided guidance on generic reference levels for intervention in situations involving prolonged radiation exposure [8.5]. In doing so, the ICRP has introduced the concept of existing annual dose as that caused by all persisting sources involving prolonged exposure. The ICRP recommends that:

(i) An existing annual dose of about 10 mSv may be used as a generic reference level below which intervention is not likely to be justifiable for prolonged exposure situations.
(ii) Below a dose of 10 mSv/a, protective actions to reduce a dominant component of the existing annual dose are still optional and might be justified. In such cases, specific action levels can be established for particular components of the generic reference level.
(iii) Above a dose of 10 mSv/a, intervention may possibly be necessary and its justification should be considered on a case by case basis.
(iv) Situations in which the annual equivalent dose thresholds for deterministic effects in relevant organs could be exceeded require intervention.

(v) An existing annual dose rising towards 100 mSv will almost always justify intervention.

Radiation exposures can also be classified as ‘normal’ exposures, where the magnitude of the exposure is fairly predictable, and ‘potential’ exposures, where exposure is feasible but not certain. In the case of a potential exposure, it may be possible to estimate the probability of occurrence and the resulting radiation exposure if it were to occur.

In assessing radiation exposures, health physicists need to consider all possible exposure routes and differences in human lifestyle and habits that can lead to higher than normal exposures. In a given situation, one combination of exposure routes and lifestyles will give the highest dose, often to only a small group of people. The group that receives the highest exposure is known as the critical group. The importance of the critical group is that radiation protection measures are generally applied to limit exposure to that group.

8.1.4. Radionuclides in the Dnieper River basin

The main radionuclides currently at elevated levels in the Dnieper River basin are ^{137}Cs, ^{90}Sr and, to a much lesser extent, long lived isotopes of plutonium from the Chernobyl accident and ^{238}U and its radioactive progeny from uranium mining and ore processing in Ukraine. A brief summary of the properties of these radionuclides is given below.

Caesium-137 is a beta emitter with a half-life of 30 years. It decays to a short lived daughter (^{137m}Ba), which is a gamma emitter. Consequently, ^{137}Cs can be a source of both internal and external exposure. Being chemically similar to potassium, caesium is taken up by plants and becomes part of the food chain. It is soluble in body fluids and, upon ingestion, is absorbed rapidly and distributed almost uniformly throughout the body. It is eliminated by the kidneys with a biological half-life in adults of 70–110 days [8.4]. Its biological half-life in children is much shorter.

Strontium-90 is a beta emitter with a high fission product yield. It has a half-life of 29 years and decays to ^{90}Y, which is a stronger beta emitter. Neither ^{90}Sr nor ^{90}Y emit gamma radiation, and most of the dose from ^{90}Sr is due to internal exposure. Strontium is a member of the alkaline earth group, which includes calcium, barium and radium. Like calcium, it is a bone seeker. About 25% of ingested ^{90}Sr is absorbed into extracellular fluid and about half this amount is deposited in bone, where it irradiates both calcified bone and adjacent bone marrow [8.4]. The effective half-life of ^{90}Sr taken up in the body is about 15 years.

Plutonium has a number of isotopes, of which ^{239}Pu (half-life 24 000 years), ^{240}Pu (half-life 6600 years) and ^{238}Pu (half-life 88 years) are the most important in terms of potential long term impact. Another isotope of plutonium, ^{241}Pu, has a half-life of 14.4 years and decays by beta emission to ^{241}Am, which is an alpha emitter with a half-life of 432 years. Most isotopes of plutonium, americium and other transuranic elements are alpha emitters, which have a range of about 24 μm in bone and 40 μm in soft tissue [8.4].

Owing to the short range of alpha particles, plutonium only represents a biological hazard when it is inside the body. Inhalation is the route of most concern for internal exposure. Deposition patterns and retention of plutonium in the lungs depend on physical and chemical properties, including its solubility and particle size. The retention half-life in the lungs is between 150 and 1000 days. If ingested in soluble form, plutonium is concentrated in the skeleton and liver and has a biological half-life of about 200 years [8.4]. Plutonium is fairly immobile in the environment and is strongly adsorbed on to soils.

Uranium-238 has a very long half-life (4.5×10^9 years). It is the first member of a naturally occurring decay chain that includes 14 radionuclides (eight alpha emitters and six beta emitters). Important members of the decay chain are ^{230}Th (half-life 80 000 years), ^{226}Ra (half-life 1600 years) and ^{222}Rn (half-life 3.8 days). Thorium-230 is a major inhalation hazard. Radium-226 is an alpha–gamma emitting bone seeker and a continual source of ^{222}Rn. Although not a major radiation hazard in its own right, radon, being a gas, is mobile in the environment and acts as a vehicle for dispersal of its short lived, alpha emitting daughters, which deposit in the lungs. Radon is the most significant isotope in terms of occupational exposure in uranium mines and is continually generated within uranium tailings dumps. It is also a major contributor to the natural radiation environment (see Table 8.1).

8.2. MAJOR SOURCES AND PATHWAYS OF HUMAN EXPOSURE IN THE DNIEPER RIVER BASIN

Radiation exposure of the population of the Dnieper River basin is caused both by naturally occurring radionuclides (^{40}K, radionuclides of ^{238}U, ^{235}U and ^{232}Th decay chains, etc.) and human-made radionuclides, mainly fission products (especially ^{137}Cs and ^{90}Sr). The pathways of human exposure include external exposure from deposited gamma emitting radionuclides and internal exposure via ingestion of contaminated food and drinking water as well as inhalation of airborne radionuclides. The major pathways of human exposure from environmental radioactivity are schematically presented in Fig. 8.1.

The concentrations of natural radionuclides in the Dnieper River basin, and associated human exposure levels, are generally close to average worldwide levels. However, in uranium mining and milling areas in the Dnipropetrovsk region of Ukraine, concentrations of uranium and its daughter radionuclides are significantly elevated in river water due to releases to the Zheltaya River and leakage from tailings into Dnieper tributaries and ultimately into the Dnieper River itself. If river water is used for drinking and/or irrigation, elevated levels of uranium compounds and its daughter radionuclides may enter the human body. Ingestion is the major pathway of human exposure, due to past and present operations of the uranium industry. However, in the immediate vicinity of uranium tailings, a person could be subjected to external exposure from gamma radiation and to internal exposure via inhalation of radon and its daughter products, and possibly tailings dust.

Whereas natural radiation has accompanied the whole of human history, significant environmental contamination with human-made radionuclides occurred during two time periods. The first period of exposure started in the 1950s, and increased in the 1960s, as the result of global stratospheric fallout from worldwide nuclear weapon testing. The second period was in 1986, when a large radioactive release occurred during the Chernobyl accident. The largest population doses occurred in the Dnieper River basin, and residual radionuclides remain a source of radiation exposure.

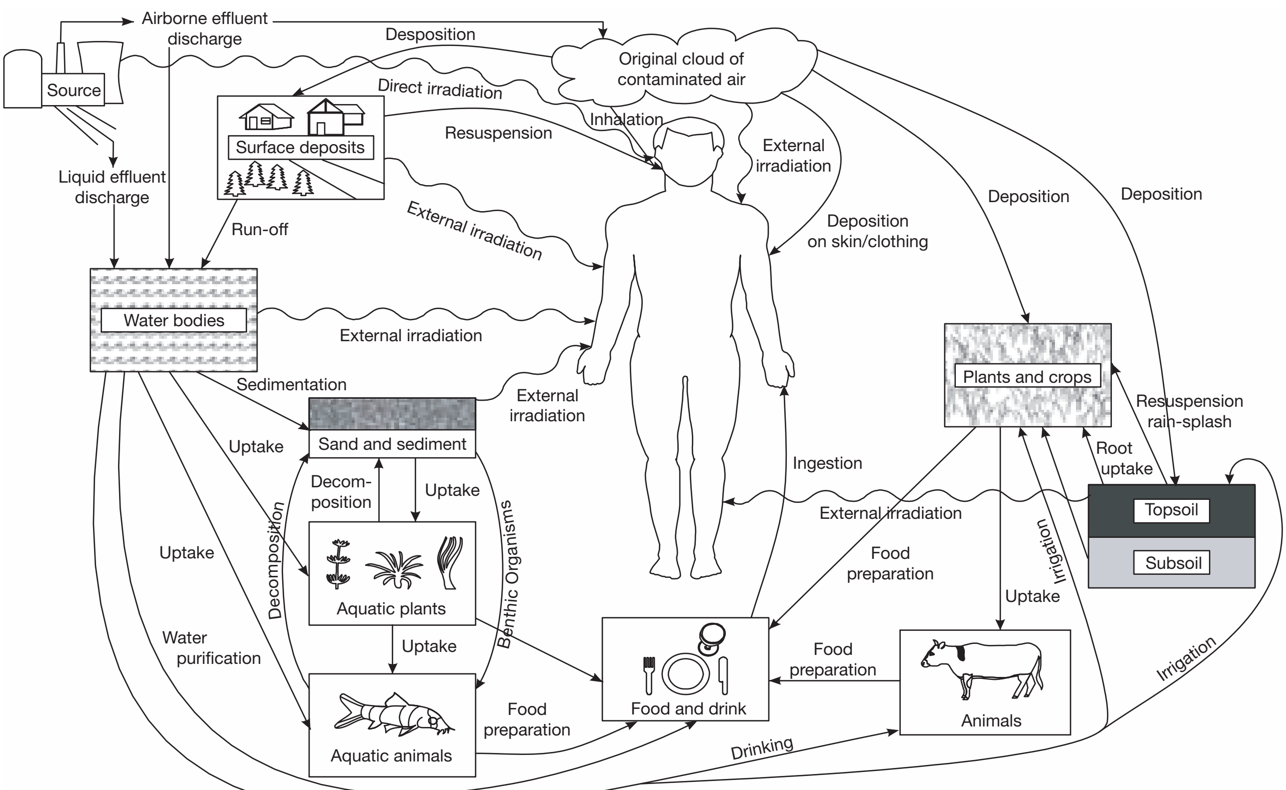

FIG. 8.1. Main environmental pathways of human radiation exposure [8.7].

Compared with the Chernobyl related environmental contamination of the Dnieper River basin with ^{137}Cs and ^{90}Sr, the historical global fallout of the same radionuclides, which happened 20–30 years earlier, can be neglected in the present dose calculations (see Ref. [8.6] for maps of the distribution of fallout from global weapons testing and the Chernobyl accident).

For completeness of public environmental dose assessment, the levels of dose caused by regular discharges of Ukrainian nuclear power plants should be considered. Reference [8.8] used the PC CREAM computer code [8.9] to calculate dose rates for conditions of actual radioactive discharges in 1988–1998 from four Ukrainian nuclear power plants located in the Dnieper River basin (Chernobyl, Khmelnitski, Rovno and Zaporozhe). For these calculations, the minimum distance between operating units and settlements was taken to be 2 km. The results show that the appropriate annual doses range from 0.07 μSv for the Khmelnitski nuclear power plant to 0.4 μSv for the Zaporozhe nuclear power plant; these doses rapidly decrease with increasing distance between the source (the nuclear power plant) and the target (the settlement). The radionuclides that contribute most to the dose are ^{14}C (long term exposure), ^{131}I, inert radioactive gases and tritium.

In the Russian Federation, gas–aerosol releases of radionuclides to the environment from RBMK reactors (the Kursk and Smolensk nuclear power plants) are higher than those from WWER units. Nevertheless, the population radiation doses resulting from releases in the areas around these plants are much lower than the site specific dose constraints. Over the first 16 years of operation of the Kursk nuclear power plant, the radiation dose to the critical group was 40 μSv or, on average, 2.5 μSv/a [8.10]. The main contributor to this dose (about 95%) was exposure due to radionuclides in airborne plumes.

From comparison of the above exposure levels from nuclear power plants with the background exposure (see Section 8.1), it is obvious that they are negligible and therefore are not considered further. The only radiological issue of concern with regard to nuclear power plants arises from possible exposure following a nuclear accident. The Chernobyl accident in 1986 was an example of a most severe nuclear power plant accident. Possible levels of human exposure in the event of an accident at a Ukrainian nuclear power plant on the Dnieper River are considered in Section 9.

8.3. MODELS OF EXTERNAL AND INTERNAL EXPOSURE

8.3.1. Model for external exposure

In this analysis we consider quasi-stationary conditions when the dose rate both in the open air and in buildings changes slowly during the year, mainly because of the presence or absence of snow cover. In the Dnieper River basin, such conditions are applicable to long lived, naturally occurring radioactive material (NORM) and fission products, from both global fallout and the Chernobyl accident. In the case of the Chernobyl accident, the dominant radionuclide for external dose calculations is ^{137}Cs, which has a half-life of 30 years and a half-life for dose reduction due to soil redistribution processes of about 50 years [8.3, 8.11]. The effective half-life of $^{137}Cs/^{137m}Ba$ gamma radiation dose rate reduction in open air due to both mechanisms is about 20 years.

In order to assess external doses to humans caused by natural radiation in temperate climate conditions, Ref. [8.3] used a simple model of humans spending 80% of their time indoors and 20% outdoors. This model can be applied to areas slightly contaminated with Chernobyl fallout. For the most significantly Chernobyl affected areas, more precise models have been developed to justify countermeasures in the early period, and to support remediation and epidemiological studies in the later period.

Deterministic models of exposure of different age and social groups of the population residing in the Dnieper River basin have been developed for the Chernobyl accident on the basis of numerous experimental investigations [8.12, 8.13]. These studies included measurements of the dose rate in different periods after the accident above virgin soil and in typical plots of settlements (including residential, industrial and recreational buildings), inhabitants' surveys about their mode of behaviour during different seasons, radionuclide analyses in profiles of virgin soil and over 10 000 measurements of individual doses using the thermoluminescence method [8.11–8.13].

According to the deterministic model presented in Fig. 8.2, the average annual effective dose E_k in the kth group of a settlement's inhabitants depends on: the absorbed dose rate in air, $\dot{D}(t)$, at a height of 1 m above an open plot of virgin soil in this settlement and its vicinity; the location factor, LF_i, which is equal to the ratio of

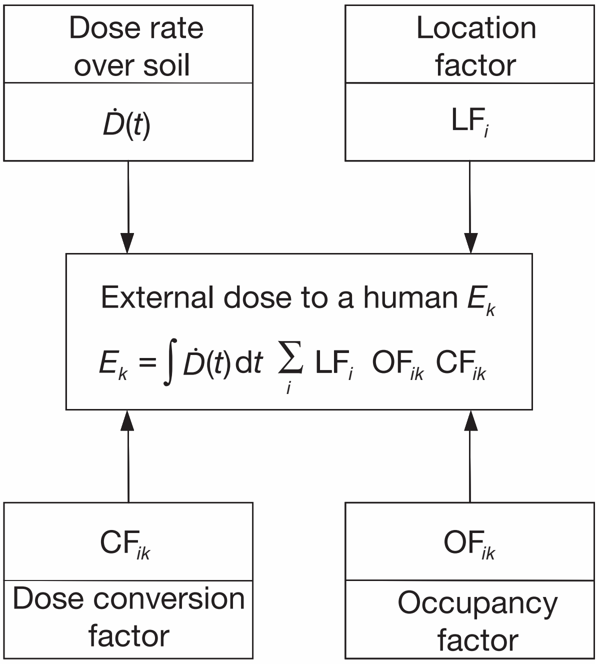

FIG. 8.2. Model of external exposure of the kth occupational group of the population (i: location index).

dose rate at the *i*th typical plot in the settlement to $\dot{D}(t)$; the occupancy factor, OF_{ik}, which is equal to the fraction of time spent during a year at the *i*th plot; and a conversion factor, CF_{ik}, which converts the absorbed dose rate in the air to the effective dose. Numerical values of the model parameters both for the Russian Federation and Ukraine can be found in Refs [8.11–8.13].

Table 8.4 presents the generic dose conversion parameters needed in order to reconstruct the past, assess the present and forecast the future average effective external doses to the adult population of a settlement located in the intermediate (100 km < D < 1000 km) zone of Chernobyl contamination based on experimental data and models developed in the Russian Federation and Ukraine [8.12, 8.13]. The values for indicated time periods for the population of a settlement are given separately for the urban and rural populations as the ratios of the mean external dose (E) to the mean ^{137}Cs soil deposition in a settlement, as of 1986 (σ_{137}) ($\mu Sv \cdot kBq^{-1} \cdot m^{-2}$). From Table 8.4, one can conclude that the urban population has been exposed to a lower dose by a factor of 1.5 to 2 compared with the dose to the rural population living in areas with similar levels of radioactive contamination. This arises because of the better shielding features of urban buildings and different occupational habits.

The parameters obtained from independent sets of Russian and Ukrainian data are in reasonable agreement. Some differences can be explained as being due to the different compositions of radionuclide deposition that occurred in different parts of the Chernobyl affected areas and to various human habits. Multiplication of the parameters presented in Table 8.4 by the mean ^{137}Cs soil deposition (as of 1986) gives an estimate of the external dose caused by gamma radiation from all the deposited radionuclides.

Depending on occupation and type of dwelling, the average doses to different social and age groups of people living in the same Russian settlement differ by a factor of 1.7 from the mean value for a settlement [8.14] — Table 8.5.

8.3.2. Model for internal exposure

The structure of a simple, Chernobyl related model of internal exposure of a person located in an area contaminated with radionuclides is presented in Fig. 8.3. The main pathways of radionuclide intake into the body of a person of *k*th age and

TABLE 8.4. RECONSTRUCTION AND PROGNOSIS OF THE AVERAGE EFFECTIVE EXTERNAL DOSE TO THE ADULT POPULATION IN THE INTERMEDIATE (100 km < D < 1000 km) ZONE OF CHERNOBYL CONTAMINATION

	Population	E/σ_{137} ($\mu Sv \cdot kBq^{-1} \cdot m^{-2}$ of ^{137}Cs)[a]				
		1986	1987–1995	1996–2005	2006–2056	1986–2056
Russian Federation [8.11, 8.12]	Rural	14	25	10	19	68
	Urban	9	14	5	9	37
Ukraine [8.13]	Rural	24	36	13	14	88
	Urban	17	25	9	10	61

[a] σ_{137} is given as for 1986.

TABLE 8.5. RATIO OF THE AVERAGE EXTERNAL EFFECTIVE DOSES IN SOME POPULATION GROUPS TO THE MEAN DOSE IN A SETTLEMENT [8.14]

Type of dwelling	Indoor workers	Outdoor workers	Herders, foresters	Schoolchildren
Wooden	0.8	1.2	1.7	0.8
One to two storey, brick	0.7	1.0	1.5	0.9
Multistorey	0.6	0.8	1.3	0.7

gender group are considered: viz. inhalation with average inhalation rate IR_k (m^3/d) of air with time dependent concentration of *r*th radionuclide AC_r (Bq/m^3) and ingestion of the set of *f*th food products, including drinking water, with consumption rate CR_{fk} (kg/d) with time dependent specific activity SA_{fr} (Bq/kg). The model is also applicable to the intake of NORMs.

Data on the radionuclide content in the air, drinking water and agricultural and natural food products are obtained from current radiation monitoring and radioecological studies. The rates of air inhalation by persons of different ages and genders for different activities are well known from physiological studies [8.15]. The consumption rate of different food products varies significantly, depending both on age and gender and on local technologies of agricultural production, collection of natural food, dietary habits, etc. For internal dose estimation after the Chernobyl accident, these data were obtained by population surveys [8.16] and analysis of statistical data. Age dependent dose coefficients for inhalation and ingestion of different

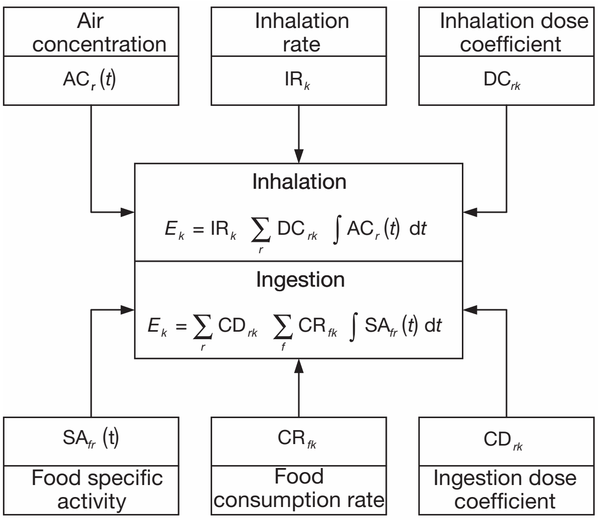

FIG. 8.3. Model of internal exposure of the kth age and gender group of the population. r: radionuclide index; f: food product index.

types of radioactive material are usually taken from ICRP publications [8.15, 8.17, 8.18].

Table 8.6 presents the generic dose conversion parameters needed in order to broadly reconstruct the past, assess the present and forecast the future average effective internal dose of the adult rural population of a settlement located in the intermediate (100 km < D < 1000 km) zone of Chernobyl contamination based on experimental data and models developed in the Russian Federation and Ukraine [8.16]. The values for each indicated time period for the population of a settlement are given separately for various soil types as the ratios of the mean internal dose (E) to the mean ^{137}Cs soil deposition in a settlement as of 1986 (σ_{137}) ($\mu Sv \cdot kBq^{-1} \cdot m^{-2}$). From Table 8.6 one can conclude that people living in areas with a higher clay content (e.g. black soil) obtained a lower internal dose because of slower radionuclide transfer from soil to plants.

The urban population of the affected areas has been exposed to lower internal doses compared with the doses to the rural population living in areas with similar levels of radioactive contamination, because of consumption of foodstuffs from non-contaminated areas and different dietary habits. The parameters obtained from independent sets of Russian and Ukrainian data significantly differ for some soil types and time periods (see Table 8.6). Some of these discrepancies can be explained by the different meteorological conditions (mainly dry in Ukraine and wet in the Russian Federation) of radionuclide deposition that occurred in different parts of the Chernobyl affected areas and different food consumption habits.

Multiplication of the parameters presented in Table 8.6 by the mean ^{137}Cs soil deposition (as of 1986) gives an estimate of the internal effective dose caused by radiation from ^{137}Cs and ^{134}Cs (for the Russian Federation, also from ^{90}Sr and ^{89}Sr). Dose estimates are given for conditions when countermeasures against internal exposure were not applied. Thyroid doses caused by intake of iodine radionuclides in the immediate aftermath of

TABLE 8.6. RECONSTRUCTION AND PROGNOSIS OF THE AVERAGE EFFECTIVE INTERNAL DOSE TO THE ADULT RURAL POPULATION IN THE INTERMEDIATE (100 km < D < 1000 km) ZONE OF CHERNOBYL CONTAMINATION

	Soil type	E/σ_{137} (μSv·kBq^{-1}·m^{-2} of ^{137}Cs)[a]				
		1986	1987–1995	1996–2005	2006–2056	1986–2056
Russian Federation [8.14]	Soddy–podzolic sandy	90	60	12	16	180
	Black	10	5	1	1	17
Ukraine [8.19]	Peat bog	19	167	32	31	249
	Sandy	19	28	5	5	57
	Clay	19	17	3	3	42
	Black	19	6	1	1	27

[a] σ_{137} is given as for 1986.

the Chernobyl accident are considered elsewhere [8.3].

For specific assessment of doses to the population of riparian settlements caused by releases of natural radionuclides from operating uranium plants or from uranium tailings into river water, a simplified procedure was used in the absence of data on concentrations in foodstuffs. In this case, only the dose resulting from consuming river water for drinking and food preparation is considered. Table 8.7 gives the dose coefficients for those radionuclides belonging to the ^{238}U decay chain that contribute most to internal human exposure from drinking water. These coefficients are used in Section 8.4.2 to estimate the annual dose to affected members of the general public.

8.4. DOSE FROM NATURAL RADIONUCLIDES

In this section, radiation exposures are reviewed for the general public and for inhabitants of some Ukrainian riparian settlements located in the Dnipropetrovsk region, where releases of uranium series radionuclides occur.

8.4.1. General public

To assess mean levels of exposure of the Ukrainian population from natural sources, we used mostly nationwide and region specific data from Ref. [8.8]. These data are largely based on Ref. [8.3], with adjustments to account for the geographical

TABLE 8.7. PARAMETERS USED FOR ESTIMATION OF AGE DEPENDENT INTERNAL DOSE FROM INTAKE OF URANIUM-238 CHAIN RADIOISOTOPES WITH DRINKING WATER [8.1, 8.17, 8.18, 8.20]

	Radionuclide	Age group (years)					
		<1	1–2	2–7	7–12	12–17	>17
Dose coefficient for ingestion (Sv/Bq)	Uranium-238	3.4×10^{-7}	1.2×10^{-7}	8.0×10^{-8}	6.8×10^{-8}	6.7×10^{-8}	4.5×10^{-8}
	Uranium-234	3.7×10^{-7}	1.3×10^{-7}	8.8×10^{-8}	7.4×10^{-8}	7.4×10^{-8}	4.9×10^{-8}
	Thorium-230	4.1×10^{-6}	4.1×10^{-7}	3.1×10^{-7}	2.4×10^{-7}	2.2×10^{-7}	2.1×10^{-7}
	Radium-226	4.7×10^{-6}	9.6×10^{-7}	6.2×10^{-7}	8.0×10^{-7}	1.5×10^{-6}	2.8×10^{-7}
	Lead-210	8.4×10^{-6}	3.6×10^{-6}	2.2×10^{-6}	1.9×10^{-6}	1.9×10^{-6}	6.9×10^{-7}
	Polonium-210	2.6×10^{-5}	8.8×10^{-6}	4.4×10^{-6}	2.6×10^{-6}	1.6×10^{-6}	1.2×10^{-6}
Annual consumption of drinking water[a] (L)		180	180	400	580	760	800

[a] Equal to total consumption of water from all sources, excluding milk, mother's milk (for infants) and water originating from oxidation of organic food components [8.17, 8.18, 8.20].

TABLE 8.8. AVERAGE ANNUAL EFFECTIVE DOSES TO THE UKRAINIAN POPULATION FROM NATURAL SOURCES

	Mean annual effective dose (mSv)		
	External	Internal	Total
Cosmic radiation	0.3	—	0.3
Cosmogenic radionuclides	—	0.02	0.02
Primordial radionuclides			
Potassium-40	0.1	0.2	0.3
Uranium-238 chain (without ^{222}Rn and its daughters)	0.1	0.2	0.3
Thorium-232 chain (without ^{220}Rn and its daughters)	0.2	0.02	0.2
Radon-222 and its daughters	—	1.3	1.3
Radon-220 (thoron) and its daughters	—	0.1	0.1
Total	0.7	1.8	2.5

conditions and dominating soil types within Ukraine.

With regard to radon concentration in dwellings located in different regions of Ukraine, Ref. [8.8] provides maps with appropriate average values derived from a special measurement programme [8.21, 8.22]. To convert the radon concentrations to effective dose, we used the model in Ref. [8.23], which is used in the Basic Safety Standards [8.1], with the accepted equilibrium factor between radon and its daughters of 0.4 rather than the value of 1.0 used in Ref. [8.8]. The resulting calculations are shown in Table 8.8.

Comparison of Tables 8.1 and 8.8 shows that the average annual effective doses to the Ukrainian population from natural sources are not significantly different from the world average value of 2.4 mSv/a. Taking into account the similarity of natural conditions in the neighbouring regions of Belarus, Ukraine and the European part of the Russian Federation, it is concluded that the estimates of public exposure given in Table 8.8 are reasonable averages for the Dnieper River basin as a whole.

8.4.2. Population of the Ukrainian uranium mining and milling areas

As discussed in Section 6, there are two areas of uranium mining and milling activity (both past and present) in the Ukrainian part of the Dnieper River basin: Zhovti Vody and Dniprodzerzhinsk and their vicinities (see Fig. 3.1). Table 8.9 gives typical concentrations of radionuclides in rivers in these areas based on monitoring data presented in Section 5. The locations considered for this analysis are: (a) on the Zheltaya River downstream of the mining–milling close to the mining area; (b) on the

TABLE 8.9. ASSESSED CONCENTRATIONS OF THE MOST RADIOLOGICALLY IMPORTANT URANIUM-238 CHAIN RADIONUCLIDES IN RIVER WATER BASED ON MONITORING DATA

	Activity concentration (Bq/L)				
	Uranium-238	Uranium-234	Radium-226	Lead-210	Polonium-210
Zheltaya River, Annovka village, 2002	1	1	0.01	<0.01	0.02
Ingulets River, Alexandria town, 2002	0.04	0.05	0.02	<0.01	0.001
Saksagan River, Kress reservoir, 2002	0.06	0.08	0.007	<0.01	0.005
Konoplyanka River, 1992–2001	0.1	0.1	0.03	0.01	0.002
Dnieper River, Dniprodzerzhinsk reservoir, 1992–2001	0.02	0.02	0.02	<0.01	0.003

TABLE 8.10. ASSESSED ANNUAL INTERNAL DOSES[a] (mSv) FROM CONSUMPTION OF RIVER WATER FOR DRINKING AND FOOD PREPARATION IN URANIUM MINING AND MILLING AREAS

	Age group (years)					
	<1	1–2	2–7	7–12	12–17	>17
Zheltaya River, Annovka village, 2002	0.28	0.10	0.13	0.14	0.17	0.12
Ingulets River, Alexandria town, 2002	0.04	0.01	0.02	0.02	0.04	0.01
Saksagan River, Kress reservoir, 2002	0.06	0.02	0.02	0.03	0.03	0.02
Konoplyanka River, 1992–2001	0.08	0.03	0.03	0.05	0.08	0.03
Dnieper River, Dniprodzerzhinsk reservoir, 1992–2001	0.05	0.01	0.02	0.03	0.04	0.01

[a] Doses calculated from assessed monitoring data (Table 8.9) are included as well as estimated contributions from ^{230}Th and radionuclides of the ^{235}U chain; in total, these increase the dose by about 20%.

banks of the Ingulets River receiving water from the highly contaminated Zheltaya tributary and Saksagan River located in the same area; (c) near the mouth of the Konoplyanka River (at present an uninhabited area); and (d) on the shores of the Dnieper River downstream of the Prydniprovsky chemical plant located within the industrial complexes at Dniprodzerzhinsk.

The data in Table 8.9 were then used along with the dose rate coefficients and the age related drinking water consumption data (see Table 8.7) to determine the annual internal doses, which are shown in Table 8.10.

Based on the available water monitoring data, the highest levels of human exposure are received by inhabitants of settlements located on the banks of the Zheltaya and Konoplyanka Rivers. The annual dose estimates are about at the level (0.1 mSv/a) recommended by the World Health Organization (WHO) [8.24] as the maximum for drinking water[2]. However, it should be noted that both of these streams are relatively small and known to be highly polluted with various contaminants; it is therefore difficult to imagine conditions in which the local population would use this water for drinking, food preparation or other domestic needs.

In contrast, water from the bigger rivers, the Ingulets, Saksagan and especially the Dnieper, is regularly used for domestic needs, including drinking and food preparation. However, according to available monitoring data, consumption of water from these rivers does not lead to human exposure levels that exceed any international safety standard for uranium chain radionuclides.

On the one hand, the dose estimations presented in Table 8.10 were made using the very conservative assumption that inhabitants of affected areas receive all their drinking water from contaminated streams. On the other hand, data on radionuclide concentrations in fish and crayfish are unavailable, and therefore this pathway could not be analysed. Thus our estimates should be considered as preliminary and with substantial uncertainties. In order to calculate dose rates from all the major human exposure pathways, additional monitoring data are required, especially those relevant to contamination levels and the consumption rate of river fish and other aquatic species.

A simple estimate of the collective dose to the population of riparian settlements caused by the annual releases of uranium chain radionuclides to the Konoplyanka–Dnieper River water can be made for the Dniprodzerzhinsk area. Appropriate simplified screening models developed by UNSCEAR [8.25] and the IAEA [8.3] have been applied to the release conditions at tailings D of the Prydniprovsky chemical plant (refer to Sections 5 and 9 for further information on the condition of these tailings). The annual release was estimated by multiplying the assessed radionuclide concentration

[2] For uranium, the chemical toxicity also needs to be considered. In the addendum to the WHO guidelines, published in 1998, a health based guideline concentration of 0.002 mg U/L was established, which is well below the limit based on radiological considerations. It has been noted by the WHO that several human studies are under way that may provide helpful additional data. At the meeting to plan the revision of the guidelines held in Berlin in June 2000 it was concluded that uranium would be a candidate for future revision when new studies are completed.

in the Konoplyanka River water (see Table 8.9) by the average annual water discharge (about 1×10^6 m^3/a). Once per hundred years the discharge is three times as high (i.e. about 3×10^6 m^3/a). The collective effective dose commitments per unit activity discharged into freshwater bodies (for screening purposes) are presented in Refs [8.3, 8.25]. Application of both models gives a crude mean estimate of the collective dose of about 0.03 man Sv and, once per hundred years, about 0.1 man Sv. Both of these values are insignificant from a radiation protection perspective.

The potential for failure of tailings dams that have not been stabilized against erosion or catastrophic failure is discussed in Section 6. Any failure and subsequent dispersal of tailings into river systems could result in significant individual and collective dose rates; however, an analysis of these dose rates would require a probabilistic based assessment for each tailings impoundment and is beyond the scope of this study.

8.5. PRESENT AND FUTURE HUMAN EXPOSURE LEVELS CAUSED BY CHERNOBYL FALLOUT

This section is concerned with current and future exposures resulting from contamination of the Dnieper River basin with radionuclides of Chernobyl origin. For completeness, some of the tables contain estimates of past effective doses.

Inhabitants of areas contaminated with radionuclides in 1986 are still being subjected both to external exposure from ^{137}Cs gamma radiation and to internal exposure due to consumption of local foodstuffs containing ^{137}Cs and, to a lesser extent, ^{90}Sr. According to model estimates and direct human measurements [8.26], inhalation of plutonium radionuclides and ^{241}Am does not significantly contribute to human doses. Thyroid doses caused by intake of iodine radionuclides were significant only during the initial period after the accident and are considered elsewhere [8.3].

Most of the dosimetric parameters needed to estimate mean Chernobyl caused external and internal doses to inhabitants of a particular settlement for a particular time period are presented in Tables 8.4 and 8.6. In broad terms, the most important factors controlling the mean external dose are the settlement type (rural or urban) and ^{137}Cs soil deposition; whereas the important controlling factors for internal dose to the rural population are the dominant soil type and ^{137}Cs soil deposition.

In accordance with the environmental behaviour of ^{137}Cs and ^{90}Sr, external exposure prevails in areas with dominantly black soils, and the contribution of internal exposure to the total (external and internal) dose does not exceed 10%. In contrast, in areas with light sandy soils, the contributions from internal and external exposure are comparable, and in areas with peaty soils internal exposure dominates. At present, along with consumption of local vegetable and animal (milk and meat) food products, consumption of natural foods (lake fish, forest mushrooms and berries, game, etc.), which is typical for the Dnieper River basin population, significantly contributes (up to 50–70%) to ^{137}Cs intake in the human body and the associated internal dose. According to numerous studies, the contribution of ^{90}Sr to the internal dose regardless of natural conditions is usually below 5%.

In towns and cities the internal dose is partially determined by radioactive contamination of foodstuffs produced in the surrounding districts. However, importation of foodstuffs from non-contaminated areas has significantly reduced intake of radionuclides, and the corresponding internal doses received by the urban population are typically a factor of two to three less than in rural settlements with an equal level of radioactive contamination.

Deviation of the dose to critical groups compared with the settlement average values varies by a factor of 1.5–2 for external exposure (see Table 8.5) and about three for internal exposure; thus about a factor two to three for total (external and internal) exposure. The group most subjected to external exposure is adults working outdoors (foresters, herders, field workers, etc.) and those living in dwellings with low shielding properties (e.g. one storey wooden houses). The group most subjected to internal exposure from ^{137}Cs is adults consuming both locally produced agricultural animal foods (milk, dairy products, etc.) and natural foods (mushrooms, lake fish, berries, etc.) in amounts exceeding average consumption rates. The critical population groups residing in particular localities are groups of people belonging to both groups of the most exposed people (i.e. subjected to elevated external and internal exposure).

TABLE 8.11. PAST (1986–2000), PRESENT (2001) AND FUTURE (2002–2056) AVERAGE CHERNOBYL RELATED EFFECTIVE DOSES (mSv) OF ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION OF ABOUT 0.04 MBq/m^2 (1 Ci/km^2) IN 1986

	Time period			
	1986–2000	2001	2002–2056	Lifetime (1986–2056)
Rural	3–13	0.05–0.15	1–3	4–16
Urban	2–8	0.03–0.1	1–2	3–10

8.5.1. General public

In the countries most affected by the Chernobyl accident (Belarus, the Russian Federation and Ukraine), areas with average ^{137}Cs soil deposition below 37 kBq/m^2 (1 Ci/km^2) are not officially considered to be affected or contaminated; human exposure levels in these areas have not required substantial protective or remediation actions since 1986. Thus for the purposes of this report those areas where no remediation actions are necessary at present are considered separately from contaminated areas and hot spots.

Depending on the level of ^{137}Cs soil deposition, people living beyond the contaminated areas (i.e. more than 80% of the Dnieper River basin area) have been subjected to Chernobyl related external exposure during the first 15 years (1986–2001) from gamma radiation of all the deposited radionuclides in the range from almost zero in low contaminated areas up to 2.5 mSv in rural settlements and up to 1.7 mSv in towns and cities with 37 kBq/m^2 of ^{137}Cs in soil. At present, they are receiving up to 0.05 mSv/a in rural settlements and up to 0.03 mSv/a in towns and cities. In the period from 2002 to 2056 (70 years after the accident), they will receive up to 0.7 mSv in villages and up to 0.5 mSv in towns and cities.

The effective internal doses (excluding short lived ^{131}I) received by the rural population strongly depend on the dominating soil type in the village and its vicinity. Thus in black soil areas people received during the first 15 years after the accident exposures ranging from almost zero in low contaminated areas up to 1 mSv (most of it in 1986) in rural settlements with 37 kBq/m^2 of ^{137}Cs in the soil. In areas with sandy, soddy–podzolic soils, the dose was two to three times as much; in areas with dominating peaty soils, the internal dose was typically an order of magnitude larger than in black soil areas.

At present, the inhabitants of low contaminated areas are receiving from ingestion of local food up to 0.004 mSv/a in black soil areas, up to 0.04 mSv/a in sandy soil areas and about 0.1 mSv/a in villages located in peaty soil areas. In the period 2002–2056 they will receive, additionally, an internal dose of less than 0.1 mSv in black soil areas, up to 0.7 mSv in sandy soil areas and about 1–2 mSv in villages located in peaty soil areas.

Table 8.11 summarizes the total exposures (external and internal) in areas of low contamination. From 1986–2000, rural inhabitants living in black soil areas received up to 3 mSv, in sandy soil areas up to 6 mSv and in peaty areas up to 13 mSv. Bearing in mind that during the same period they received about 30–40 mSv of natural background radiation, non-intervention in these areas appears to have been sound policy. This conclusion is also relevant to current and future human exposures in low contaminated areas.

8.5.2. Inhabitants of contaminated areas

The total area of the Dnieper River basin where the ^{137}Cs contamination of soil, as of 1993–1995, was ≥0.04 MBq/m^2 is about 85 000 km^2 (see Table 4.2). Within this area, there were inhabited regions with an average ^{137}Cs soil deposition of up to 3 MBq/m^2 (80 Ci/km^2 in 1993–1995, 100 Ci/km^2 in 1986) where the application of protective actions in the early period and remediation actions in the long term have been important measures to protect human health. Owing to the substantial social importance and costs of these actions, there have been more monitoring and dose assessment studies in these areas than in ‘non-affected’ areas.

The assessment of public doses given below is based on numerous measurements of the content of ^{137}Cs, ^{90}Sr and plutonium radionuclides in soil in many thousands of localities, ^{137}Cs and to a lesser extent ^{90}Sr concentrations in foodstuffs, in vivo whole body measurements of ^{134}Cs and ^{137}Cs in

inhabitants in many hundreds of localities, post-mortem measurements of ^{90}Sr and plutonium radionuclides in tissues, as well as individual external dose measurements in about 100 localities. Models of human exposure have been developed (see Section 8.3) based on some of these measurements and verified in other studies.

In order to avoid presentation of dosimetric data on a site by site basis, mean effective doses to adult residents of rural and urban localities have been determined as a function of soil ^{137}Cs concentration and predominant soil type. The ^{137}Cs soil concentration is subdivided into two grades: 0.04–0.6 MBq/m^2 (1–15 Ci/km^2) and above 0.6 MBq/m^2 (i.e. actually 0.6–4 MBq/m^2 (15–100 Ci/km^2) as of 1986). The level of 0.04 MBq/m^2 is considered as a conventional border between 'non-contaminated' and 'contaminated' areas. In areas contaminated with ^{137}Cs above 0.6 MBq/m^2, application of active countermeasures (i.e. agricultural restrictions), decontamination measures and recommendations to restrict consumption of locally gathered natural foods (forest mushrooms and berries, lake fish, etc.) have been mandatory.

8.5.2.1. *External exposure*

For the period 1986–2000 the mean external doses to residents of rural settlements with ^{137}Cs soil deposition of 0.04–0.6 MBq/m^2 were in the range 2–30 mSv, whereas in settlements with soil deposition of 0.6–4 MBq/m^2 the dose ranged from 30 to 200 mSv, taking into account decontamination of the most contaminated settlements carried out in 1986–1989. At present, the mean annual external doses to the residents of the same two groups of rural settlements are 0.05–0.7 mSv and 0.7–2.4 mSv, respectively. Naturally, the inhabitants of settlements with the highest levels of radioactive soil contamination receive the most elevated doses; in some of the settlements the annual external doses are above the national action level of 1 mSv.

Calculations based on the dosimetric models presented in Section 8.3 show that, by 2001, the residents had already received about 70% of the lifetime external dose caused by the Chernobyl fallout. During the coming years (2001–2056) they will receive the remaining 30%, i.e. 1–13 mSv and 13–80 mSv, respectively, in the two groups of settlements described above.

The external doses to urban residents have been estimated to be a factor of 1.5–2 lower than in villages with equal ^{137}Cs soil deposition.

8.5.2.2. *Internal exposure*

The mean internal doses to residents of rural settlements strongly depend on the soil properties. For assessment purposes, soils are classified into three major soil types: (a) black or chernozem soil; (b) podzol soil (including both podzol sandy and podzol loamy soils); and (c) peat–bog or peat soil. In the settlements with ^{137}Cs soil deposition of 0.04–0.6 MBq/m^2, the mean internal effective doses accumulated from 1986 to 2000 are in the range of about 1–12 mSv for black soil, 3–30 mSv for podzol soil and 8–120 mSv for peat soil. In the settlements with higher ^{137}Cs soil deposition, located predominantly in podzol soil areas, the accumulated doses reached about 100 mSv even after account is taken of countermeasures.

At present, the mean annual internal doses received by residents of rural settlements are less than 0.1 mSv (black soil), 0.03–0.4 mSv (podzol soil), 0.1–2 mSv (peat soil) and 0.4–2 mSv (podzol soil above 0.6 MBq/m^2). The most elevated internal doses in some of the settlements are above the national action level of 1 mSv; these are now being received by the inhabitants of settlements with the highest levels of radioactive soil contamination or by these living in peaty areas with modest ^{137}Cs soil deposition.

The dosimetric models presented in Section 8.3 predict that by 2001 the residents had already received at least 75% of their lifetime internal dose due to ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{89}Sr in the Chernobyl fallout. During the coming years (2001–2056) they will receive the remaining 25% (i.e. less than 1 mSv for black soil, 0.5–7 mSv for podzol soil and 2 to about 30 mSv for peat soil). In the most contaminated podzol soil areas, an effective dose of 7–50 mSv can still be expected.

The internal doses to urban residents have been estimated to be a factor of 1.5–2 lower than in villages with equal ^{137}Cs soil deposition.

For critical groups in contaminated areas, wild foods (forest mushrooms, game, forest berries, fish) can make an important contribution to dose [8.14, 8.16, 8.27, 8.28]. Reference [8.29] studied ^{137}Cs intake of the rural population in the Bryansk region of the Russian Federation and found that natural foods contributed about 20% of the total uptake in 1987 but up to 80% in 1994–1999. The relative contribution of wild foods to the internal dose has risen gradually because of the substantial reduction of the radionuclide content in both vegetable and animal agricultural foods, while the contamination

TABLE 8.12. PAST (1986–2000) AND FUTURE (2001–2056) MEAN CHERNOBYL RELATED EFFECTIVE DOSES (mSv) TO ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION ABOVE 0.04 MBq/m^2 (1 Ci/km^2) IN 1986

	Caesium-137 in soil (MBq/m^2)	Soil type					
		Black		Podzol		Peat	
		1986–2000	2001–2056	1986–2000	2001–2056	1986–2000	2001–2056
Rural	0.04–0.6	3–40	1–14	5–60	1–20	10–150	3–40
	0.6–4	—		60–300	20–100	—	
Urban	0.04–0.6	2–30	1–9	4–40	1–13	8–100	2–20

TABLE 8.13. ANNUAL (2001) MEAN CHERNOBYL RELATED EFFECTIVE DOSES (mSv) TO ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION ABOVE 0.04 MBq/m^2 (1 Ci/km^2) IN 1986

	Caesium-137 in soil (MBq/m^2)	Soil type		
		Black	Podzol	Peat
Rural	0.04–0.6	0.05–0.8	0.1–1	0.2–2
	0.6–4	—	1–5	—
Urban	0.04–0.6	0.03–0.4	0.05–0.6	0.1–1

of wild foods has decreased much more slowly. In the latter period, the highest contributions to ^{137}Cs intake (and, by inference, internal dose) were forest mushrooms, followed by forest berries, game and lake fish. Reference [8.29] found similar trends in a study in 1996 of residents of Kozhany (Bryansk region), located on the coast of a highly contaminated lake, where natural foods contributed an average of 50–80% of ^{137}Cs intake. Men were more likely to eat natural foods than women and there was a positive correlation between consumption of mushrooms and fish. The average annual internal dose due to ^{137}Cs was estimated to be 1.2 mSv for men and 0.7 mSv for women in 1996.

8.5.2.3. *Total dose*

Table 8.12 summarizes the mean total (external and internal) effective doses accumulated during 1986–2000 and forecast for 2001–2056. Table 8.13 gives the annual dose in 2001.

Figure 8.4 shows the geographical pattern of cumulated effective doses to the population of the

TABLE 8.14. EFFECTIVE DOSES TO THE POPULATION IN SOME CONTAMINATED DISTRICTS OF THE BELARUSIAN PART OF THE DNIEPER RIVER BASIN

Region	District	Caesium-137 soil deposition[a] (MBq/m^2)	Effective dose[a] for the time period (mSv)		
			1986–2000	2001–2015	1986–2015
Gomel	Bragin	0.8	50	13	63
Gomel	Narovlya	0.8	48	12	60
Gomel	Vetka	0.75	42	8	50
Gomel	Korma	0.5	37	9	46
Mogilev	Krasnopolye	0.7	37	4	41
Mogilev	Slavgorod	0.4	30	7	37
Mogilev	Bykhov	0.2	13	4	17
Brest	Stolin	0.1	10	2	12

[a] Mean values for the district.

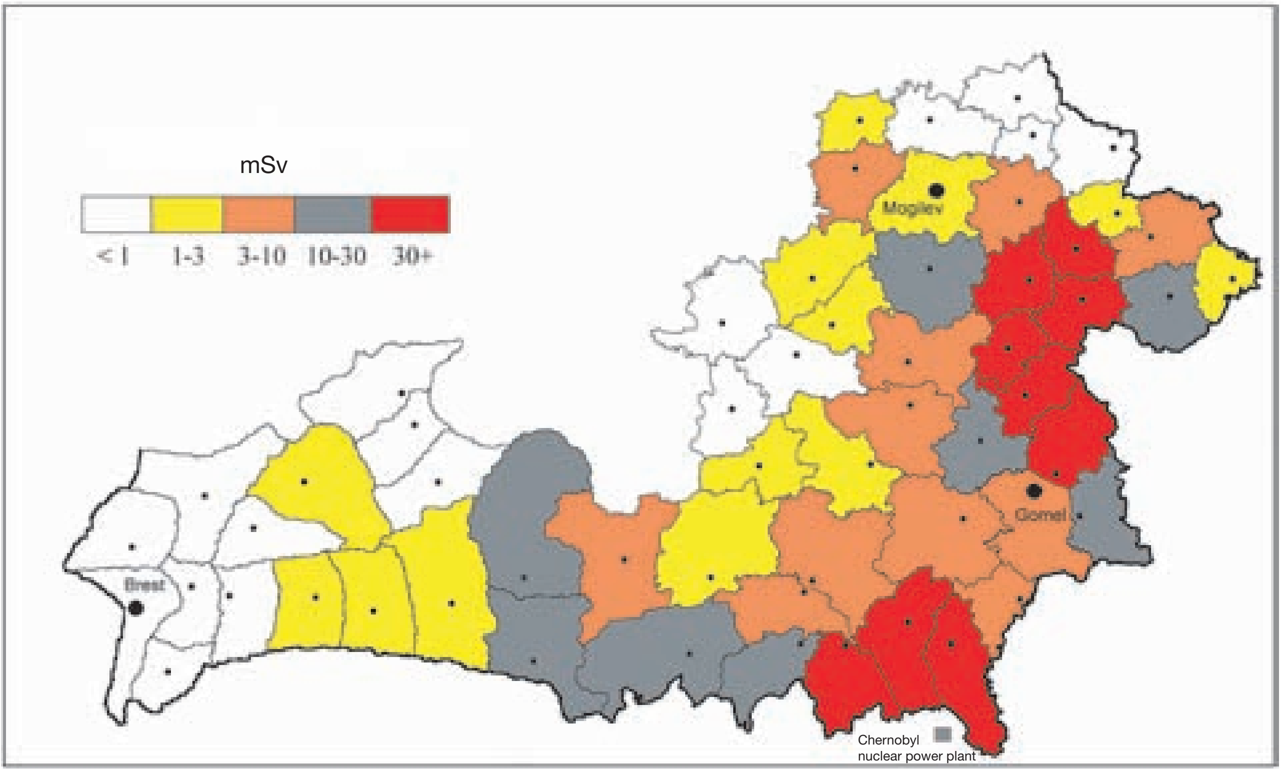

FIG. 8.4. Geographical pattern of effective dose from external and internal exposure among the population of the Dnieper River basin for 1986–2000.

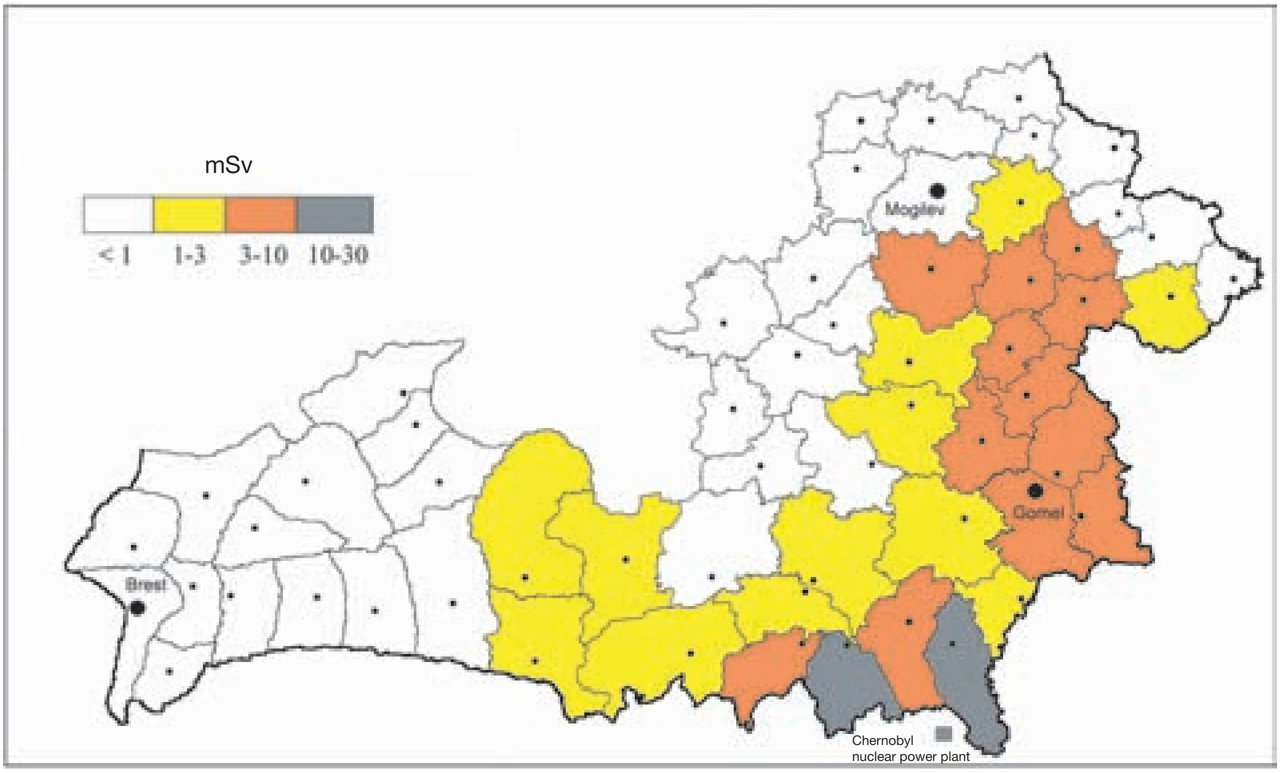

FIG. 8.5. Prognoses of expected effective doses to the population of the Dnieper River basin within Belarus for 2001–2015.

Belarusian part of the Dnieper River basin for 1986–2000 and Fig. 8.5 shows prognoses for 2001–2015. The average effective doses to the population of selected contaminated districts are given in Table 8.14 [8.30].

The relative contributions of external and internal exposure pathways vary in different regions because of the following factors:

(a) Differences in agricultural and radioecological conditions of contaminated regions, leading to considerably different values for the transfer factor of ^{137}Cs from soil to agricultural products;
(b) Differences in implementation of countermeasures between high and low contaminated territories.

Figures 8.6 and 8.7 illustrate the time dependent contributions of the exposure pathways to the mean dose received by inhabitants of two areas in the Belarusian part of the Dnieper River basin: the Gomel–Mogilev caesium spot (predominantly with podzol soils and agricultural countermeasures applied) and the Belarusian section of the Brest region (with podzol and peaty soils and a high ^{137}Cs soil to plant transfer factor).

For the Gomel–Mogilev region, external exposure dominates, whereas in the Brest region internal exposure contributes about 70% of the total dose because of the high ^{137}Cs soil to plant transfer factor. For settlements with normal transfer factors such contribution is in the range from 15% to 35% [8.30].

In order to assess the contributions of different pathways and their components to the effective dose, the dosimetric models given in Refs [8.30–8.32] were applied to the conditions of a

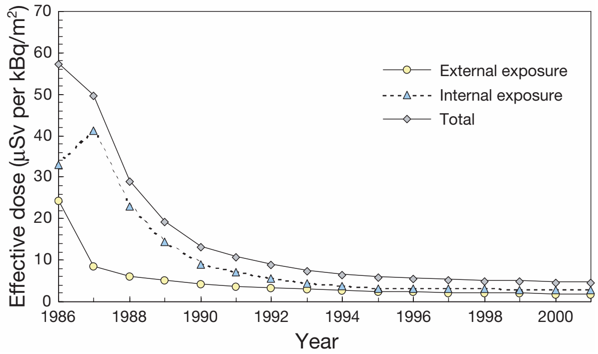

FIG. 8.7. Dynamics of the contributions of internal and external exposures to the total dose in the Belarusian section of the Brest region.

carefully studied Belarusian village, Svetilovichi, located in the podzol soil area. Figure 8.8 shows the contributions of the various pathways.

External exposure from soil is the largest contributor to dose; however, ingestion of local food is also important. Other pathways (drinking water, eating of fish, swimming, exposure from the shore) are insignificant for the average person.

According to the data presented in Table 8.13, the mean annual effective dose in the most contaminated settlements and moderately contaminated settlements located in peaty soil areas reached 2–5 mSv. Correspondingly, the dose received by critical population groups in these settlements is estimated to be in the range 4–10 mSv. In some cases, after taking account of the natural background (2 mSv), the existing annual dose (see Section 8.1.3) could exceed the ICRP recommendation of 10 mSv at which intervention should be considered [8.5].

From Table 8.12 it can be concluded that the lifetime dose (1986–2056, or 70 years after the accident) in the most contaminated settlements

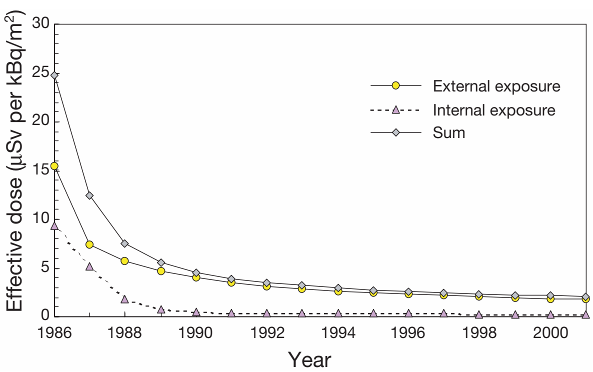

FIG. 8.6. Dynamics of the contributions of internal and external exposures to the total dose in the Gomel–Mogilev caesium spot.

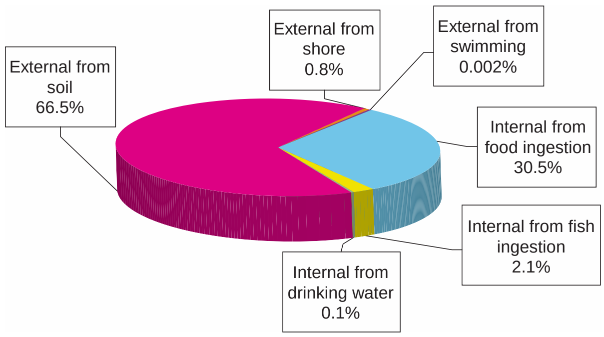

FIG. 8.8. Contributions of different pathways to the effective dose received by the general population of Svetilovichi, Gomel region, Belarus, in 1998–1999.

where countermeasures were undertaken will be about 0.4 Sv, and without countermeasures would exceed 0.5 Sv. Correspondingly, the lifetime dose to critical population groups in these settlements would exceed 1 Sv, which is the intervention level for resettlement established in the Basic Safety Standards [8.1]. Thus resettlement of people from the settlements with an initial ^{137}Cs soil deposition of 3 MBq/m^2 and more should be retrospectively assessed as having been justified at that time. Currently, since people have already received more than 70% of their lifetime dose and for the next 50 years the mean committed dose hardly exceeds 100 mSv (≈200 mSv in the critical group), resettlement is no longer justified.

In reality, most of the inhabitants of settlements with such a high level of radioactive contamination, and many others exposed to lower levels of contamination (by factors of three to five), were resettled to non-contaminated areas mainly in the spring and summer of 1986 and later, up to 1990. In the most contaminated settlements, only a few hundred people remained, predominantly elderly people who had refused to relocate to other areas.

The inhabitants of the settlements of the Gomel and Mogilev regions in Belarus and the Bryansk region of the Russian Federation, where ^{137}Cs soil contamination exceeds 1 MBq/m^2, are subjected to the highest exposure. In many tens of the settlements, the average annual exposure level still exceeds the national action level of 1 mSv. According to the methodology of this report, the settlements located in the Chernobyl accident areas, where average total annual doses to inhabitants caused by environmental ^{137}Cs and ^{90}Sr range from 1 to about 5 mSv, should be considered as local hot spots where remediation actions are still needed in order to reduce human exposure levels. These hot spots are considered further in Section 9.

8.6. CONTRIBUTION OF AQUATIC PATHWAYS

The model for internal exposure described in Section 8.3.2 is applicable to both terrestrial and aquatic pathways. The discussion in Section 8.5 was concerned mainly with terrestrial pathways. This section discusses the contribution of aquatic pathways, including drinking water, ingestion of fish and other aquatic species, and irrigation of crops with river water.

8.6.1. General public

The contribution of freshwater pathways to the public exposure is dependent on the direct consumption of water and fish containing radionuclides as well as the flooding of land used for livestock grazing and haymaking, and utilization of river water for irrigation of agricultural land, which leads to subsequent human exposure via terrestrial pathways. In the lower Dnieper River reaches, not subjected to direct radionuclide contamination in 1986, almost all the Chernobyl exposures are attributed to water pathways; however, the dose itself is very low. In most of the directly Chernobyl contaminated areas the human dose is much higher (see Section 8.5), but it is mostly attributable to terrestrial pathways.

Although individual doses are not of concern to the general public living in areas of low contamination, water pathways along the Dnieper cascade in Ukraine require further analysis because of the large number of people who are exposed. Three pathways need to be considered, as discussed in Sections 8.6.1.1–8.6.1.3.

8.6.1.1. Consumption of drinking water from the Dnieper reservoirs

The Dnieper cascade is a source of drinking water for more than eight million people. The main consumers of drinking water from the Dnieper River live in the Dnipropetrovsk and Donetsk regions. In Kiev, Dnieper River water is used by more than 750 000 people.

8.6.1.2. Consumption of fish taken from the Dnieper reservoirs

The Dnieper reservoirs are used intensively for commercial fishing. The annual catch is more than 25 000 t. There was no increase or decrease in fishing after the Chernobyl accident.

8.6.1.3. Consumption of agricultural products grown on lands irrigated using water from the Dnieper reservoirs

In the Dnieper River basin within Ukraine there are more than 1.8×10^6 ha of irrigated agricultural land. Almost 72% of this territory is irrigated with water from the Kakhovka reservoir. About 50% of the irrigated area is used for forage planting. Vegetables occupy less than 10% of the planted

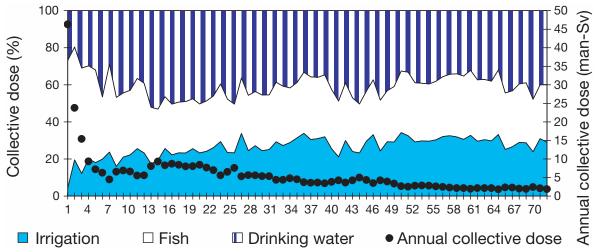

FIG. 8.9. Collective effective dose and percentage breakdown according to water use pathway for the Kiev region population as a function of time from 1986.

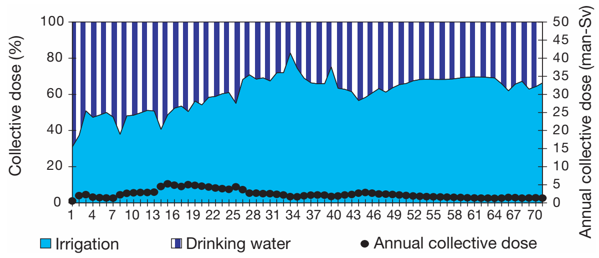

FIG. 8.11. Collective effective dose and percentage breakdown according to water use pathway for the Crimea population as a function of time from 1986.

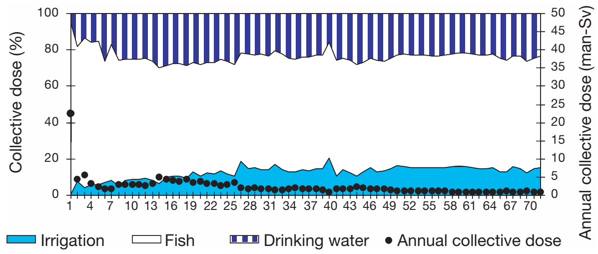

FIG. 8.10. Collective effective dose and percentage breakdown according to water use pathway for the Poltava region population as a function of time from 1986.

area. Milk production from irrigated areas also needs to be considered.

In the early 1990s estimates were made of the collective dose to people from these three pathways for a period of 70 years after the accident (i.e. from 1986 to 2056) [8.33, 8.34]. A long term hydrological scenario was analysed using the computer model WATOX [8.35]. Historical data were used to account for the natural variability in river flow. Dose assessment studies were carried out to estimate the collective dose from the three pathways [8.36]. Figures 8.9–8.11 show the collective dose and the breakdown according to the pathway for three regions: Kiev, Poltava (water drawn from the Kremenchug reservoir) and Crimea (water drawn from the Kakhovka reservoir). These calculations assume that no further protective measures are undertaken.

Figures 8.9 and 8.10 show that the annual collective dose decreased rapidly in the first five years after the accident and more slowly thereafter. This is not true of the Crimea region, due to the buffering effects of distance from the source. Currently, the annual collective dose is about 8 man Sv for the Kiev region, 4 man Sv for the Poltava region and 5 man Sv for the Crimea region.

Tables 8.15–8.17 show estimates of collective dose from these three pathways for 1999, a year of intense spring flooding that washed out radionuclides (especially ^{90}Sr) from the Pripyat floodplain (see discussion in Section 4). For this case, the dose from ^{90}Sr dominates and irrigation is the main pathway. Note that these data differ somewhat from those in Figs 8.9–8.11, because the former study was carried out before 1999 and the extreme flooding in that year could not have been anticipated.

TABLE 8.15. COLLECTIVE DOSE ESTIMATES DUE TO TAP WATER INGESTION BY THE POPULATION ALONG THE DNIEPER RIVER CASCADE DURING 1999

Reservoir	Population	Collective dose (man-Sv)		
		Strontium-90	Caesium-137	Total
Kiev	500 000	0.57	0.09	0.66
Kanev	250 000	0.15	0.02	0.17
Kremenchug	900 000	0.46	0.03	0.48
Zaporozhe	2 000 000	1.05	0.04	1.09
Kakhovka	4 000 000	2.05	0.03	2.09
Total	8 250 000	4.3	0.2	4.5

TABLE 8.16. ESTIMATED COLLECTIVE DOSE DUE TO FISH INGESTION BY THE POPULATION ALONG THE DNIEPER RIVER CASCADE DURING 1999

Reservoir	Fish catch (t)	Collective dose (man-Sv)		
		Strontium-90	Caesium-137	Total
Kiev	1 520	0.08	0.15	0.22
Kanev	760	0.02	0.04	0.06
Kremenchug	2 730	0.07	0.04	0.11
Zaporozhe	6 060	0.15	0.07	0.22
Kakhovka	13 900	0.29	0.05	0.34
Total	24 970	0.60	0.35	0.95

TABLE 8.17. ESTIMATED COLLECTIVE DOSE DUE TO CROP AND MILK PRODUCTION ALONG THE DNIEPER RIVER CASCADE DURING 1999

Reservoir	Collective dose (man-Sv)		
	Strontium-90	Caesium-137	Total
Kiev	1.03	0.03	1.06
Kanev	0.57	0.01	0.58
Kremenchug	1.89	0.01	1.90
Zaporozhe	0.99	0.003	0.99
Kakhovka	17.33	0.27	17.4
Total	21.8	0.32	21.9

8.6.2. Hot spots: closed lakes

In Section 4 the concentrations of radionuclides in river water and some aquatic species were reported. It was shown that the concentrations of radionuclides in flowing rivers are now quite low and do not present a significant radiation exposure problem. The exception is a number of ‘closed’ lakes (without regular outflow) located in peaty areas, where the concentrations of ^{137}Cs (and to a lesser extent ^{90}Sr) in both water and fish are much higher than in the nearest rivers. These concentrations do not significantly decrease with time, and in many lakes still exceed the permissible levels for drinking water and especially for fish (see Section 4).

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 predatory fish such as perch or pike may be quite high in lakes with long water retention times, as found in Scandinavia and the Russian Federation [8.29, 8.37–8.39]; for example, the concentration of ^{137}Cs in the water of Lakes Kozhanovskoe and Svyatoe, located in the severely contaminated part of the Bryansk region of the Russian Federation, was still high in 1996: concentrations were 10–20 Bq ^{137}Cs/L and 0.6–1.5 Bq ^{90}Sr/L [8.38]. The concentrations of ^{137}Cs in the muscles of crucian (*Carassius auratus gibeio*) sampled in Lake Kozhanovskoe were within the range 5–15 kBq/kg and in pike (*Esox lucius*) within the range 20–90 kBq/kg [8.29, 8.38]. The activity of ^{137}Cs in inhabitants of Kozhany village, located along the coast of Lake Kozhany, as measured by whole body counters in the summer of 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 [8.3]. Taking into account seasonal changes in ^{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.

Closed lakes are assessed to be local hot spots and are considered further in Section 9.

8.7. CONCLUSIONS

(a) The average dose rate to Ukrainian citizens from natural radiation sources is about 2.5 mSv/a, which is close to the global average. This value is also considered to be a reasonable estimate of the average dose rate to the population of the Dnieper River basin as a whole.

(b) The inhabitants of areas contaminated with radionuclides from the Chernobyl accident in 1986 are still being subjected both to external exposure from ^{137}Cs gamma radiation and to internal exposure due to consumption of local foodstuffs containing ^{137}Cs and, to a lesser extent, ^{90}Sr. The most important factors controlling the mean external dose are the settlement type (rural or urban) and the level of ^{137}Cs soil deposition (in kBq/m^2). For internal exposures, the most important factors are the soil type and the level of ^{137}Cs soil deposition. On average, effective doses to the inhabitants of rural settlements are higher than those to urban dwellers.

(c) From 1986 until 2000 rural inhabitants in ‘unaffected’ areas (^{137}Cs fallout < 0.04 MBq/m^2) living in black soil areas received effective radiation doses of up to 3 mSv, in sandy soil areas up to 6 mSv and in peaty soil areas up to 13 mSv. Bearing in mind that during the same period they received about 30–40 mSv of natural background radiation, the policy of non-intervention in these areas can be retrospectively assessed as justified.

(d) Currently, the inhabitants of areas of low contamination from Chernobyl fallout are receiving from ingestion of local foods up to 0.004 mSv/a in black soil areas, up to 0.04 mSv/a in sandy soil areas and about 0.1 mSv/a in villages located in peaty soil areas. External doses rates are up to 0.05 mSv/a in rural settlements and up to 0.03 mSv/a in towns and cities.

(e) In ‘affected’ areas, the current mean annual external doses received by residents of rural settlements are 0.05–0.7 mSv in regions where the ^{137}Cs soil deposition ranges from 0.04 to 0.6 MBq/m^2 and 0.7–2.4 mSv where the soil deposition is from 0.6 to 4 MBq/m^2. The external doses to urban residents have been estimated to be a factor of 1.5–2 lower than in villages with equal ^{137}Cs soil deposition.

(f) In ‘affected’ areas, the current mean annual internal doses to residents of rural settlements are less than 0.1 mSv (black soil), 0.03–0.4 mSv (podzol soil), 0.1–2 mSv (peat soil) and 0.4–2 mSv (podzol soil above 0.6 MBq/m^2). The most elevated internal doses in some of the settlements are above the national action level of 1 mSv; these are now being received by the inhabitants of settlements with the highest levels of radioactive soil contamination or by these living in peaty soil areas with modest ^{137}Cs soil deposition.

(g) Dosimetric models have been developed and tested to estimate past, present and future radiation exposures from all Chernobyl related pathways. The models predict that, by 2001, people in affected areas had already received at least 75% of their lifetime internal dose due to ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{89}Sr in Chernobyl fallout. Dose rates will decrease slowly with time over the next 50 years as deposited ^{137}Cs (half-life 30 years) decays and is made less available by soil redistribution processes.

(h) For critical groups in Chernobyl contaminated areas, wild foods (e.g. forest mushrooms, game, forest berries and fish) can make an important contribution to dose; for example, in one study in the Bryansk region of the Russian Federation, ‘natural’ foods contributed from 50% to 80% of ^{137}Cs intake. The average annual internal dose due to ^{137}Cs was estimated to be 1.2 mSv for men and 0.7 mSv for women.

(i) In most cases, aquatic pathways (drinking water, fish consumption and irrigation) make only a small contribution to the total dose from Chernobyl sources. At times of flooding of the Pripyat floodplain, dose rates increase somewhat due to washout of ^{90}Sr. Furthermore, in some closed lakes the concentration of ^{137}Cs remains high and high levels of contamination are found in fish. People who illegally catch and eat contaminated fish may receive internal doses in excess of 1 mSv/a from this source.

(j) Routine releases of radionuclides from operating nuclear reactors in the Dnieper River basin do not contribute significantly to

radiation exposure of communities living in their vicinity.

(k) More data are required in order to make reliable estimates of exposures of people living in uranium affected areas. Estimates of exposure from the drinking water pathway suggest low dose rates, except in small areas that are unlikely sources of drinking water.

(l) Further work is needed to assess the potential short term and long term doses that might be received if tailings impoundments adjacent to waterways in Ukraine were to fail and release tailings and/or contaminated water into adjacent rivers.

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9. RADIOLOGICAL HOT SPOTS IN THE DNIEPER RIVER BASIN

9.1. CONCEPT OF RADIOLOGICAL HOT SPOTS

The UNDP–GEF Dnieper Basin Environmental Programme utilizes the water assessment methodology known as global international waters assessment (GIWA) [9.1]. As part of a detailed assessment of pollutant sources, the GIWA methodology requires identification of the geographical location of hot spots and assessment of their impact. According to the extent of its impact, a hot spot can be further classified as either a transboundary hot spot, a national hot spot or a local hot spot.

For non-radioactive contaminants, the UNDP–GEF project defines a hot spot as a location where the maximum permissible concentrations of contaminants in water are currently exceeded. The IAEA team considers that, for radioactive contaminants, a somewhat modified definition should be used having regard for international principles of radiation protection and radioactive waste management.

The IAEA has proposed nine principles for the management of radioactive waste: (1) protection of human health; (2) protection of the environment; (3) protection beyond national borders; (4) protection of future generations; (5) burden on future generations; (6) national legal framework; (7) control of radioactive waste generation; (8) radioactive waste management independences; and (9) safety of radioactive waste management facilities [9.2]. These principles need to be applied in determining and assessing radiological hot spots.

As discussed in Section 8, limits on exposure of workers and the general public to radiation have been recommended by the ICRP [9.3]. These recommendations were adopted by the IAEA and incorporated in the Basic Safety Standards [9.4]. Based on these exposure limits, advisory and regulatory bodies may apply generic or site specific models to derive radiological criteria, reference levels or maximum permissible levels for radioactivity in air, water, soil or biota.

One of the cornerstones of radiation protection is the ALARA principle, which states that exposures should be as low as reasonably achievable, economic and social factors being taken into account (see Section 8.1.3). This poses an additional criterion to be met when considering appropriate countermeasures to reduce radiation doses to workers and the general public.

Fruitful discussions on the definition of a hot spot, especially in the context of radiological hazards, took place at a UNDP–GEF organized workshop in Kiev in September 2002 and at a project meeting at the IAEA in Vienna in October 2002.

Following discussions at the Kiev workshop, the following definitions were adopted for this study:

(a) Hot spot. A technical facility, object or local natural site that is contaminated with radionuclides or, in the future, could become a source of environmental radioactive contamination above reference levels or could result in human or biota exposure above radiological criteria.
(b) Transboundary hot spot. A hot spot that is, or in the future could become, a source of environmental radioactive contamination above reference levels or could result in human or biota exposure above radiological criteria on the territory of another country.
(c) National hot spot. A hot spot that occupies, or in the future could occupy, a substantial national territory and that has no significant transboundary impacts.
(d) Local hot spot. A hot spot that occupies a local area.

In this analysis a distinction is also made between actual (i.e. current) and potential (i.e. possible future) hot spots. Potential hot spots are facilities, objects or sites that are not currently a major problem but could be in the future if appropriate countermeasures are not undertaken.

In addition to these actual and potential hot spots, an accident at a nuclear power plant is considered in this section because of its potential for considerable transboundary impacts.

9.2. LIST OF THE CANDIDATE RADIOACTIVE HOT SPOTS

On the basis of the information discussed in Sections 4–7, the following list of candidate hot spots was selected by the IAEA expert group as requiring further assessment before possible classification (as actual or potential hot spots, and as transboundary, national or local hot spots):

(a) The Pripyat River floodplain within the CEZ;
(b) The Chernobyl cooling pond;
(c) The Chernobyl shelter in the event of its collapse;
(d) The CEZ (both in Belarus and Ukraine);
(e) Highly contaminated areas outside the CEZ, especially closed lakes and ponds in Belarus, the Russian Federation and Ukraine;
(f) Contaminated sediments in the Kiev reservoir;
(g) Sites in Ukraine where uranium ores were, or are being, processed;
(h) Radioactive waste storage/disposal facilities.

Possible nuclear accident sites include all the nuclear power plants in the Dnieper River basin or immediately adjacent to it, viz.:

(i) Kursk nuclear power plant;
(ii) Smolensk nuclear power plant;
(iii) Rovno nuclear power plant;
(iv) Khmelnitski nuclear power plant;
(v) Zaporozhe nuclear power plant;
(vi) South Ukraine nuclear power plant;
(vii) Ignalina nuclear power plant.

All sites from this candidate list were assessed, having regard for the above criteria, on the basis of existing monitoring data and/or simulations of possible releases.

9.3. ASSESSMENT OF THE HOT SPOTS IN THE CHERNOBYL AFFECTED AREAS

9.3.1. Pripyat River floodplain upstream of the Chernobyl nuclear power plant

The hottest spot in the Chernobyl affected area along the Pripyat River is the heavily contaminated floodplain upstream of the Chernobyl nuclear power plant (within a distance of 10 km upstream of the Yanov bridge) near the city of Pripyat (see Fig. 9.1).

The floodplain can be inundated by a flood of 25% probability (on average once per four years), where the maximum discharge exceeds 2000 m^3/s. The first assessments of the consequences of flooding based on mathematical models were performed in 1989–1990 [9.5, 9.6]. The modelling considered the Pripyat River and all downstream reservoirs on the Dnieper River system. Using the 2-D COASTOX model it was shown that, for the 25% probability case (the lowest flood inundating this territory), the concentration of ^{90}Sr in water at the Yanov bridge would increase to about 10 000 Bq/m^3. The Ukrainian national maximum permissible level for ^{90}Sr concentration at that time was 3700 Bq/m^3; currently it is 2000 Bq/m^3.

The fluxes of radionuclides from the Dnieper reservoirs into the Black Sea through the Dnieper–Bug estuary were evaluated using the 3-D model THREETOX [9.7], with special emphasis on the role of the estuary as a river–sea interface for radionuclide transport. Figures 9.2 and 9.3 show the simulation of the vertical profile of ^{137}Cs and ^{90}Sr for the month of July 1987. As explained in Section 4, ^{137}Cs tends to become fixed to the clay sediments that are deposited in the deeper parts of the reservoirs, and, consequently, very little flows through the cascades to the Dnieper–Bug estuary. However, although the ^{90}Sr concentration decreases with distance from the source (mainly due to dilution), about 40–60% passes through the cascade and reaches the Black Sea, where it is diluted with saline water. The outflow of ^{137}Cs from the Dnieper–Bug estuary in the two year period May 1986–April 1988 was 0.7 TBq, which represents about a half of the total input to the Dnieper system (1.4 TBq). However, the outflow of ^{90}Sr was 15.5 TBq, representing 92% of the total input of 16.8 TBq. The analysis showed that, due to the low rate of deposition of ^{90}Sr in the reservoirs and in the estuary, most of the ^{90}Sr that was washed out from the Pripyat floodplain was transported to the Black Sea via the river–reservoir–estuary system. This situation remains the same today, although the levels of radionuclides are lower.

The construction of a dyke to prevent the flooding of the left side of the contaminated floodplain was recommended in 1989–1990 as the most effective urgent water protection countermeasure. Before the dyke was constructed, the first large scale inundation of this floodplain took place on 21 January 1991, due to an ice jam in the channel

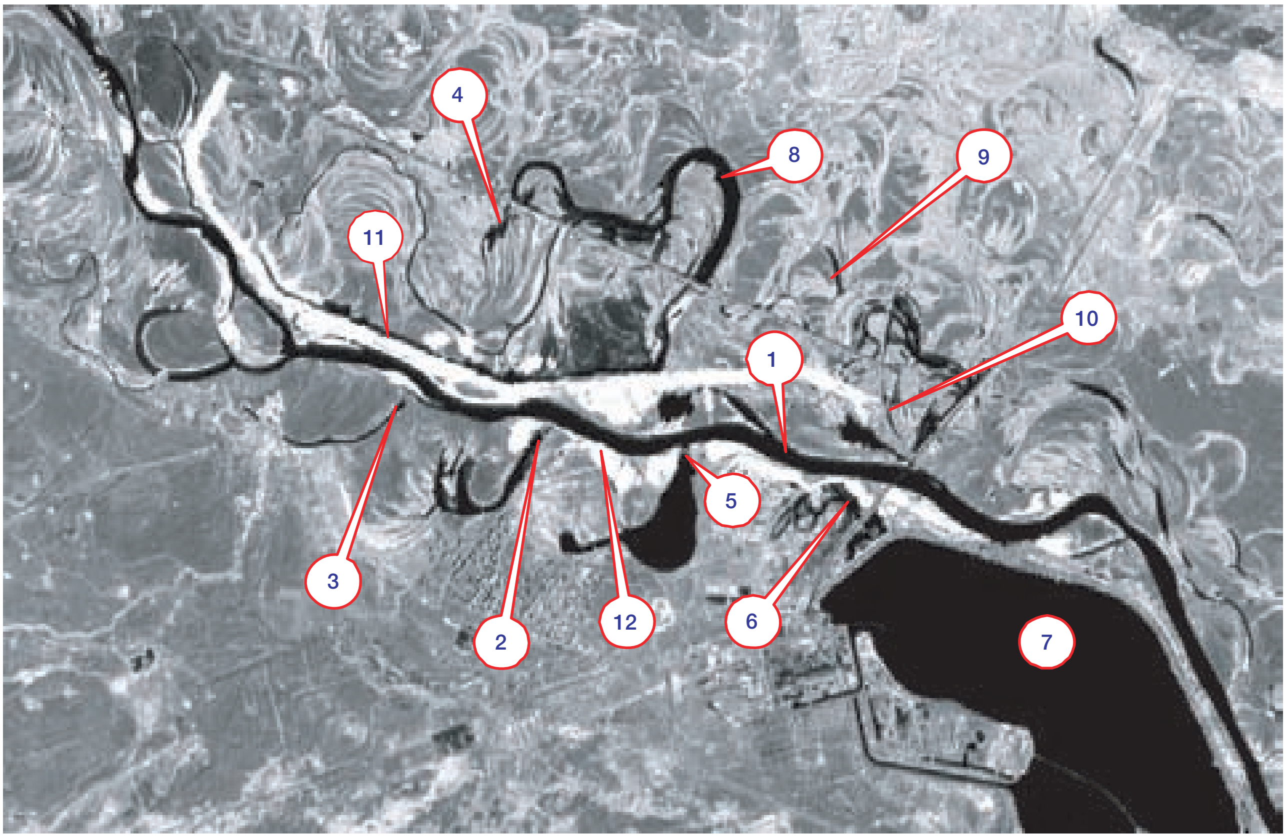


FIG. 9.1. Aerial photograph taken in 2000 showing the reclamation work along the Pripyat River in the Chernobyl near zone. The dashed line near location 6 is the position of the geological section through the Chernobyl nuclear power plant. 1: Pripyat River; 2, 3, 5, 8: former channels closed off from the river in 1986; 4: Lake Gloubokoe; 6: Lake Azbuchin (covered with sand); 7: cooling pond; 9: reclaimed area with the pumping station; 10: water flow control gate; 11: water protection dyke on the left bank (built in 1992); 12: water protection dyke on the right bank (built in 1999).

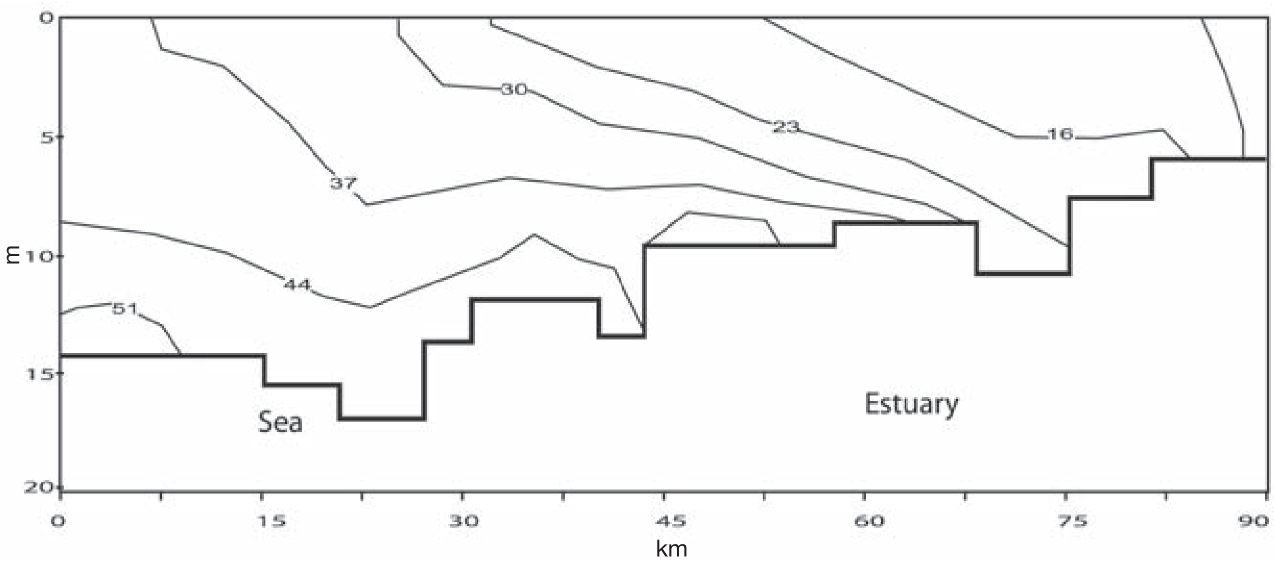


FIG. 9.2. Simulated distribution of dissolved ^{137}Cs (Bq/m^3) in a vertical cross-section of the Dnieper–Bug estuary in July 1987.

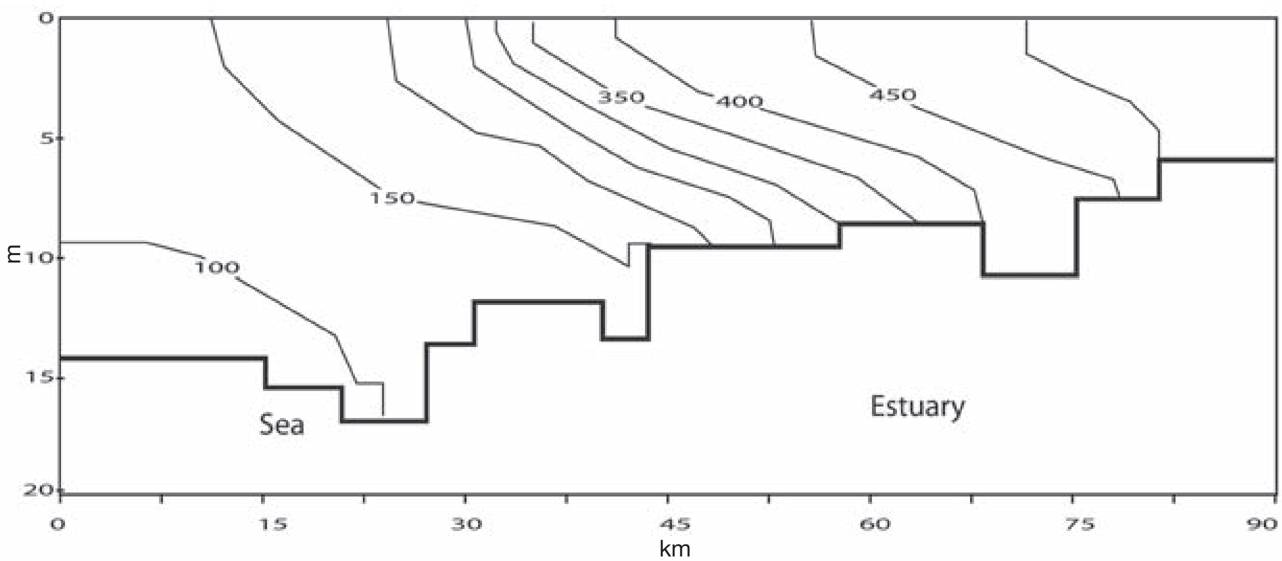


FIG. 9.3. Simulated distribution of dissolved ^{90}Sr (Bq/m^3) in a vertical cross-section of the Dnieper–Bug estuary in July 1987.

of the Pripyat River at the Chernobyl nuclear power plant. The measured data confirmed the modelling prediction; ^{90}Sr concentrations of 11 000 Bq/m^3 were measured at the Yanov bridge. The washout from the floodplain in January 1991 produced peaks in ^{90}Sr and ^{137}Cs concentrations in the Pripyat River (see Section 4, Fig. 4.13). The propagation of this 'signal' from the vicinity of the Chernobyl nuclear power plant was measured along the 900 km pathway from the Pripyat River alongside the Chernobyl nuclear power plant to the Dnieper–Bug estuary via the Dnieper reservoirs.

During 1991–1992 a protective dyke was constructed to prevent the flooding of the most contaminated areas on the left bank floodplain (see Fig. 9.1). The cost effectiveness of this countermeasure has been estimated by calculating the averted collective dose as a result of the remedial actions [9.8, 9.9]. The direct cost of the remedial work on the left bank was about $15 million. It was estimated that this countermeasure would result in an averted collective dose of 600–700 man Sv over a period of 75 years. Ignoring ongoing maintenance costs, this countermeasure was justified based on a monetary value of about $40 000 per averted man-Sv.

The effectiveness of the engineering works was demonstrated during the high summer rain flood in 1993, the winter ice jam inundation in 1994 and the historic flood of 1999. This countermeasure also had a positive social impact due to the wide publicity in the media about the success of this aquatic protection measure in the Chernobyl area.

The construction of this dyke has reduced the radionuclide fluxes to the Pripyat River; however, as was described in Section 4, during each significant spring flood in the 1990s there was a measurable increase in the concentration of ^{90}Sr in the Dnieper reservoirs, caused by radionuclide wash-off from the contaminated and still unprotected Pripyat floodplain areas. The highest flood since the Chernobyl accident took place in the spring of 1999, when the maximum discharge of 3000 m^3/s from the Pripyat River was the highest since the historically high flood of 1979 (4500 m^3/s). The construction of the right bank dyke was not completed at that time and part of the right bank floodplain was flooded for two weeks (see Section 4, Fig. 4.17), primarily due to the dyke overflow. As a result of these wash-off processes, the maximum measured concentration of ^{90}Sr at the city of Chernobyl (10 km downstream of the Yanov bridge) was 2000 Bq/m^3, and the ten day averaged concentration had a maximum of 1500 Bq/m^3, which is close to the maximum permissible concentration of ^{90}Sr in the Ukrainian drinking water standard of 2000 Bq/m^3.

The above mentioned maximum concentration of ^{90}Sr (2000 Bq/m^3) at the outlet of the contaminated floodplain during the 1999 flood (maximum discharge: 3000 m^3/s) is in agreement with an earlier prediction [9.10] made as part of an

TABLE 9.1. SIMULATED AVERAGED CONCENTRATIONS OF STRONTIUM-90 IN THE PRIPYAT RIVER AT THE OUTLET OF THE CONTAMINATED FLOODPLAIN FOR THE EXISTING LEFT BANK DYKE AND AFTER CONSTRUCTION OF THE RIGHT BANK DYKE [9.10]

Q (m^3/s)	Strontium-90 (Bq/m^3), only left bank dyke	Strontium-90 (Bq/m^3), left bank and right bank dykes
2000	2148	1259
2500	2926	1222
3100	2000	1074
4300	1444	926
6000	1296	926

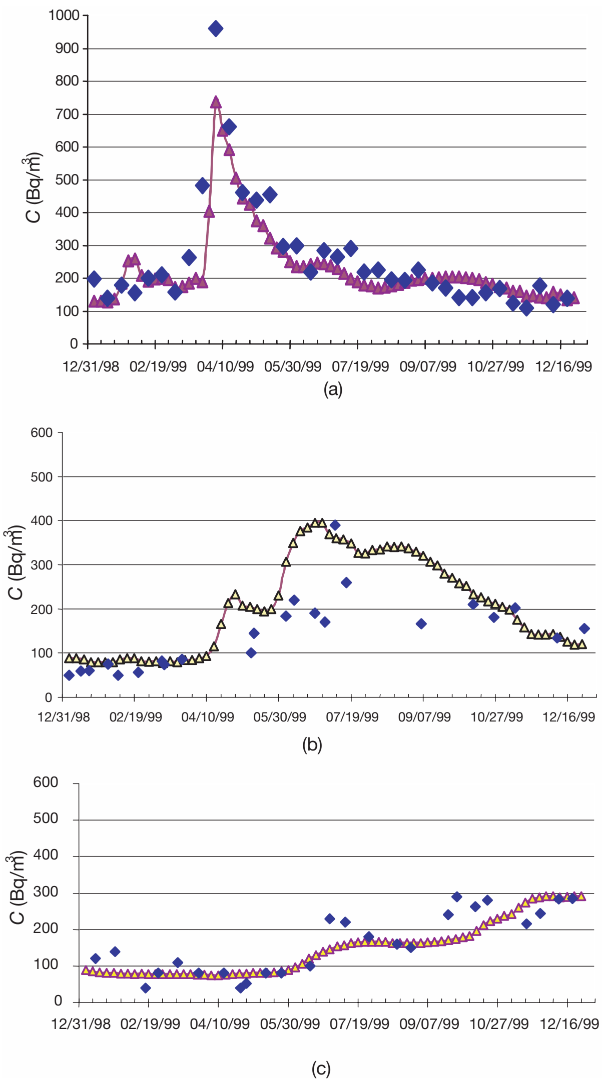


FIG. 9.4. Ten day averaged concentrations of ^{90}Sr at the dams of the hydropower plants of (a) Kiev reservoir, (b) Zaporozhe reservoir, (c) Kakhovka reservoir in comparison with simulation results (triangles) of the 1-D model. C: ^{90}Sr activity concentration in water.

assessment of the effectiveness of the construction of the dykes (see Table 9.1).

The propagation of the ^{90}Sr peak through the Dnieper reservoir cascade was simulated by the 1-D model RIVTOX. Figure 9.4 shows good agreement between the 1-D model and measured concentrations. The peak concentrations of ^{90}Sr generated from wash-off of the small floodplain area at the Chernobyl nuclear power plant were measured at the Kiev hydropower plant on 10 April 1999, at Zaporozhe (Dnieper hydropower plant) at the end of June, and in November near the Kakhovka hydropower plant. The long travel time to the Kakhovka hydropower plant is explained by the size of the Kakhovka reservoir, which has a length of 250 km and a volume of 16 km^3.

Estimates of the collective dose from the floods of 1999 are reported in Section 8.6.1. These show the continuing importance of ^{90}Sr wash-off during periods when the Pripyat floodplain is inundated.

A long term assessment of ^{90}Sr dynamics in the Kiev reservoir, assuming no further remedial works, is presented in Fig. 9.5. The scenario of the worst radiological conditions was based on a

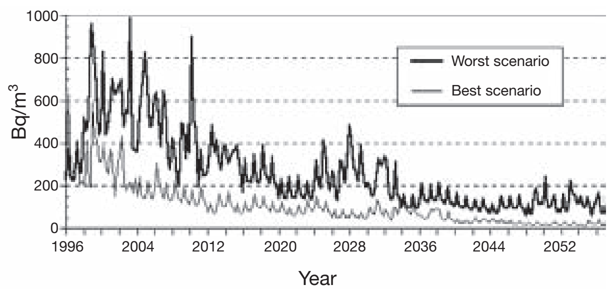


FIG. 9.5. Simulation of the long term fate of ^{90}Sr in the Kiev reservoir [9.10].

sequence of high water years in the next decade. The modelling results demonstrate that the large southern Kakhovka reservoir, while dampening the seasonal oscillations, will, after some years, have practically the same ^{90}Sr concentration as the Kiev reservoir.

Modelling studies of the effect of completing the right bank dyke construction show a significant reduction in ^{90}Sr concentrations during periods of flooding (see Table 9.1) and a corresponding reduction in dose to the downstream population. The estimated reduction in collective dose over the next 70 years is 150–300 man Sv [9.11].

The results presented in this section show that the Pripyat River floodplain upstream of the Chernobyl nuclear power plant continues to be a hot spot that generates fluxes of ^{90}Sr through the Dnieper cascade and into the Black Sea during each high flood. The intensity of this hot spot would be diminished by completion of the construction of the right bank protection dyke in the CEZ.

9.3.2. Chernobyl cooling pond

As noted in Section 2, the Chernobyl cooling pond covers an area of approximately 23 km^2 and contains approximately 149×10^6 m^3 of water. It is located between the Chernobyl nuclear power plant and the Pripyat River (see position 7 in Fig. 9.1). The total inventory of radionuclides in the pond is estimated to be in excess of 200 TBq (about 80% ^{137}Cs, 10% ^{90}Sr, 10% ^{241}Pu and less than 0.5% each of ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am), with the deep sediments containing most of this activity. The ^{90}Sr annual flux to the Pripyat River from the cooling pond via groundwater was estimated in a recent study [9.12] as 0.37 TBq (i.e. a factor of 10–30 less than the annual ^{90}Sr fluxes via the Pripyat River during recent years). Accordingly, the cooling pond cannot be considered as an actual hot spot.

Currently, the water level is kept artificially high: 6 m above the average water level in the Pripyat River. However, this will change when the cooling systems at the Chernobyl nuclear power plant are finally shut down and pumping of water into the pond is terminated. As the pond dries out, the sediments will be partly exposed and subject to dispersal.

Another potential problem that needs to be considered is a breach in the cooling pond (as a result of erosion, a terrorist attack or any other reason), after which a large amount of contaminated water and sediment would be released into the Pripyat River. The assessment of the cooling pond as a potential hot spot was provided within the framework of a recent project [9.12]. It was shown in this study that the resuspension of the dried sediments would produce only local effects and would not significantly influence the contamination of the Dnieper River system.

An analysis of the consequences of a cooling pond dam break was undertaken in a specialized modelling study. The 2-D lateral–longitudinal radionuclide transport model COASTOX was used to simulate overland flow, suspended sediment transport and radionuclide transport both in the cooling pond and on the neighbouring floodplain after a dam break. The model was tested within various studies of radionuclide transport in the Chernobyl zone [9.6, 9.10, 9.13] and was included in the Hydrological Dispersion Module of the European Union decision support system RODOS [9.14]. The model has been recently applied to simulate radionuclide wash-off from small watersheds [9.15, 9.16]. It consists of separate modules describing overland flow, sediment transport, erosion/deposition processes, radionuclide transport in solution and on suspended sediments by overland flow, and contamination of the upper soil layer. The objectives of the simulations were to evaluate discharge of ^{137}Cs and ^{90}Sr to the Pripyat River following a partial breach in the cooling pond. The initial total radionuclide concentrations of ^{137}Cs were set to 0.089 Bq/L in the Pripyat River and 2.6 Bq/L in the cooling pond. The corresponding values for ^{90}Sr were 0.3 Bq/L and 1.9 Bq/L, respectively.

Figures 9.6–9.8 illustrate the dynamics of inundation of the surrounding territory after a hypothetical dam failure involving a 150 m long breach. The ^{90}Sr concentration averaged over the river cross-section downstream of the cooling pond in solution and on sediments is shown in Figs 9.9 and 9.10.

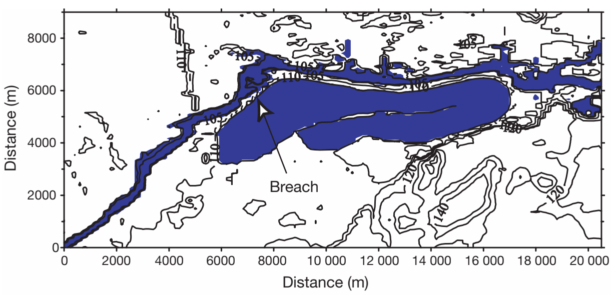


FIG. 9.6. Inundated territory 30 s after a dam failure involving a 150 m breach.

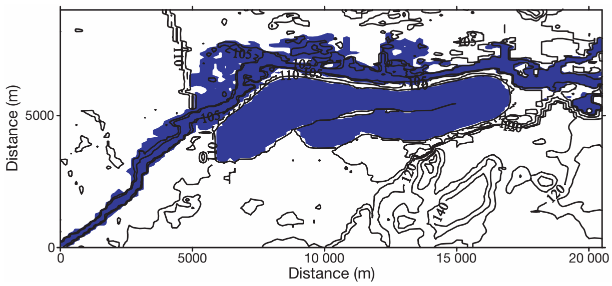


FIG. 9.7. Inundated territory 500 min after a dam failure involving a 150 m breach.

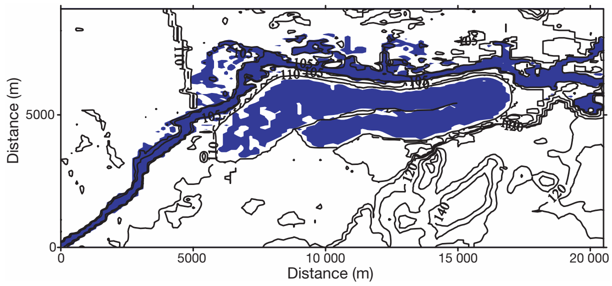


FIG. 9.8. Inundated territory 30 h after a dam failure involving a 150 m breach.

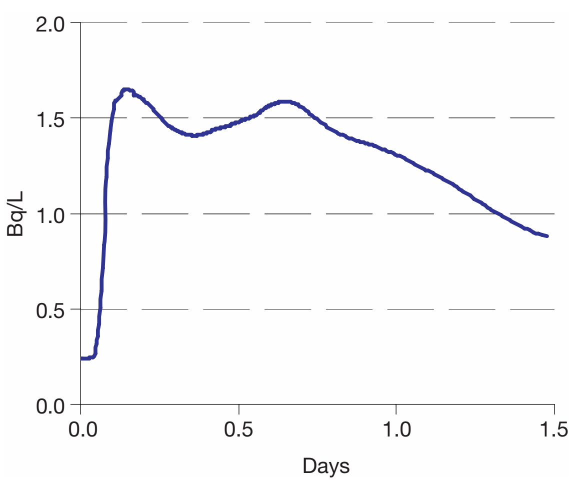


FIG. 9.9. Concentration of ^{90}Sr in the Pripyat River in solution downstream of the cooling pond.

The radionuclide discharge of soluble ^{90}Sr to the Pripyat River increases approximately 10 and 20 times for a dam failure with a 60 m and 150 m breach, respectively. Similarly, the discharge of ^{137}Cs in soluble form to the Pripyat River increases approximately 30 and 60 times. The output of the 2-D modelling integrated over the cross-section downstream of the cooling pond has been used as input data to the 1-D model of the transport of the radionuclides through the whole Dnieper reservoir cascade. The data for ^{90}Sr are shown in Figs 9.11 and 9.12.

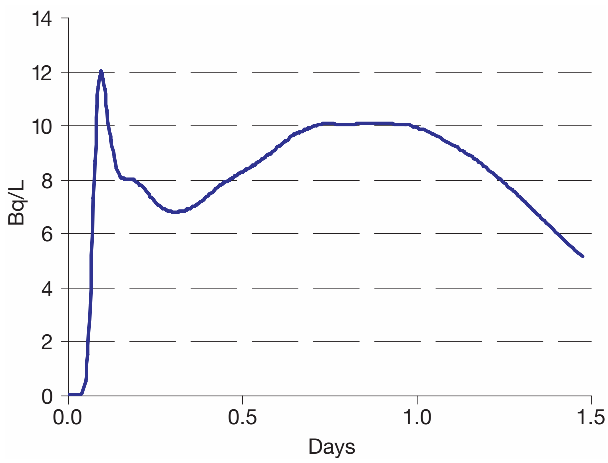


FIG. 9.10. Concentration of ^{90}Sr on suspended sediments in the Pripyat River downstream of the cooling pond.

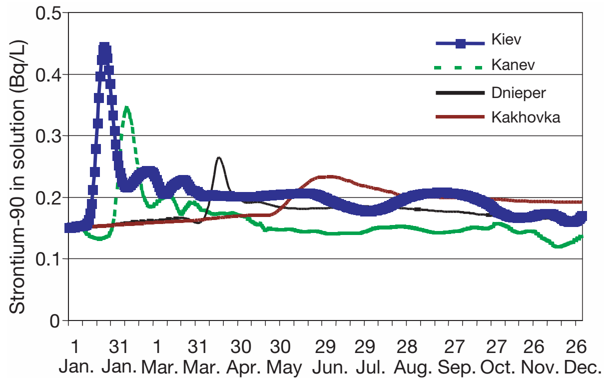


FIG. 9.11. Dynamics of ^{90}Sr in solution along the cascade of the Dnieper reservoirs after a 150 m breach in the cooling pond dam.

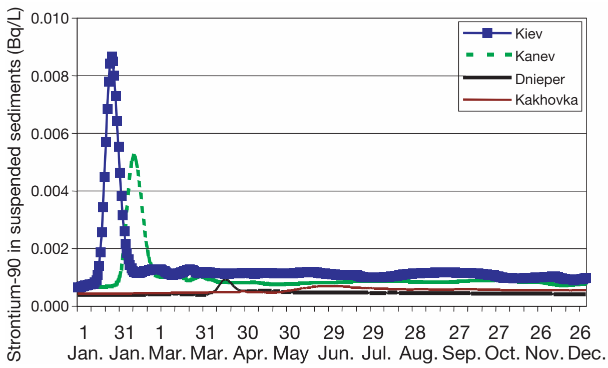


FIG. 9.12. Dynamics of ^{90}Sr in suspension along the cascade of the Dnieper reservoirs after a 150 m breach in the cooling pond dam.

The results of the simulation of a dam break can be compared with the results for the last large flood in 1999 (Fig. 9.4). From this comparison it is clear that, for the dam break scenario, the maximum

^{90}Sr concentration in the Kiev reservoir is a factor of two less than that during the flood in 1999. The comparison of annual fluxes of ^{90}Sr shows that the annual flux after a dam break is about 75% of the annual flux for the high spring flood. In contrast, the maximum concentration of ^{137}Cs is low (0.06 Bq/L in the Kiev reservoir) and therefore could not have a significant influence on individual doses via aquatic pathways.

The general conclusion from the above analysis is that the Chernobyl cooling pond can be considered as a potential local hot spot in the event of a dam break, but that the impact would be lower than that due to periodic flooding of the right bank (see Section 9.3.1).

After the cooling pond is decommissioned, the heavily contaminated sediments will become exposed. This could lead to dispersal by wind and water as well as exposure via human intrusion. At that time (after 2007) it will be necessary to carry out remedial work involving removal of the most contaminated sediments and covering/revegetation of the bottom of the pond.

9.3.3. Chernobyl shelter

As noted in Section 3, the Chernobyl shelter was constructed hastily in 1986 in order to prevent further escape of radioactivity into the environment and to protect personnel working on the site. Figures 3.2 and 3.3 show the damaged reactor before and during construction of the shelter. The accident entirely destroyed the core and severely damaged the reactor building, turbine hall and nearby structures.

The shelter contains between 173 and 200 t of nuclear fuel (from a total core load of 215 t), with an estimated activity of up to 750 PBq (20×10^6 Ci) of ^{238}U and ^{235}U and their daughter products as well as long lived fission and neutron activation products, including ^{137}Cs, ^{90}Sr, plutonium radionuclides and ^{241}Am [9.17, 9.18]. Most of the fuel is now contained in a lava-like matrix containing many inclusions of various uranium compounds, finely dispersed fuel dust and aerosols.

The current shelter is not acceptable as a permanent solution to the problem of containment of the residual fuel. Already there are holes and defects in the structure and the possibility of collapse cannot be excluded. Construction of a new safe confinement (NSC) at an estimated cost of $768 million is expected to be complete by 2008. The project is being funded by 20 western governments, the European Union and Ukraine. The structure is envisaged to be a moveable steel arch 120 m long, 100 m high and spanning 260 m. It will be slid into place along a set of steel rails. The structure will be designed to last at least 100 years.

Currently, contamination of the environment by radioactive substances from the shelter may occur in two principal ways: (1) release of fuel dust into the atmosphere through openings in the shelter if there is a collapse of internal structures; and (2) migration of radionuclides through the subsurface together with water that is inside the shelter (see Fig. 9.13).

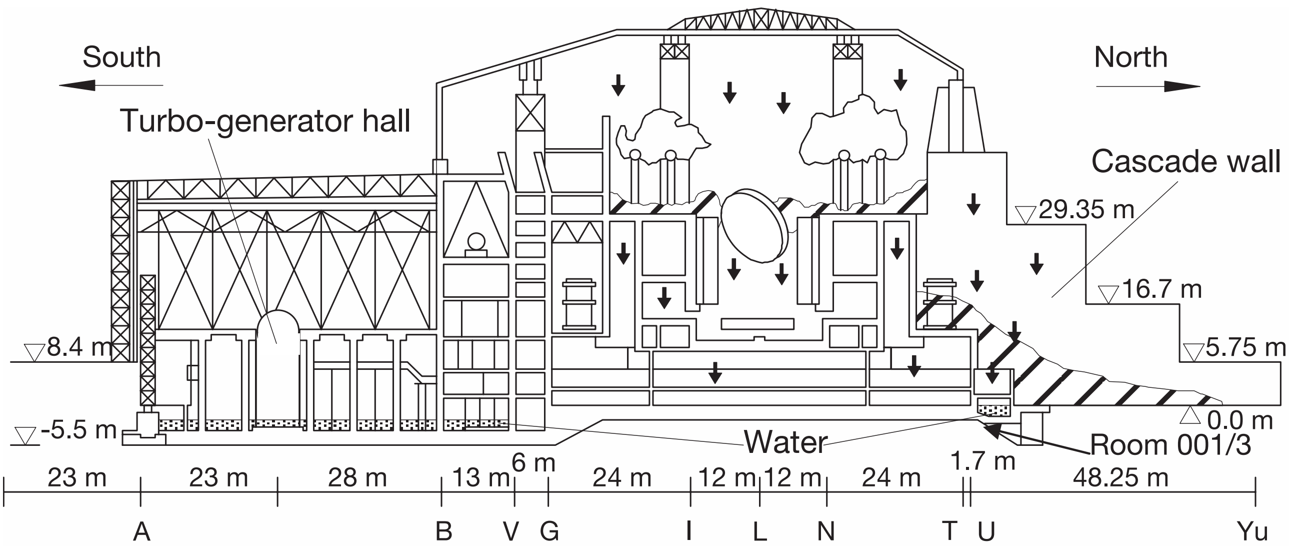


FIG. 9.13. Chernobyl unit 4 shelter, showing water pathways [9.17].

An environmental impact assessment for the NSC is being prepared. It considers the environmental pathways in the event of a collapse of the existing shelter, both before and after the NSC is constructed [9.19, 9.20].

If the existing shelter collapses before the NSC is constructed, it has been estimated that there will be atmospheric dispersion and subsequent fallout of 10.4 TBq of ^{137}Cs, 5.04 TBq of ^{90}Sr and 0.18 TBq of ^{239,240}Pu [9.19]. Depending on the atmospheric conditions at the time, there may be transboundary impacts.

The airborne pathway is considered elsewhere [9.19]; the following analysis focuses on waterborne pathways. Two mechanisms are considered:

(a) Atmospheric dispersion from a collapse followed by fallout and surface water transport;
(b) Radionuclide transport from the shelter to the Pripyat River via groundwater.

9.3.3.1. Assessment of Dnieper River basin contamination due to surface water transport

The atmospheric fallout from a collapse of the shelter will be partly deposited in the floodplain and, to a lesser extent, directly into the Pripyat River. Figures 9.14–9.17 compare the densities of contamination of ^{90}Sr and ^{137}Cs for the worst case scenario for the water pathway with the actual deposition densities from the Chernobyl accident.

Table 9.2 gives estimates of the radioactivity deposited in the watershed area or directly into water. Two scenarios have been considered:

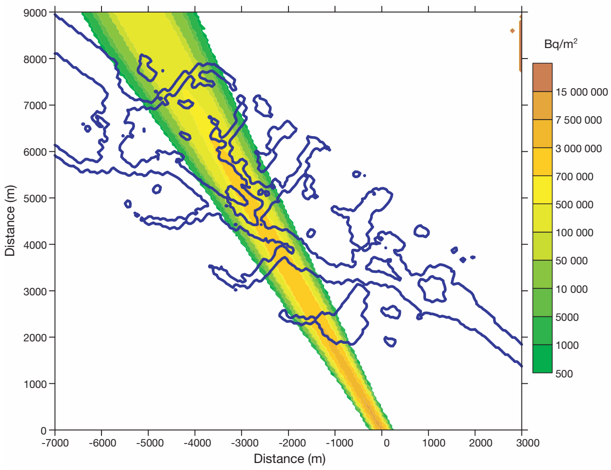


FIG. 9.14. Strontium-90 density for the worst case hydrological scenario.

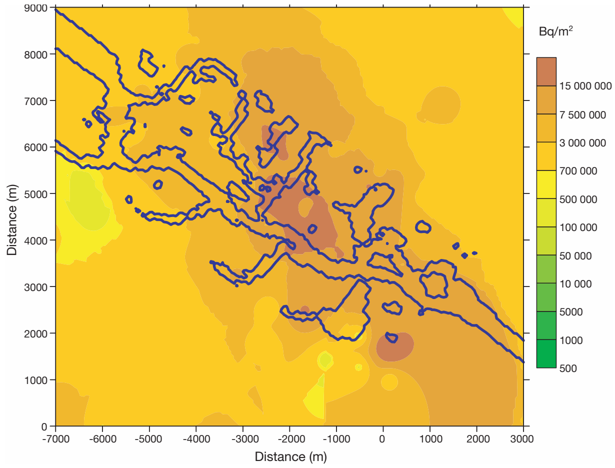


FIG. 9.15. Strontium-90 density due to the Chernobyl accident, upstream of the Yanov bridge.

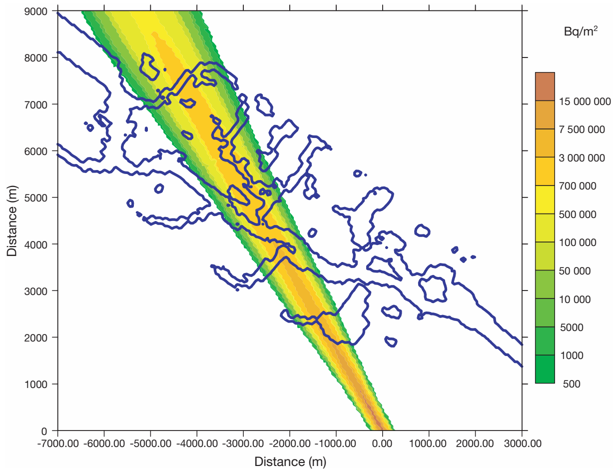


FIG. 9.16. Caesium-137 density for the worst case hydrological scenario.

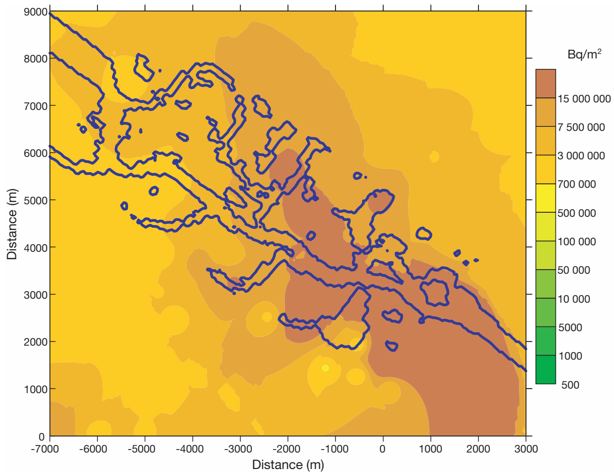


FIG. 9.17. Caesium-137 density due to the Chernobyl accident, upstream of Yanov bridge.

TABLE 9.2. TOTAL AMOUNT OF RADIONUCLIDES DEPOSITED ON WATER AND ON THE NEAR-PRIPYAT TERRITORY FOR TWO SCENARIOS INVOLVING THE COLLAPSE OF THE EXISTING SHELTER [9.19]

Area of contamination	Total activity (TBq)			
	No NSC		Under NSC	
	Strontium-90	Caesium-137	Strontium-90	Caesium-137
1. All areas presented in Figs 9.14–9.17 outside the floodplain protection dyke	3.7	8.0	0.26	0.53
2. Part of 1 covered by water	0.8	1.7	0.05	0.11
3. Part of 1 on land	2.9	6.3	0.21	0.42

collapse with no NSC and collapse under the NSC. Contamination within the area of the left bank protection dyke (beyond position 11 in Fig. 9.1) has not been considered because it could not be washed out into the Pripyat River.

In the modelling exercise it was assumed that any fallout that deposited directly on to water (row 2 in Table 9.2) would be diluted in the Pripyat River within one hour. It was also assumed that heavy rain was falling and 50 mm of precipitation occurred over the next two days. (This amount corresponds to the monthly average for this area.) For the radionuclides deposited on land it was assumed that 10% was removed from the floodplain by the inundating flood flow and washed into the river during the next 11 h and over the following two days. This percentage was determined to be a conservative upper estimate based on modelling studies of the radionuclide transport from this floodplain [9.6, 9.10].

The upper estimate of the coefficient for ^{90}Sr washing out from the Chernobyl watersheds due to rain is 2×10^{-4} mm^{-1}; this means that 1% of the total amount of ^{90}Sr will be washed out into the river during the assumed 50 mm rainfall. The wash-off coefficients of ^{137}Cs have lower values; however, we have used the same 1% as a conservative upper estimate. The total amount of the radionuclides washed out by the flooding (10%) and by the rainfall (1%) was assumed to be distributed in the following way: 60% during 11 h of the first day, 30% during the second day and 10% during the third day. The ^{90}Sr and ^{137}Cs releases to the Pripyat River over the three days are presented in Table 9.3.

For transuranic elements, the same assumptions give total releases to the Pripyat River for the no NSC case as follows: $^{239,240}Pu$ = 0.04 TBq, ^{241}Am = 0.015 TBq.

The 1-D model RIVTOX was used in this assessment. It was developed at the Institute of

TABLE 9.3. PREDICTED RELEASE OF RADIOACTIVITY INTO THE PRIPYAT RIVER FOR TWO SCENARIOS OF A SHELTER COLLAPSE

Period	Activity (TBq)			
	No NSC		Under NSC	
	Strontium-90	Caesium-137	Strontium-90	Caesium-137
First hour	0.78	1.74	0.053	0.115
Eleven hours of the first day	0.19	0.41	0.013	0.027
Second day	0.10	0.21	0.007	0.014
Third day	0.03	0.07	0.002	0.005
Total	1.10	2.43	0.075	0.160

Mathematical Machines and Systems Problems Cybernetics Centre in Kiev to solve water contamination and use problems of Ukrainian rivers after the Chernobyl accident [9.6, 9.21, 9.22]. The radionuclide transport part of the model is based on the approaches of the TODAM model [9.23]; however, adsorption–desorption processes have been accounted for and simplifications have been made in regard to the particle size of sediments. RIVTOX was validated for the Clinch River (Tennessee) within the framework of the IAEA VAMP programme [9.24] and for the Dudvah River–Vah River system; the latter is a Danube tributary [9.25]. The model includes a submodel of radionuclide transport and two submodels for the driving forces (hydraulics and sediment transport).

The results of the simulation of ^{137}Cs and ^{90}Sr concentrations in the Dnieper reservoir cascade for the no NSC scenario are presented in Fig. 9.18. In these graphs 'normal conditions' (i.e. no shelter collapse) are shown as a thin line. The concentrations are plotted as cross-sectional averages at the hydropower plants. The peak ^{90}Sr concentrations are 700 Bq/m^3 at the Kiev hydropower plant and 390 Bq/m^3 at the Kanev hydropower plant. After dilution in the large Kremenchug reservoir, the concentration diminishes to 225 Bq/m^3; the peak arrives at the Kremenchug hydropower plant more than 150 days after passing through the Kiev reservoir. The peak arrives at the Kakhovka hydropower plant 330 days after passing through the Kiev reservoir and has a value of 178 Bq/m^3, which is only 45 Bq/m^3 greater than for 'normal conditions'. The Ukrainian drinking water limit for ^{90}Sr is 2000 Bq/m^3, so even at the Kiev hydropower plant the peak concentration for a shelter collapse would be only 35% of the drinking water limit.

A collapse of the shelter would increase the annually averaged ^{90}Sr concentration at the Kiev hydropower plant by 24 Bq/m^3 (or 12.5%) in the first year and by 17–20 Bq/m^3 (or 12–14%) at the Dnieper and Kakhovka hydropower plants in the second year.

The ^{137}Cs peak concentrations caused by a collapse of the shelter have significant values only in the Kiev reservoir (455 Bq/m^3 in solute and 175 Bq/m^3 on suspended sediments) and in the Kanev reservoir (137 Bq/m^3 in solute and 74 Bq/m^3 on suspended sediments). Further downstream, at the Kremenchug reservoir, the peak concentration is only 5 Bq/m^3 above the level of 'normal conditions' (Fig. 9.19).

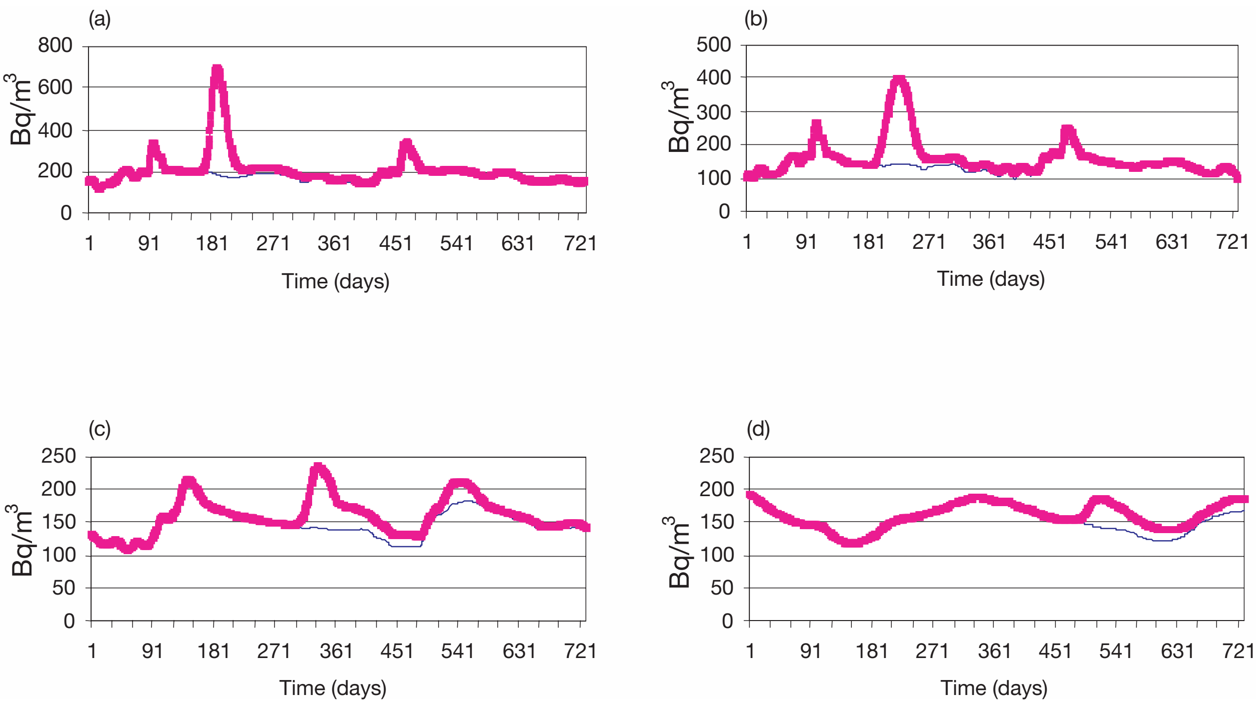


FIG. 9.18. Simulated ^{90}Sr concentrations in the Dnieper reservoirs after a hypothetical shelter collapse for the 'no NSC' case (bold line) and under normal conditions (thin line). (a) Strontium-90, Kiev reservoir; (b) ^{90}Sr, Kanev reservoir; (c) ^{90}Sr, Kremenchug reservoir; (d) ^{90}Sr, Kakhovka reservoir.

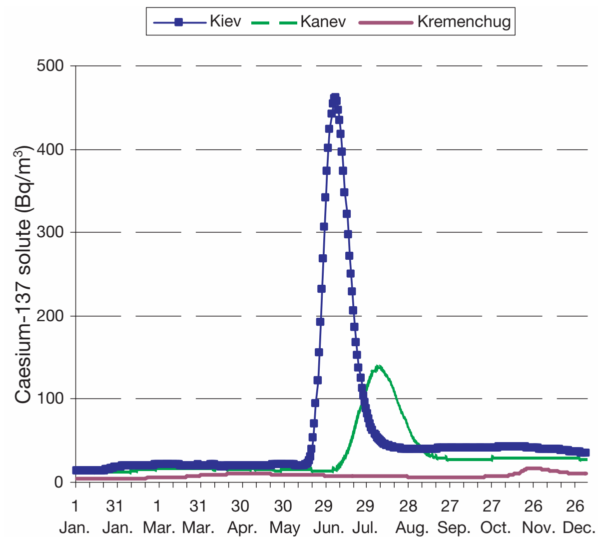


FIG. 9.19. Propagation of ^{137}Cs in solute through the Dnieper reservoirs after the 'shelter collapse, no NSC' scenario.

At the Kiev reservoir, the annual averaged ^{137}Cs concentration is 19.6 Bq/m^3 (87% greater than the 'normal conditions') in the first simulation year, while at the Kanev reservoir the annual concentration exceeds 7.3 Bq/m^3 (45% above the 'normal conditions'). In the second simulation year, due to radionuclide exchange processes (adsorption and desorption) with the contaminated bottom sediments, the annual averaged ^{137}Cs concentration is still 50–60% greater in the Kiev and Kanev reservoirs than under 'normal conditions'.

For ^{238}Pu, $^{239,240}Pu$ and ^{241}Am, the simulated concentrations at the Kiev hydropower plant are less than 1 Bq/m^3 and much less than the maximum permissible levels for these radionuclides. Therefore, for these radionuclides, fallout from the collapsed shelter has no significant dose impact on the Dnieper River system.

The results of this modelling assessment demonstrate that fallout on the Pripyat floodplain after a potential collapse of the shelter can produce a supplementary release of ^{90}Sr and ^{137}Cs from the CEZ via the Pripyat River to the Dnieper reservoirs. The peak concentrations in the upper reservoirs of ^{90}Sr could approach those predicted during high spring floods; however, they would not result in a significant impact on the annual doses via aquatic pathways. After construction of the NSC, the consequences of a shelter collapse would be significantly diminished. Completion of the construction of the right bank protective dyke also will decrease the Pripyat River contamination in the event of a shelter collapse, due to a reduction in the area subject to flooding.

9.3.3.2. Radionuclide flux from the shelter to the Pripyat River via groundwater

As noted earlier, water is currently able to enter the existing shelter through a number of breaks in the containment. This problem has been investigated in a recent report [9.26], which concludes that the actual volume of water ingress is no more than 2000 m^3/a.

The investigation used tracers that were injected both via the dust suppression system and locally into the bubbling pond area. It was demonstrated that the water, which flows from the northern and central parts of unit B and the Nuclear Island auxiliary system, accumulates in room 001/3 (see Fig. 9.13). The water then flows through the dividing wall into the unit 3 drainage water collection system. The experimentally determined water egress rate was 1300 m^3/a. Visual observations indicate a leakage value of 840 m^3/a. Therefore the egress rate from room 001/3 was estimated to range from 840 to 1300 m^3/a.

Water from the eastern part of unit B ingresses to room 018/2, where there are sumps for the drainage water collection system. It is highly likely, therefore, that water from the eastern part of unit B also flows into unit 3. The volumes were estimated to be within the range 390–850 m^3/a. Therefore, the combined egress rate from rooms 001/3 and 018/2 is no more than about 2000 m^3/a.

Essentially the same conclusions about the water fluxes in the shelter were reached in a more recent report [9.17]. The existing information [9.17, 9.26] demonstrates the importance of room 001/3, in which water accumulates. Infiltration of the heavily contaminated water from this pool through the floor is the main source of the contamination of the vadose zone and groundwater beneath the shelter.

The water in the shelter is a source of the radionuclide fluxes via the vadose zone beneath the shelter and then via groundwater to the Pripyat River. The modelling assessment of these radionuclide fluxes before construction of the NSC and under the impact of the NSC were considered in the NSC environmental impact assessment studies [9.19, 9.20], which are summarized below.

The data of contamination of the water in the shelter, based on Ref. [9.26], have recently been updated [9.17]. In the latest report it is estimated that the activities of radionuclides in water in room

001/3 are as follows: 5.2×10^9 Bq/m^3 for ^{137}Cs, 1.0×10^9 Bq/m^3 for ^{90}Sr and 360 Bq/m^3 for ^{239}Pu.

The 2-D vertical model SUSTOX was used to describe radionuclide transport in the vadose zone and in groundwater to the Pripyat River, which is 2.5 km from the shelter in the direction of the groundwater flow [9.27]. The use of a 2-D model is conservative (i.e. predicts a greater radionuclide concentrations in the subsurface water because it does not account for the lateral dispersion and dilution that occurs under more realistic conditions).

SUSTOX has been validated and used in previous studies of radionuclide transport in the subsurface environment of the shelter [9.27, 9.28]. In SUSTOX, adsorption and desorption between exchangeable sorbed solid and fixed solid phases are considered as non-equilibrium exchangeable processes that are described by first order kinetic equations. In cases where the influence of thermal gradients on flow fields and transport through the gas phase is negligible, SUSTOX produces results similar to the MSTS code developed at the Pacific Northwest National Laboratory [9.29, 9.30]. SUSTOX uses a more detailed description of the radionuclide exchanges between the solid and liquid phases of porous media than MSTS.

Figure 9.20 shows the vertical profile used for the modelling calculations [9.19]. It includes the drainage system, the incoming channel, a cross-section of the shelter and the Pripyat River.

Two scenarios were simulated, the current condition (without the NSC) and after NSC construction. The radionuclide migration from the shelter to the Pripyat River through the subsurface flow was simulated for ^{90}Sr, ^{137}Cs and ^{239}Pu for both scenarios 1 and 2. As a part of the assessment, a sensitivity analysis was also performed to evaluate the dispersivity values.

The values of the distribution coefficient K_d used in the study were: ^{90}Sr = 1.0 L/kg, ^{137}Cs = 2.0 L/kg and plutonium = 30 L/kg. The exchange rate coefficients, hydraulic conductivities and dispersivity values used for different soils are presented with model descriptions in Ref. [9.19].

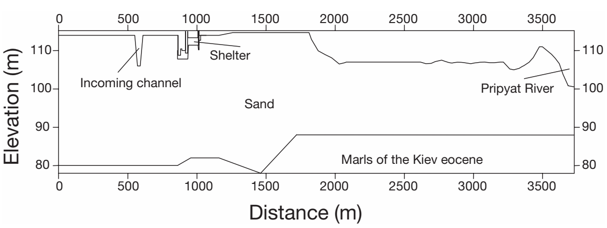


FIG. 9.20. Geological section from the shelter to the Pripyat River in the north-north-west direction. The position of the section is shown in Fig. 9.1.

9.3.3.3. Scenario 1: Shelter without the new safe confinement

Scenario 1 considers the radionuclide contamination of the subsurface environment due to water infiltration from room 001/3 under the current hydrological conditions. The water in room 001/3 was fixed at a depth of 1.4 m, or 112.8 m above sea level. The water levels in the incoming channel and the Pripyat River were assigned at 109.82 m and 104.2 m, respectively. The hydrological conditions were not changed during the simulation.

Figure 9.21 shows the predicted ^{90}Sr concentrations after 100 years [9.19]. A ^{90}Sr concentration of 4×10^9 Bq/m^3 is located less than 100 m from the shelter. (Note that the shelter is located at 1000 m in this simulation.) Even the 100 Bq/m^3 concentration level is reached only 600 m from the shelter, compared with the distance of 2.5 km from the shelter to the Pripyat River.

It would take approximately 800 years for ^{90}Sr to reach the Pripyat River, as shown in Fig. 9.22.

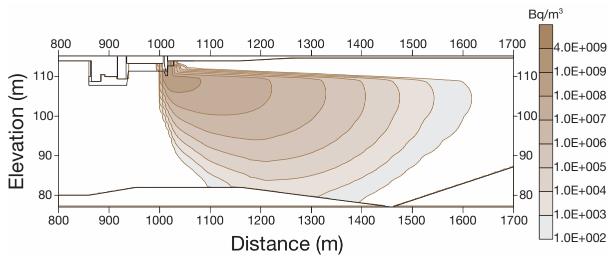


FIG. 9.21. Predicted ^{90}Sr concentrations in the aqueous phase without the NSC after 100 years.

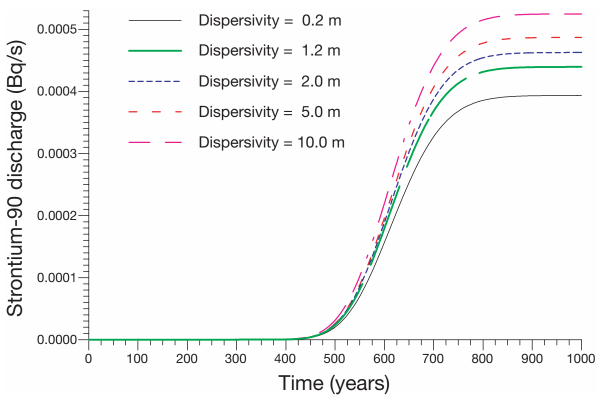


FIG. 9.22. Sensitivity of ^{90}Sr seepage into the Pripyat River from the shelter on the longitudinal hydraulic dispersivity.

With its half-life of 29.1 years, ^{90}Sr would be reduced to 5.7 × 10^{-9} of its original concentration due to radionuclide decay. This is reflected in the trivial ^{90}Sr influx (approximately 0.0004 Bq/s) to the river at that time. When this ^{90}Sr influx is fully mixed with the average Pripyat River discharge of 404 m^3/s, the resulting ^{90}Sr concentration in the river would be only 1 × 10^{-6} Bq/m^3, as compared with the current ^{90}Sr level of 100 Bq/m^3. Note that the Ukrainian drinking water limit is 2000 Bq/m^3. Thus infiltration of ^{90}Sr from the shelter will not cause any harmful impacts on the Pripyat River.

Predicted ^{137}Cs concentrations after 100 years are shown in Fig. 9.23 [9.19]. Compared with ^{90}Sr, ^{137}Cs moves much more slowly, and even after 2000 years its plume is still only 200 m from the shelter. The radionuclide decay over 2000 years would reduce the ^{137}Cs concentration by a factor of 1 × 10^{-20}. Thus ^{137}Cs would not cause any harmful impacts on the Pripyat River and on humans through the aquatic pathway.

Owing to its high adsorption to the soil matrix, ^{239}Pu migrates at a much slower rate than ^{90}Sr or ^{137}Cs; however, its half-life is much longer (24 000 years). The predicted flux is shown in Fig. 9.24 [9.19]. The maximum groundwater ^{239}Pu influx from the shelter into the Pripyat River is 2 Bq/s. When this influx is fully mixed with the average Pripyat River discharge of 404 m^3/s, the resulting ^{239}Pu concentration in the river would be only 0.005 Bq/m^3, as compared with the current ^{239}Pu level of 0.25 Bq/m^3. As stated above, the Ukraine regulatory limit of ^{239}Pu is 1000 Bq/m^3. Thus infiltration of ^{239}Pu from the shelter even without the NSC will not cause any harmful impacts on the Pripyat River.

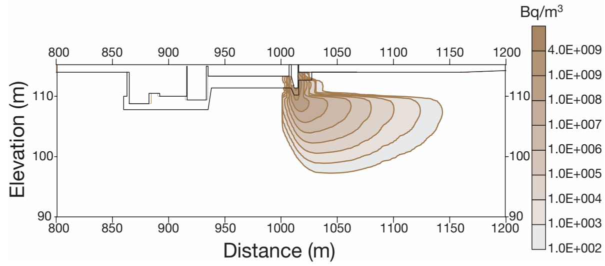


FIG. 9.23. Predicted ^{137}Cs concentrations in the aqueous phase without the NSC after 100 years.

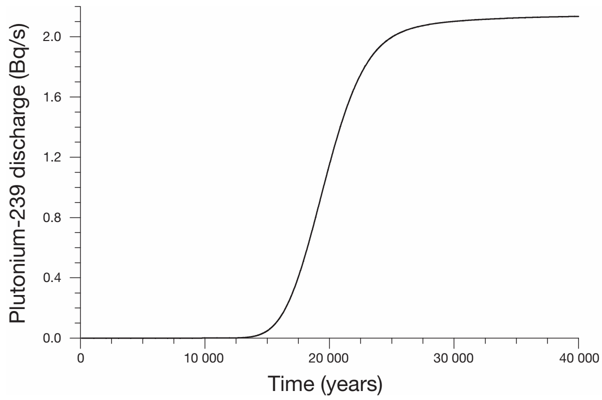


FIG. 9.24. Predicted ^{239}Pu seepage discharge to the Pripyat River from the shelter (K_d = 30 mL/g).

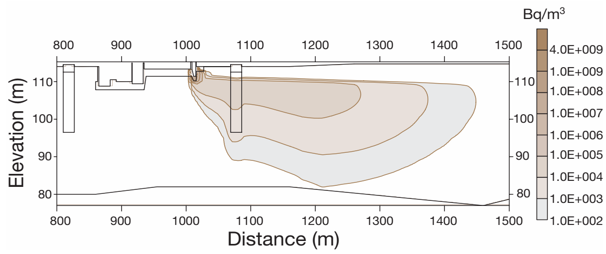


FIG. 9.25. Predicted ^{90}Sr concentrations in the aqueous phase with the NSC after 100 years.

9.3.3.4. Scenario 2: Shelter with the new safe confinement

Scenario 2 assumes no water influx to room 001/3. Thus the water level in room 001/3 decreases to zero over 1.5 years after NSC construction, due to water leakage through the concrete floor and walls of the room, and water evaporation. The impact of NSC construction was simulated by also imposing a more permeable barrier and the NSC piles [9.19]. It was assumed that the NSC would last 100 years and that after that time all radionuclides in the shelter would be removed. All other assumptions are the same in scenarios 1 and 2.

Comparison between Fig. 9.21 (without the NSC) and Fig. 9.25 (with the NSC) reveals that the NSC would make the ^{90}Sr concentrations smaller than those without the NSC because of less ^{90}Sr infiltration through the shelter's concrete floor, with less or no driving force of water in room 001/3. This would further reduce the ^{90}Sr concentrations and influx to the Pripyat River.

Modelling studies have also been carried out for migration of ^{137}Cs and ^{239}Pu with the NSC in place [9.19]. In both cases the flux to the Pripyat River is negligible.

This assessment concludes that, with or without the NSC, there would be no adverse impacts on the Pripyat River from infiltration of ^{90}Sr, ^{137}Cs and ^{239}Pu in the shelter. Although the

shelter is considered a hot spot because of its potential for human exposure via various other mechanisms, the Pripyat–Dnieper river pathway does not lead to any significant exposures of current or future generations.

9.3.4. Chernobyl exclusion zone (Ukrainian and Belarusian parts)

This section considers contaminated areas of the CEZ other than the floodplain, the shelter and the cooling pond, which are discussed above.

As was described in Section 4, the secondary contamination of water bodies by ^{137}Cs in the CEZ has decreased significantly during the 17 years after the accident, and now the concentrations of ^{137}Cs in the rivers are significantly lower than the maximum permissible levels. However, the secondary post-accident source of ^{90}Sr fluxes into the surface waters is still significant.

The water in small rivers, creeks and small floodplain lakes in the area close to the Chernobyl nuclear power plant even today has ^{90}Sr concentrations, during the spring floods, of 1–100 Bq/L (i.e. higher than the Ukrainian and Belarusian maximum permissible levels). The most contaminated water bodies are Lake Glubokoe (100–300 Bq/L), Pripyat Zaton (80–100 Bq/L), Semikhody Zaton (30–40 Bq/L) and Glinitsa creek (10 Bq/L). Although the concentrations exceed the maximum permissible levels, the total input of these sources into the flux from the Chernobyl zone via the Pripyat River is relatively small.

The total ^{90}Sr flux from the Pripyat River into the Kiev reservoir has varied over the past ten years from 3 to 10 TBq/a, increasing in the years of high floods. Analysis of the contribution of the different sources to the total ^{90}Sr flux from the Pripyat River to the Kiev reservoir (see Section 4, Table 4.15) shows that 64–74% of the flux in different years is generated in the CEZ. In the last year of high flood (1999), 50% of this flux was generated by the contaminated floodplain.

During periods of high water, the temporary storage locations for radioactive waste in the vicinity of the Pripyat River are inundated. During inundation the activity of ^{90}Sr in the river water at the local areas around these waste dumps was observed to be in the range 10–100 Bq/L. However, the ^{90}Sr flux from all disposal sites into the Pripyat River at present does not exceed 0.035–0.07 TBq/a.

The total contribution of Pripyat River tributaries (Uzh, Braginka, Sakhan) to the waterborne transport of radionuclides from the CEZ over the past five years does not exceed 9–13%, and considering all the sources does not exceed 5–6%.

After the Chernobyl accident the Polessye State Radioecological Reserve was established within the territory of Belarus by decision No. 59-5 of the BSSR Council of Ministers on 24 February 1988. It includes an area within the 30 km exclusion zone. The total area is 1700 km^2 and includes polluted soils of the Khoiniki, Bragin and Narovlya districts of the Gomel region.

The Polessye State Radioecological Reserve is located in the Pripyat River catchment, with the Pripyat River and a group of small rivers and channels, the largest of which are the Slovechno River, Pogonyanskj channel, Nizhnya Braginka River and Nesvich River. In these small rivers, a reduction in runoff of ^{137}Cs has been observed for several years; however, the concentrations of ^{90}Sr still exceed the national maximum permissible level during flood periods.

It can be concluded that the CEZ as a whole should be considered as a hot spot. The radionuclide concentration in some water bodies within the CEZ exceeds the maximum permissible levels. The most dynamic source term component of the CEZ, which provides the major part of the flux from the CEZ to the Dnieper reservoirs in the years of high floods, is the Pripyat River floodplain upstream of the Chernobyl nuclear power plant.

9.3.5. Affected areas outside the Chernobyl exclusion zone: closed lakes

As described in Section 4, since the Chernobyl accident the ^{137}Cs concentration in the rivers, lakes and ponds with running water has decreased approximately by one half every two years [9.31]. As a consequence, the concentration of this radionuclide in river water and fish, even in the most contaminated areas, is currently well below the intervention level. However, the water ^{137}Cs contamination in lakes with standing water and slow water running systems has decreased at a much slower rate and remains quite high even today [9.32, 9.33].

Some of the most contaminated lakes are near the Besed River. These include the Belarusian lakes Revuchee, Svyatskoe and Svyatoe and the Russian lakes Kozhanovskoe and Svyatoe (see Fig. 9.26). (Note that there are two lakes named Svyatoe. Lake Svyatoe in the Russian Federation is near the village

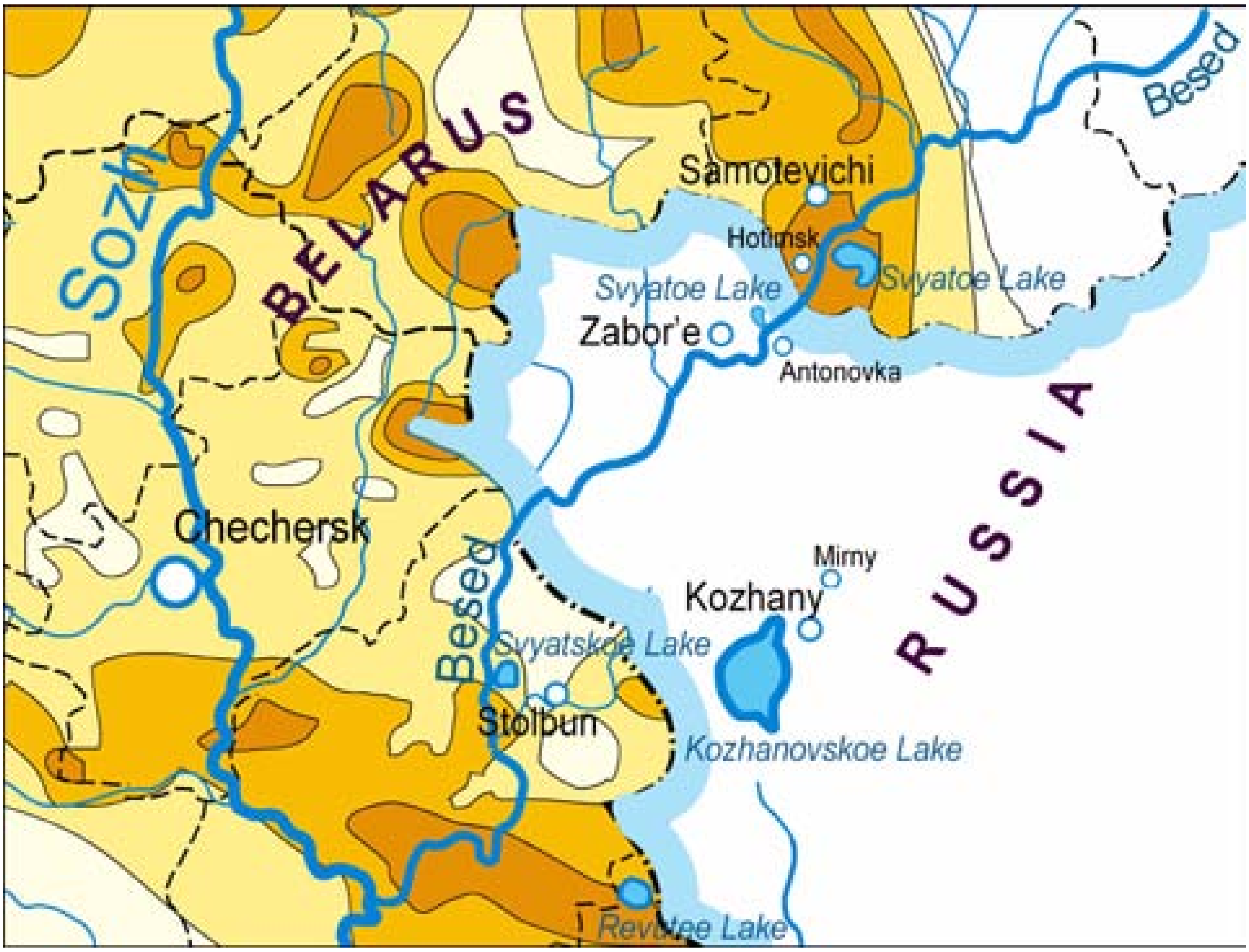


FIG. 9.26. Location of some contaminated lakes along the Besed River in the Dnieper River basin.

of Zaborje, Bryansk region. This lake has a surface area of 100 000 m^2 and an average depth of 3 m. Lake Svyatoe in Belarus is near the village of Mokroe, Mogilev region. It has a surface area of 260 000 m^2 and an average depth of 2.8 m.)

Contaminated lakes exist in all three countries. Specific information is provided in the following sections.

9.3.5.1. Russian Federation

Figure 9.27 shows the ^{137}Cs concentrations in Lake Kozhanovskoe and Lake Svyatoe near the Besed River as a function of time. The decline in concentrations with time has been very slow. In the first lake, the ^{137}Cs concentration is still at the intervention level (11 Bq/L), and in the second it is about 50% of the limit.

Table 9.4 illustrates the high levels of ^{137}Cs in fish living in Lakes Kozhanovskoe [9.33] and Svyatoe [9.32]. The table also shows the consumption limit to reach the annual dose of 1 mSv. This assumes that fish are the only source of ^{137}Cs intake and so would need to be adjusted downwards having regard for other intakes (such as

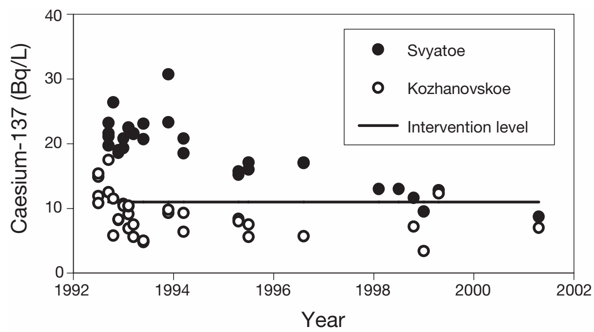


FIG. 9.27. Dynamics of ^{137}Cs concentration in the waters of Lakes Svyatoe and Kozhanovskoe [9.32, 9.34]. Note: The intervention level is a Russian national standard established by the Russian Standards of Radiation Safety, 1999 (11 Bq ^{137}Cs/L).

TABLE 9.4. CAESIUM-137 CONCENTRATION IN FISH TISSUE IN LAKES KOZHANOVSKOE AND SVYATOE

	Fish	Period	Caesium-137 (kBq/kg)	Consumption limit (kg/a)
Kozhanovskoe	*Carassius carassius*	1998–1999	5–10	10.3
Kozhanovskoe	*Esox lucius*	1998–1999	6–12	8.6
Kozhanovskoe	*Rutilus rutilus*	1998–1999	2–6	19.3
Svyatoe	*Carassius carassius*	1998–2001	6–12	8.6

mushrooms, milk and meat). It has been demonstrated that consumption of such fish can lead to substantial radiation doses to members of the public (see Section 8.6.2).

9.3.5.2. Belarus

A systematic study has been conducted on three lakes in Belarus — Svyatskoe, Rislavskoe and Revuchee. These are typical of the polluted region of the Gomel region, but differ in their trophic, hydrological and physicochemical characteristics. Lakes Svyatskoe and Rislavskoe are dynamic, with sharply expressed stratification of the water. However, the temperature stratification of water is absent in Lake Revuchee.

Table 9.5 shows the characteristics of these lakes. The percentage of ^{137}Cs in suspension is 1–2% for Lakes Svyatskoe and Rislavskoe and 9% for Lake Revuchee. The levels of ^{137}Cs contamination in Lake Svyatskoe (Besed River basin), Lake Revuchee (Iput River basin) and Lake Rislavskoe are close to the national permissible levels for drinking water and food (^{137}Cs in drinking water, 10 Bq/L; for fish, 370 Bq/kg). The ^{137}Cs concentrations in bottom sediments at some sites in Lake Revuchee (10 345–18 260 Bq/kg) and Lake Svyatskoe (11 618–16 430 Bq/kg) are so high that seepage from low level waste storage facilities into the lakes is suspected.

In these lakes, ^{137}Cs is particularly concentrated in some predatory fish species; for example, in Lake Svyatskoe the ^{137}Cs concentration was 19 410 Bq/kg (crude weight) in perch, 17 430 Bq/kg in pike and 5800–21 100 Bq/kg in roach. In Lake Revuchee the corresponding values were 4150 Bq/kg for pike and 1940–3500 Bq/kg for crucian. These are considerably in excess of the limits of 370 Bq/kg given in Ref. [9.35].

Lake Svyatoe, a non-draining (closed) lake in the Mogilev region of Belarus, was selected for an experiment on the effect of potassium on ^{137}Cs accumulation in fish. Potassium is chemically similar to caesium and can replace it on sediments and in biota. The K^+ concentration in the lake water prior to the experiment was relatively low (~1 mg/L), and the ^{137}Cs activity ranged from 3.8 to 4.9 Bq/L. Prior to the experiment the ^{137}Cs concentrations in fish were among the highest of all aquatic systems affected by the Chernobyl accident, being from 8.4 to 17.5 kBq/kg (wet weight) for rudd, from 12.4 to 16.7 kBq/kg for roach, from 58 to 105 kBq/kg for perch and up to 56 kBq/kg for pike. To study the effect of the dissolved K^+ concentration on ^{137}Cs accumulation and retention in fish, 14.5 t of potassium fertilizer was spread over the ice cover of the lake. After application of the fertilizer, the potassium concentration in the lake water increased to 10 mg/L. This increased the ^{137}Cs concentration in water to an average value of 12.7 Bq/L, as a result of ^{137}Cs desorption from bottom sediments. In spite of the increase in ^{137}Cs in the water, there was a steady decrease of ^{137}Cs concentrations in the two fish species under consideration during the experiment (see Fig. 9.28), to approximately 30–50% of their original values [9.36].

Thus, by applying KCl fertilizer to the ice covered surface of the lake, the ^{137}Cs content in fish was reduced by a factor of two to three, the efficiency of the countermeasure, as expected, being reduced by desorption of ^{137}Cs from bottom sediments. The long retention time of potassium in the lake water means that a single dose of fertilizer could be effective for many years.

TABLE 9.5. LIMNOLOGICAL CHARACTERISTICS OF LAKES SVYATSKOE, RISLAVSKOE AND REVUCHEE (1996)

	Svyatskoe	Rislavskoe	Revuchee
Area of water surface (m^2)	79 200	80 000	200 000
Average depth (m)	5.5	3.5	1.4
Maximum depth (m)	11	6	2
Average ^{137}Cs density on the catchment (kBq/m^2)	440	2900	1300
Concentration of dissolved ^{137}Cs (Bq/L)	7	17	6
Concentration of ^{137}Cs, on suspensions (Bq/L)	0.09	0.1	0.5
Concentration of ^{137}Cs in bottom sediments (kBq/m^2)	300–1000	680–3555	400
Concentration of ^{137}Cs in fish (kBq/kg dry weight)	Roach: 15.9; pike: 70.2; perch: 58.6	European carp: 14.4	European carp: 8.8; pike: 13.7

9.3.5.3. *Ukraine*

During 1991–1995 a survey was conducted of more than 3000 water bodies located in the districts of Zhytomyr, Kiev, Rovno, Chernihiv and other regions that were contaminated by the Chernobyl accident. Such screening research resulted in a 'contamination cadastre' [9.37] of water bodies (lakes, ponds, small reservoirs) that have elevated levels of contamination. The survey identified 40 water bodies in the district of Rovno, 87 in the district of Zhytomyr, 27 in the district of Kiev, 28 in the Volinsky district and several water bodies in other areas where increased risks were expected from the use of water. These risks involved the use of water for irrigation, fishing and fisheries, raising of water birds, game hunting, etc. The analysis of risks was conservative in that dose calculations used worst case scenarios based on maximum concentrations and, often, sporadic measurements [9.37, 9.38].

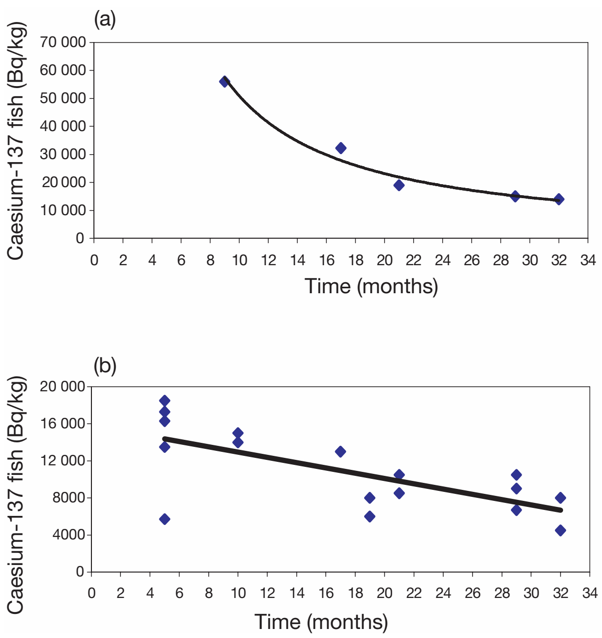


FIG. 9.28. Rate of decrease of ^{137}Cs specific activity of fish after adding potassium (February 1998) to Lake Svyatoe water (May 1997–September 1999). (a) Pike (Esox lucius); (b) rudd (Scardinius erythrophalmus).

Despite the conservative nature of the analyses, the study showed that about 2% of the surveyed water bodies in the districts of Rovno and Zhytomyr had levels of ^{137}Cs and ^{90}Sr in excess of the provisional permissible level of 2 Bq/L. Data for radionuclides in fish and birds showed a significant bio-enhancement compared with water; for example, the concentration of ^{137}Cs in Lake Bile water was 1.5 Bq/L, whereas concentrations in fish were 450 Bq/kg and in aquatic birds were 50–75 Bq/kg. In some other small ponds, the level of ^{137}Cs contamination in fish exceeded the permissible levels for Ukraine (150 Bq/kg).

The main source of radiation exposure for people living in the vicinity of these water bodies remain:

(a) The use of drinking water from wells;
(b) Irrigation from these wells in horticultural practices;
(c) Fishing;
(d) Raising domestic aquatic birds at these water bodies;

(e) Using water from contaminated sources for livestock (meat and milk production).

In Ukraine some countermeasures have been trialled at some fishery ponds in the Zhytomyr region and near Ivankov in the Kiev region [9.39]. The most effective measure involved the use of clean food for feeding young fish, followed by relocation of the growing fish before harvesting into a pond with a decontaminated bottom. However, such measures have only been applied to experimental fishery ponds. No chemical water treatment for natural lakes has been practised in Ukraine.

9.3.5.4. Overall assessment of closed lakes

The results reported in this section and in Section 8.6.2 show that some closed lakes in the Dnieper River basin remain hot spots. Moreover, the modelling presented in Section 4 demonstrates that the problem will persist for some time.

The most effective countermeasure to this problem is to restrict use of these water bodies for fishing or other purposes noted above. There is also a need for continued education of the public in the safe use of water resources and measures to reduce radiation exposure.

9.3.6. Affected areas outside the Chernobyl exclusion zone: Kiev reservoir

The Dnieper reservoirs are the receptors for radionuclides washed out from the CEZ. Caesium-137 washed from the CEZ or directly deposited as fallout during the accident phase is strongly absorbed by water sediments and ultimately is deposited on the bottom sediments of the reservoirs, especially the Kiev reservoir. Information on the current distribution of ^{137}Cs on sediments is presented in Section 4.7.3.

The current inventory of ^{137}Cs in the Kiev reservoir is about 75 TBq (2000 Ci), see Table 4.22, mostly in sediments at the bottom of the reservoir. The maximum accumulation of ^{137}Cs is observed near the mouth of the Pripyat River and in the zone of deposition of the silted fraction near Strakholesie (see Section 4, Fig. 4.32). The sandy deposits on the left bank of the reservoir have remained quite clean during the whole post-accident period.

Representatives of the ‘green movement’ have expressed concern that sediments in the Kiev reservoir might be resuspended during periods of high flood and that this could result in levels of ^{137}Cs in drinking water above the permissible limit. For this reason, the sediments are assessed in this section as a possible local hot spot.

The reservoir, with a volume of 3.7 km^3 (at the normal operational water level), has an average depth of about 3 m in its northern section up to the mouth of the Teteriv River; the depth increases in the southern part to about 10–12 m.

A detailed numerical analysis was carried out using the 3-D radionuclide transport model THREETOX [9.13]. The model was tested on monitoring data for the Kiev reservoir and then applied to simulate the redistribution of radionuclides in the water and bottom sediments of the reservoir for an average spring flood (maximum discharge, Q_M = 3000 m^3) and a very high spring flood (Q_M = 9000 m^3). Figure 9.29 shows a simulation of the changes in the activity of bottom sediments of the Kiev reservoir before and after such hypothetical floods.

In the initial stages of a high flood, the processes of sedimentation dominate over processes of bottom erosion, and accumulation of contaminated sediments takes place. However, during the next stage, as flow velocities increase, erosion of bottom sediments occurs. This results in a decrease of ^{137}Cs activity in the bottom deposits. Finally, as the flow rate decreases, sedimentation of suspended material again dominates over erosion processes, and an increase in the content of radionuclides in the bottom sediments is observed.

The simulations show that the total amount of ^{137}Cs suspended from the bottom of the reservoir during the highest flood will not exceed 7% of the total inventory (i.e. about 5.3 TBq (140 Ci)). The concentration of suspended ^{137}Cs during a high flood is significantly higher than that during an average flood (compare Figs 9.30 and 9.31); however, the concentration in solution is lower due to dilution. Therefore it is concluded that, during high floods, resuspension of contaminated sediments will not increase the total radionuclide concentration in water (solution plus suspended sediment) above the permissible level.

This analysis shows that the sediments in the Kiev reservoir are not a hot spot because the contamination is largely held on bottom sediments that are not available for significant uptake into biota under normal or flood conditions. Moreover, the impact of these sediments will decline with time because of decay and burial under non-contaminated sediments.

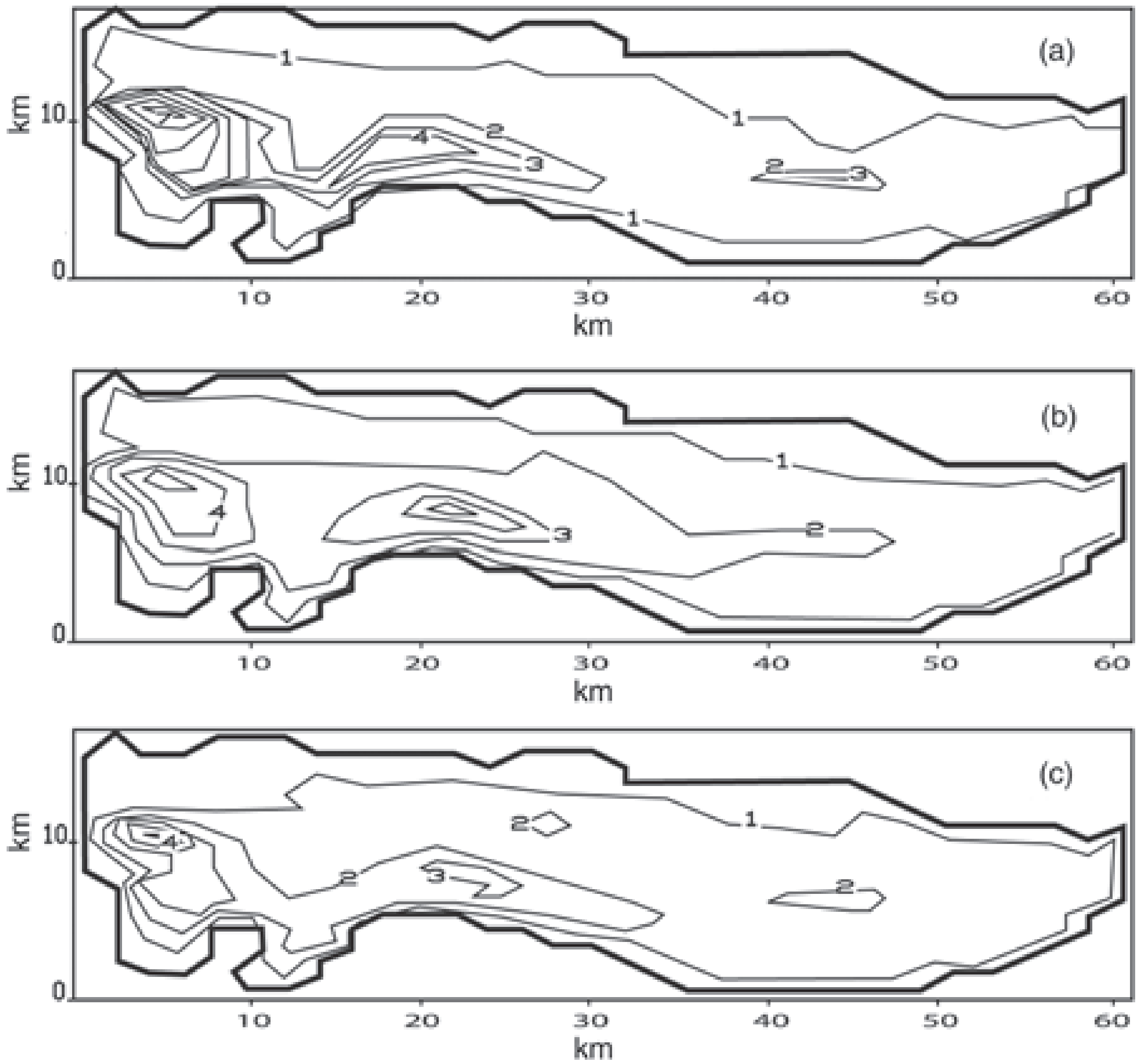


FIG. 9.29. Density contours of ^{137}Cs on the bottom sediments of the Kiev reservoir: (a) before a flood; (b) after an average flood; and (c) after a high flood (contour of '1' corresponds to 37 kBq/m^2 or 10^{-6} Ci/m^2).

9.4. URANIUM PROCESSING SITES IN UKRAINE

Uranium ores have been processed in Ukraine for over 50 years. Estimates of the quantity of waste generated from these activities vary (because of mixing of radioactive and non-radioactive waste at some sites); however, the latest official figure [9.40] is that there are 65.5×10^6 t of uranium tailings with a total activity of 4.4 PBq (120 000 Ci). The total area of tailings impoundments is 542 ha.

An overview of uranium mining and ore processing in Ukraine with an emphasis on radiological and environmental impacts is presented in Section 6. There are two main processing sites, the Prydniprovsky chemical plant at Dniprodzerzhinsk, which was shut down in 1991, and the hydrometallurgical plant at Zhovti Vody, which is still in operation. In addition, there are several mining sites where ores were or are being mined.

In the early years of uranium mining and ore processing, little attention was paid to the environmental impact of operations or the management of tailings. Consequently, tailings were often deposited in inappropriate locations and were not properly rehabilitated upon closure of the site.

Recently, guidance has been provided by the IAEA on the management of radioactive waste

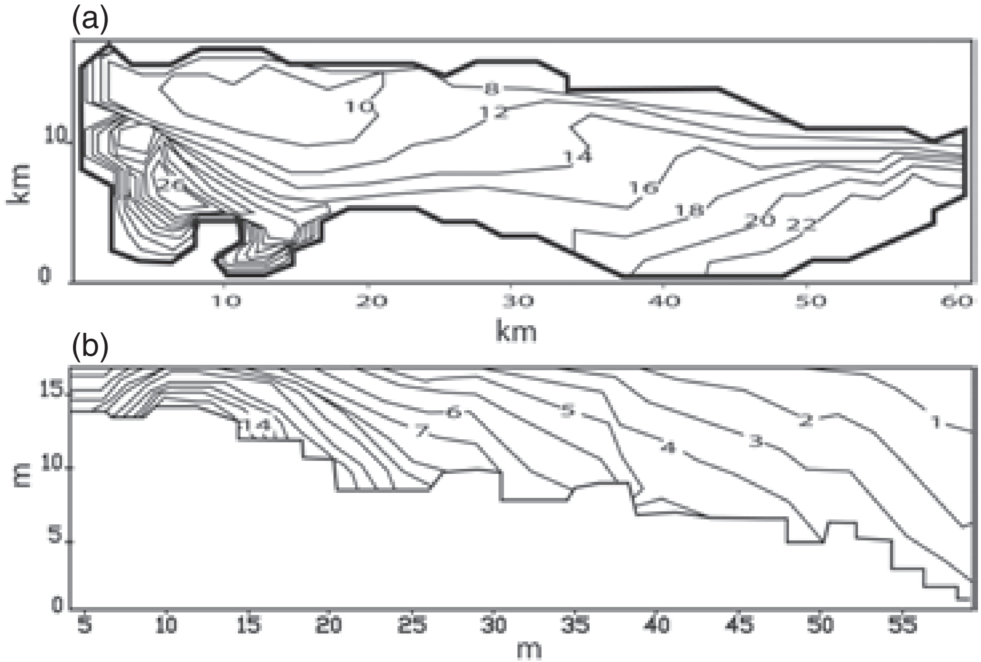


FIG. 9.30. Lateral–longitudinal distribution of ^{137}Cs (pCi/L) in solution in the upper layer of the Kiev reservoir (a) and vertical–longitudinal distribution of ^{137}Cs (pCi/L) on suspended sediments during peak discharge ($Q = 3000\ m^3/s$) of an average flood (b). (Note: 1 pCi/L = 0.037 Bq/L.)

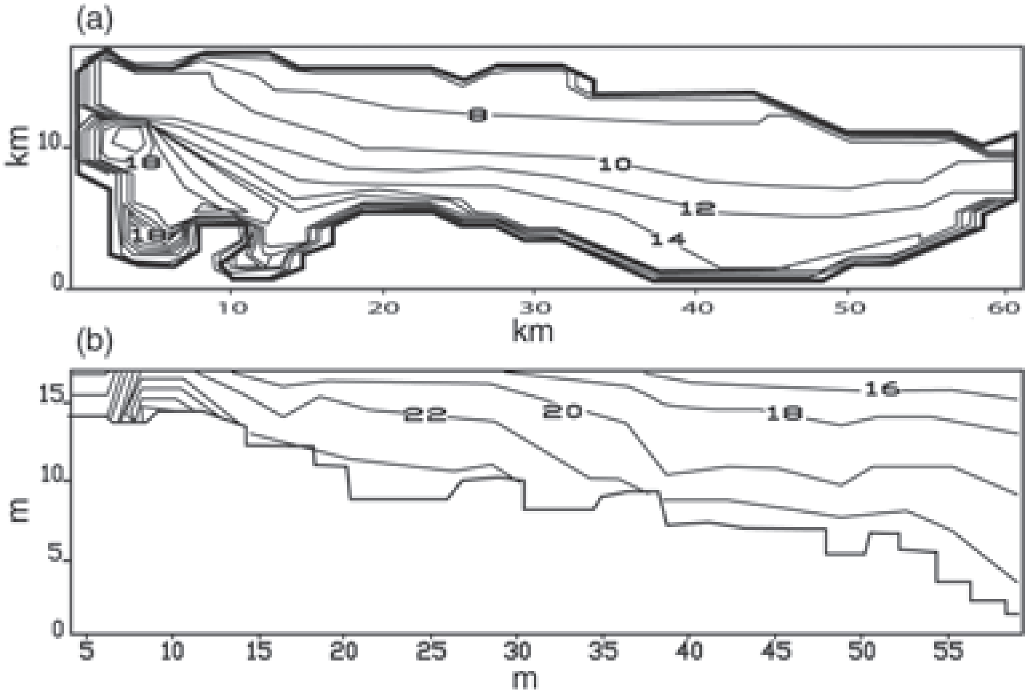


FIG. 9.31. Lateral–longitudinal distribution of ^{137}Cs (pCi/L) in solution in the upper layer of the Kiev reservoir (a) and vertical–longitudinal distribution of ^{137}Cs (pCi/L) on suspended sediments during peak discharge ($Q = 9000\ m^3/s$) of a high flood (b). (Note: 1 pCi/L = 0.037 Bq/L.)

from the mining and milling of ores [9.41]. The guide applies primarily to new facilities, although review of existing facilities against the guidelines is recommended:

(a) The strategy for management of waste should be consistent with the principles of radioactive waste management [9.2]. Two of these principles are the most appropriate to long lived radioactive waste such as uranium tailings. These are Principle 4 (Protection of Future Generations) and Principle 5 (Burden on Future Generations).
(b) Access to and dispersion of tailings needs to be restricted for long periods into the future. For this reason, tailings structures should have high stability against floods, erosion and earthquakes.
(c) Disposal of waste below ground level generally provides a higher degree of protection against surface erosion and human intrusion and requires less maintenance.
(d) Engineering controls may fail because of natural processes such as erosion. Such events are probabilistic in nature. Due attention needs to be given to the probability of the event occurring and to its likely impact on the integrity of the disposal system.
(e) Financial mechanisms should ideally be put in place so that the requirements for closure and post-closure monitoring can be met.
(f) Waste management structures should be closed when they are no longer needed, and to the maximum extent possible while operations are still continuing.
(g) Safety assessments should be carried out to cover the operational, closure and post-closure phases of the facility. These assessments should consider all significant scenarios and pathways by which workers, the public and the environment may be subject to radiological and non-radiological hazards.
(h) Radiological protection should be optimized so that doses are ALARA.

The project team visited the Prydniprovsky chemical plant and inspected several of the tailings sites in the area. Discussions were also held with technical experts on both operational and administrative aspects of the operations. No visits were made to Zhovti Vody or the uranium mines and so, for these sites, reliance was placed on information available in the open literature.

There appears to be only very limited information on the radionuclide levels in the environment in the vicinity of the Prydniprovsky chemical plant or the industrial sites at Zhovti Vody. Some information is presented in Section 6 on elevated levels of some radionuclides in the seepage, runoff and local rivers. Levels in rivers are generally below the maximum permissible levels in drinking water. Section 8 gives a few estimates of dose based on a limited consideration of pathways. Clearly there is a need for a comprehensive analysis based on more extensive monitoring data and consideration of all pathways, including airborne exposures (radon and daughters), foodstuffs (especially fish), drinking water and external radiation.

The Prydniprovsky chemical plant is part of a very large chemical complex that consists of chemical, nuclear and metallurgical plants bordering on the shores of the Dnieper River (see Section 6, Fig. 6.3). Some of the plants are still in operation, while others have closed down, leaving the equipment and other facilities in a state of neglect. The Prydniprovsky chemical plant site needs to be assessed holistically in order to understand the respective contributions of the facilities to pollution of the Dnieper River basin and the effects of interactions between the major waste storage areas. Essentially there needs to be an overall plan for the site, which will include rehabilitation of sites along with possible further industrial development.

At Zhovti Vody, countermeasures have been carried out at some mines and tailings impoundment sites. The large KBZh tailings site, which contains 19×10^6 t of radioactive waste, has been partly rehabilitated, but restoration is still incomplete because of financial problems.

The project team considers that tailings are the main problem at the Dniprodzerzhinsk and Zhovti Vody sites due to the potential for environmental and human health impacts over many generations. The main radionuclides in the tailings, ^{230}Th (half-life 80 000 years) and ^{226}Ra (half-life 1600 years), affect the overall radioactivity in the tailings. Consequently, there will be little decline in radioactivity for thousands of years. Although remedial works have been carried out at a few locations, most of the tailings are in an unsatisfactory condition.

Tailings are deposited at a number of unsatisfactory locations within the Prydniprovsky chemical plant. The most substantial waste pile is at the

tailings D site, which contains about 1.5 PBq of radionuclides. The tailings are covered with phosphogypsum, a fine powdery waste from the fertilizer industry, to variable thicknesses (see Fig. 9.32). The banks of the tailings D pile are steep and on two sides drop away to the Konoplyanka River, which is a small waterway that flows into the Dnieper River (see Section 6, Figs 6.3 and 6.4). Preliminary estimates were given in Section 6 of releases of radionuclides to the Konoplyanka River via surface and seepage, but such estimates need to be refined by more specialized studies. The potential for erosion of this tailings pile over time appears high and needs to be assessed further.

Recent assessments of the Sukachevskoe tailings C site (see Fig. 6.3 for location) and, in particular, its dried up beaches, suggest that this site could be a significant source of secondary contamination because of dispersion of contaminated phosphogypsum by wind. The Ecological Inspection of the Dnipropetrovsk region has reported contamination of agricultural products grown on the surrounding farming area near the villages of Taromskoe and Sukachevka. Further work is needed to assess the significance of this contamination.

The project team, having regard for the IAEA guidelines and, in particular, Principles 4 and 5 of Ref. [9.2], concludes that the Dniprodzerzhinsk site and the waste storage areas at Zhovti Vody are hot spots.

Safety assessments need to be undertaken at these facilities and submitted to the national regulatory authority. In considering appropriate countermeasures, the following guidance from the IAEA should be considered [9.2]:

(a) When existing waste management facilities cannot meet the post-closure risk constraints or dose constraints, efforts should be made to minimize risk and dose to what is reasonably achievable. In judging what is reasonably achievable in such cases, the dose at which intervention would be considered today is an appropriate benchmark. This is around 10 mSv/a.
(b) The option of relocating tailings to a more favourable site for closure would not normally provide the optimum strategy because of the large volumes of waste to be moved.
(c) If the cost associated with different options is the main factor for consideration, then a quantitative cost–benefit analysis may be used. Such an analysis should consider the time period over which radiation doses and other impacts are to be integrated, spatial cut-off points and the monetary value of averting a unit of collective dose.

9.5. WASTE STORAGE/DISPOSAL FACILITIES

The following waste storage facilities were considered as potential local hot spots:

(a) The Ecores facility near Minsk;
(b) RADON type radioactive waste storage sites at Kiev and Dnipropetrovsk;
(c) Waste storage facilities at nuclear power plants.

Technical information on these facilities is presented in Section 7.

9.5.1. Ecores facility

The Ecores facility comprises two closed trenches and two repositories that are being progressively filled. It accepts radioactive waste from the nearby Sosny Institute and from more than 100 organizations from the industrial, research and medical sectors. The facility is 2 km from the Slouch River and within the Dnieper River basin, but remote from the Dnieper River. This facility is below the current international standards for the engineered disposal of low and intermediate level waste. The project team considers Ecores to be a potential hot spot with a possible medium impact at the local level. Reconstruction of Ecores is in progress and this will reduce the potential for human exposure and environmental impact.

9.5.2. RADON radioactive waste storage sites in Ukraine

Information on the RADON radioactive waste storage sites in Kiev and Dnipropetrovsk is provided in Section 7. These facilities contain large quantities of radioactive waste, including spent radiation sources and tritium bearing liquids and gases. Tritium has leaked from the Kiev radioactive waste storage site towards the Vita River, but concentrations in surface waters are below the maximum permissible levels for drinking water.

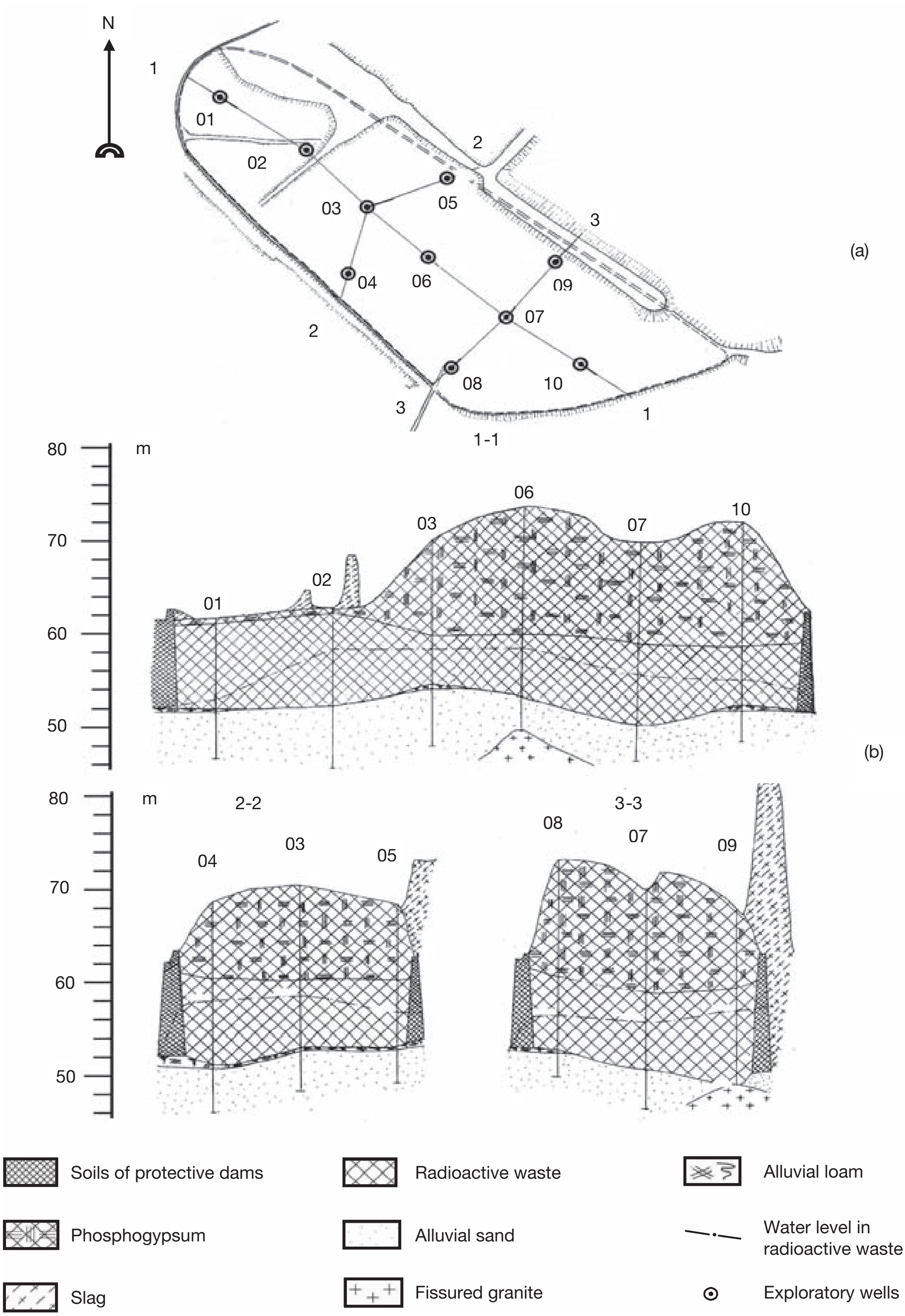


FIG. 9.32. Layout (a) and cross-sections (b) of tailings D [9.45].

The RADON facilities in Ukraine were designed to standards prevailing in the 1960s to 1980s and are not in accordance with modern standards of containment. Storage tanks and other equipment have deteriorated with time and there is a need to construct new facilities. These facilities are considered to be potential local hot spots until the most hazardous waste, particularly liquids, is transferred to new facilities.

9.5.3. Waste storage facilities at nuclear power plants

At nuclear power plants, radioactive waste is stored in buildings with at least two levels of containment. The risk of escape of radioactivity from these facilities is assessed to be low. Spent fuel storage at nuclear power plants has been a problem in Ukraine, since storage facilities in several cases are close to capacity and new facilities are required to accommodate the increasing quantity of spent fuel. Progress is being made in this area with construction of new facilities for dry storage of fuel. The project team considers that waste and spent fuel storage at nuclear power plants is satisfactory and that such facilities should not be regarded as actual or potential hot spots.

9.6. POTENTIAL ACCIDENTS AT NUCLEAR POWER PLANTS

Section 5 gives detailed information on nuclear power plants in the Dnieper River basin (and adjacent areas) and on initiatives undertaken to improve nuclear safety. The project team's analysis of discharge and monitoring data for nuclear power plants in Ukraine and the Russian Federation shows that routine discharges are generally well below authorized limits and do not contribute to significant contamination of the environment. Dose rates to residents living in the vicinity of nuclear power plants are very low (see Section 8.2).

A major accident at a nuclear power plant, although highly unlikely, could result in major transboundary impacts. The accident at Chernobyl nuclear power plant unit 4 is an example of the transboundary effects of a near worst case nuclear disaster. Since that accident, Russian built reactors have been subject to many national and international reviews, and upgrades have been undertaken with the aim of improving nuclear safety.

Systems for emergency preparedness and response have also been introduced for Ukrainian and Russian nuclear power plants, based on the IAEA's recommendations (see Section 5). Strengthening of these systems requires further development of the automatic monitoring (early warning) system around each nuclear power plant and of the real time decision support system for off-site emergency management.

In this report we provide a preliminary analysis of the consequences of a major nuclear accident in terms of concentrations of ^{137}Cs in waterways within the Dnieper River basin. The accident is assumed to occur at the Zaporozhe nuclear power plant, which is situated on the bank of the Kakhovka reservoir at a distance of about 1 km from the city of Energodar (see Fig. 9.33). The Dnieper–Bug estuary is situated downstream of the Kakhovka reservoir and has a direct connection with the Black Sea.

An accident at the Zaporozhe nuclear power plant has the greatest potential for releases that will lead to direct fallout on the Dnieper River as well as transboundary impacts (via transport to the Black Sea). In this analysis, only the water pathway is considered and impact is measured in terms of concentrations and fluxes of ^{137}Cs. No attempt is made to estimate radiation doses.

In 2002 the European Union decision support system RODOS [9.42] was installed in Ukraine, customized to the conditions of the Zaporozhe nuclear power plant site and connected to the Numerical Weather Prediction Model and local monitoring systems. The Atmospheric Dispersion Module of the RODOS system was used for this simulation. The scenario for the release was taken from a number of possible default scenarios used in the RODOS system for WWER-1000-ST2. The source term scenario was taken from Ref. [9.43] and is described in detail in Ref. [9.44]. The hypothetical accident is initiated by the following combination of events:

(a) Loss of coolant from the primary circuit caused by a complete instantaneous break of an 850 mm diameter pipe;
(b) Full loss of the electric power supplies of the nuclear power plant;
(c) Failure to start emergency diesel generators;
(d) Failure to get water from two backup supplies.

This combination of events results in melting of the fuel and a steam explosion that causes

FIG. 9.33. The Kakhovka reservoir and the Dnieper–Bug estuary (left lower corner).

destruction of the containment. For this extreme and hypothetical accident, Table 9.6 gives estimates of the total released radioactivity as a fraction of the total radioactivity in the WWER-1000 reactor core. The duration of the release is assumed to be 24 h.

The project team's analysis of the possible consequences of this accident was based on the worst source term scenarios for this type of reactor plus the worst meteorological conditions for contamination of the Dnieper reservoir system. The wind velocity was low (0.5–1 m/s) and the intensity of precipitation was high (up to 10 mm/h), so that the released radioactivity was deposited close to the source. The simulated fallout density for the chosen scenario is shown in Fig. 9.34.

The data generated by this simulation were transferred to the THREETOX model for simulation of ^{137}Cs dispersion in the Kakhovka reservoir and then transport to the Dnieper–Bug estuary. The downstream travel distance after fallout is about 70 km in the Kakhovka reservoir and 69 km in the Dnieper–Bug estuary.

Figures 9.35 and 9.36 show the dispersion with time in the Kakhovka reservoir. For this low probability scenario, 23 PBq of ^{137}Cs is deposited in the reservoir and the concentration in water soon after the accident is more than 10^7 Bq/m^3.

Figures 9.37 and 9.38 show dispersion in the Dnieper–Bug estuary. The peak concentration is delayed and reduced in magnitude. However, even after 300 days, the concentration is still of the order of 10^4 Bq/m^3.

Some of the deposited ^{137}Cs is taken up by sediments in the Kakhovka reservoir and the Dnieper–Bug estuary (see Fig. 9.39(a)). However, most (14 PBq) is transported to the Black Sea, where the maximum influx is 1.5 GBq/s (see Fig. 9.39(b)). In contrast, the total ^{137}Cs release during the Chernobyl accident was 85 PBq, yet only 1 TBq reached the Black Sea. This shows that proximity to the Black Sea coupled with adverse weather conditions could, in the event of a major accident at the Zaporozhe nuclear power plant, lead to serious transboundary

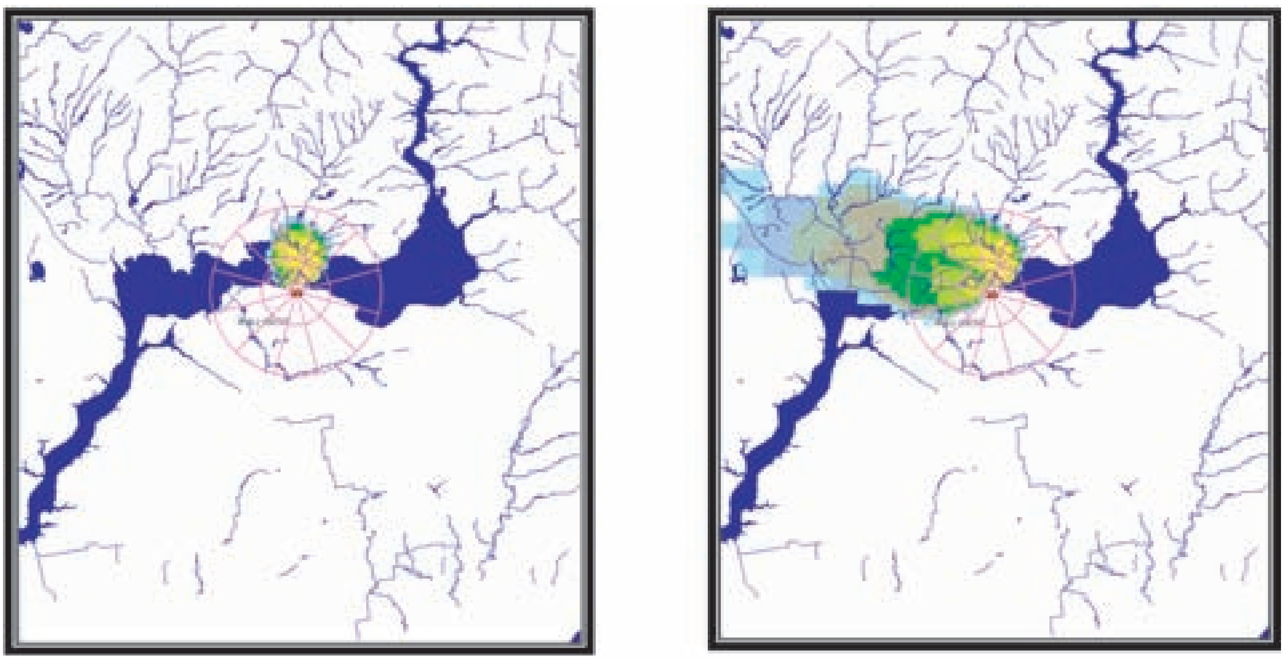
TABLE 9.6. RADIOACTIVE RELEASE TO THE ATMOSPHERE IN AN EXTREME HYPOTHETICAL ACCIDENT AS A FRACTION OF THE RADIONUCLIDE ACTIVITY IN THE WWER-1000 REACTOR CORE

Element released	Release fraction of the radionuclide at each accident stage			
	Before explosion (0–1 h)	Steam explosion (instantaneous)	After explosion (1–24 h)	Total (0–24 h)
Xenon, krypton	5×10^{-5}	0.7	0.16	0.86
Iodine, bromine	5×10^{-5}	0.7	0.16	0.86
Caesium, rubidium	4×10^{-6}	0.45	1×10^{-2}	0.46
Tellurium	4×10^{-6}	0.29	4×10^{-2}	0.33
Strontium, barium	2×10^{-6}	0.06	1×10^{-3}	0.06
Ruthenium	0	0.37	8×10^{-3}	0.37
Lanthanum	0	2×10^{-3}	3×10^{-4}	2×10^{-3}

contamination. These conclusions need to be verified by more rigorous calculations for a range of scenarios.

It must be emphasized that the scenario examined above is based on a hypothetical and most improbable sequence of events and adverse weather conditions. Nevertheless, it demonstrates the need for an enhanced decision support system that includes modules that forecast direct releases into the water and post-accident contamination of water bodies. Such a system, in association with other emergency control measures, could greatly reduce the dose to individuals in the event of a nuclear accident.

As discussed in Section 5.9.3, information exchange between nuclear power plant emergency units and regional authorities also needs to be improved.



(a) (b)

FIG. 9.34. Density of ^{137}Cs fallout (a) after 1 h and (b) at the end (24 h) of a simulated accidental release.

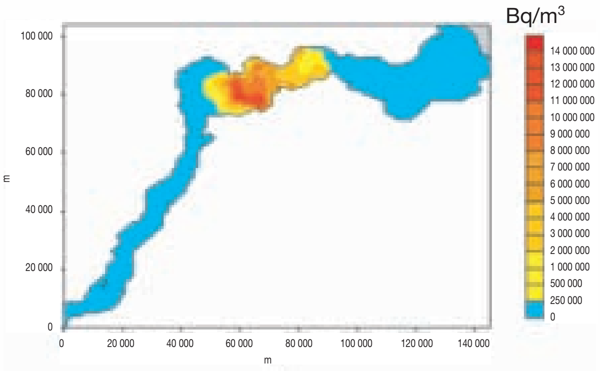


FIG. 9.35. Concentration of ^{137}Cs in solution near the water surface of the Kakhovka reservoir 10 days after the beginning of a simulated accidental release.

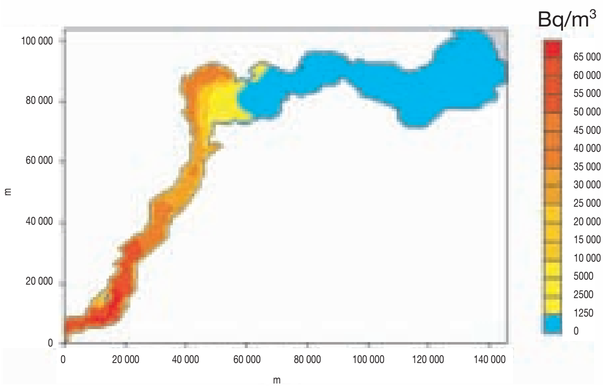


FIG. 9.36. Concentration of ^{137}Cs in solution near the water surface of the Kakhovka reservoir 104 days after the beginning of a simulated accidental release.

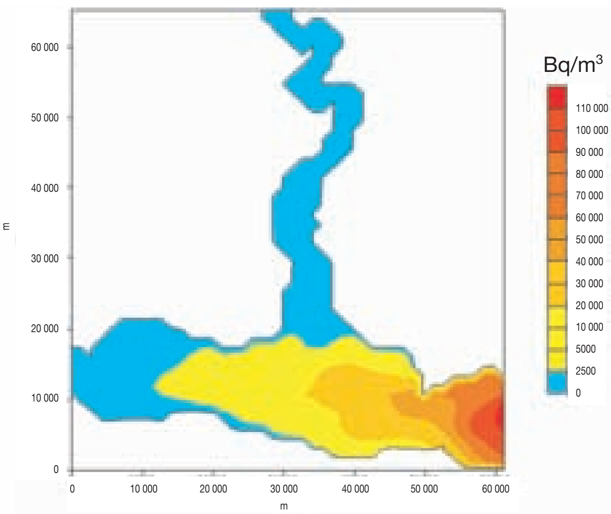


FIG. 9.37. Concentration of ^{137}Cs in solution in the surface waters of the Dnieper–Bug estuary 100 days after the beginning of a simulated release.

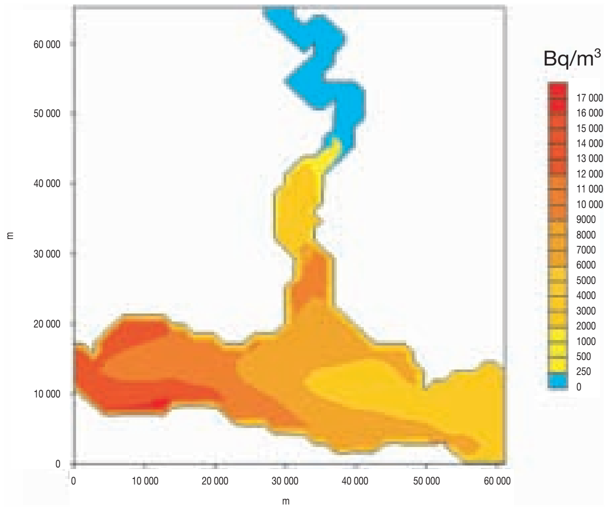


FIG. 9.38. Concentration of ^{137}Cs in solution in the surface waters of the Dnieper–Bug estuary 303 days after the beginning of a simulated release.

9.7. FINAL CLASSIFICATION OF HOT SPOTS

A preliminary list of candidate hot spots is given in Section 9.2. Based on the analyses in this section, the project team's final classification of hot spots is given below.

Actual hot spots:

(a) The Pripyat floodplain area within the CEZ. This is assessed to be a transboundary hot spot with a current impact and a greater impact during times of high flooding.
(b) The radioactive waste dumps on the former Prydniprovsky chemical plant site in Dniprodzerzhinsk and of the uranium processing operations in Zhovti Vody. These are actual national hot spots with a potential for a major impact over a very long period if impoundment structures erode or fail catastrophically.
(c) Inhabited areas in the three countries with high levels of Chernobyl caused radioactive contamination, including closed lakes in which concentrations of ^{137}Cs in fish or drinking water exceed the permissible levels. These are local hot spots but occur in all three countries.

Potential hot spots:

(i) The Chernobyl shelter in the event of its collapse (transboundary hot spot).

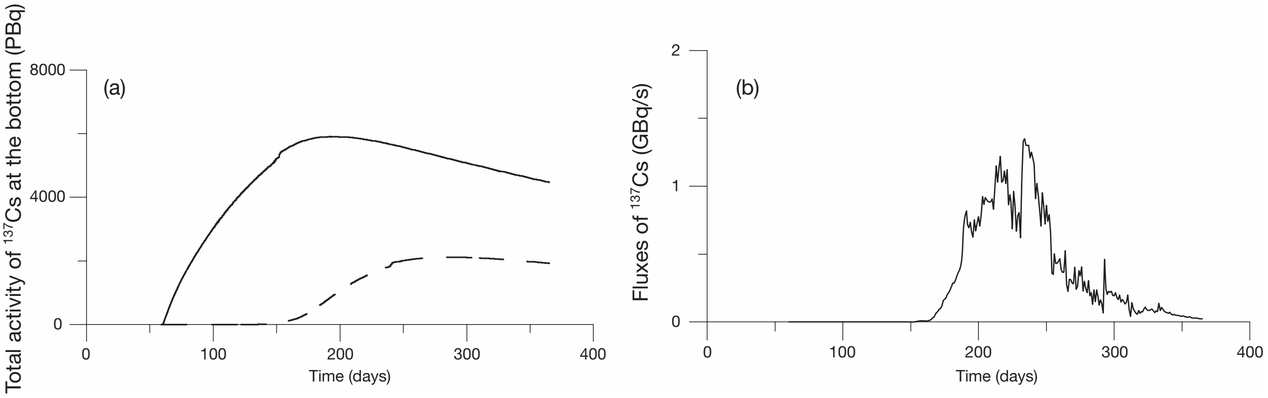


FIG. 9.39. (a) Total activity of ^{137}Cs at the bottom of the Kakhovka reservoir and the Dnieper–Bug estuary (solid line: the Kakhovka reservoir; dashed line: the Dnieper–Bug estuary). (b) Flux of ^{137}Cs into the Black Sea (solid line: ^{137}Cs in solution).

(ii) The Chernobyl cooling pond in the event of a dam failure (national hot spot).
(iii) The Ecores and RADON facilities at Kiev and Dnipropetrovsk, until reconstruction is complete (local hot spots).

Nuclear accident: A major accident at a nuclear power plant is considered to be of low probability, having regard for major and ongoing improvements at nuclear power plants in the Russian Federation and Ukraine. However, a large release would have considerable transboundary impacts, especially in the Black Sea if the source were in the south of Ukraine (such as the Zaporozhe nuclear power plant).

The hot spots listed above would need to be given special consideration in any prioritization of countermeasures to reduce radiological health impacts in the Dnieper River basin.

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10. MAJOR CONCLUSIONS

10.1. INTRODUCTION

Detailed conclusions on each of the major topics are presented at the end of each section. This section lists the more important conclusions for each topic and the final classification of hot spots. Section 11 gives recommendations for the SAP and NAPs.

10.2. CHERNOBYL AFFECTED AREAS

(1) High levels of radioactivity remain within the CEZ. Important hot spots within this zone are the floodplain along the Pripyat River, the Chernobyl nuclear power plant cooling pond and the Chernobyl shelter.

(2) There is still transboundary transfer of radionuclides (mainly ^{90}Sr) by rivers within the Dnieper River basin. The most important source is the floodplain of the Pripyat River within the CEZ.

(3) The concentrations of ^{137}Cs and ^{90}Sr in river waters of the Dnieper River basin have decreased significantly and are now below the maximum permissible levels set by the national authorities and recommended by expert international organizations. Almost all the ^{137}Cs washed out of contaminated areas is immobilized in bottom sediments within the reservoirs of the Dnieper River. The impact of these sediments is low and will decline further with decay and further deposition of sediments on top of the contaminated sediments.

(4) Lakes with no regular outflows still present a radiological problem arising from higher levels of ^{137}Cs in water and fish.

(5) The levels of radioactivity in forest foods (wild game, mushrooms, berries) in some Chernobyl affected areas are above permissible levels, as are those in milk and beef produced by cattle grazing on contaminated floodplains.

10.3. NUCLEAR POWER PLANTS

(6) Routine discharges from nuclear power plants in the Russian Federation and Ukraine are generally well below authorized limits and do not contribute to significant contamination of the environment.

(7) A legislative and regulatory basis established in both the Russian Federation and Ukraine ensures that all nuclear power plants operate with a valid licence. A legal mechanism exists for regulatory body review and assessment of plant safety and renewal of plant licences on a regular basis.

(8) In recent years the safety of RBMK and WWER reactors has been subject to considerable regulatory and international scrutiny. Major engineering upgrades have been undertaken to improve safety. An international in-depth safety assessment process is under way to optimize the improvement programmes. There is room for improvement in emergency preparedness and response.

10.4. URANIUM MINING AND MILLING

(9) Uranium mining and milling in Ukraine has had a negative impact on the environment. The most serious problem is caused by about 100×10^6 t of tailings and other radioactive waste from past and current operations. Most of the tailings dumps have not been properly rehabilitated and will pose a long term problem unless they are properly stabilized. Tailings D at Dniprodzerzhinsk is considered to have the greatest potential for pollution of the environment because of its proximity to the Dnieper River, the evidence of current seepage and the possibility of catastrophic failure of the impoundment. The situation in the region of tailings C and adjacent to it needs regular control, and decisions on further use should be taken with regard to IAEA recommendations and on the basis of a cost–benefit analysis.

(10) There is a paucity of data on the levels of radionuclides in the vicinity of uranium mines and mills and radioactive waste impoundments. Consequently, it is not possible to estimate the current or future dose rates from these sources with any degree of accuracy.

(11) There is a need to urgently start the development of modern standards on the protection of the environment, radiation safety and monitoring in the zone of influence of the uranium sites, consistent with the requirements of Ukrainian law and the recommendations of international organizations such as the IAEA.

10.5. OTHER RADIOLOGICAL SOURCES

(12) Medical and industrial uses of radioisotopes do not pose significant risks to the population of the Dnieper River basin. Radioactive sources with a high radioactivity could be a source of local exposure. Regulatory authorities should ensure that they are properly licensed and managed.

(13) There are many disposal or temporary storage sites for Chernobyl waste in Belarus, the Russian Federation and Ukraine. There is a need to continue to monitor and characterize the most hazardous of these sites; however, their impact appears to be quite localized and does not represent a major source of contamination of surface waters.

(14) There are two RADON type waste storage facilities at Kiev and Dnipropetrovsk in the Ukrainian section of the Dnieper River basin. Further safety assessments need to be undertaken to assess their environmental impact.

(15) The Ecores State facility near Minsk does not comply with international standards for the storage or disposal of radioactive waste. This facility is a potential source of radioactive contamination of the local population, but not of the Dnieper River basin as a whole.

10.6. HUMAN EXPOSURE TO RADIATION

(16) The average dose rate to Ukrainian citizens from natural radiation sources is about 2.5 mSv/a, which is close to the global average. This value is also considered to be a reasonable estimate of the average dose rate to the population of the Dnieper River basin as a whole.

(17) The inhabitants of areas contaminated with radionuclides from the Chernobyl accident in 1986 are still being subjected both to external exposure from ^{137}Cs gamma radiation and to internal exposure due to consumption of local foodstuffs containing ^{137}Cs and, to a lesser extent, ^{90}Sr. The most important factors controlling the mean external dose are the settlement type (rural or urban) and the level of ^{137}Cs soil deposition (in kBq/m^2). For internal exposures, the most important factors are the soil type and the level of ^{137}Cs soil deposition. On average, effective doses to the inhabitants of rural settlements are higher than those to urban dwellers.

(18) The average total annual doses to the inhabitants of settlements located in the Chernobyl accident areas, caused by environmental ^{137}Cs and ^{90}Sr, range from 0.1 to about 5 mSv. In many tens of settlements the average annual exposure level still exceeds the national action level of 1 mSv.

(19) Dosimetric models have been developed and tested to estimate past, present and future radiation exposures from all Chernobyl related pathways. The models predict that, by 2001, people in affected areas had already received at least 75% of their lifetime internal dose due to ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{89}Sr in Chernobyl fallout. Dose rates will decrease slowly with time over the next 50 years as deposited ^{137}Cs (half-life 30 years) decays and is made less available by soil redistribution processes.

(20) For critical groups in Chernobyl contaminated areas, wild foods (e.g. forest mushrooms, game, forest berries and fish) can make an important contribution to dose; for example, in one study in the Bryansk region of the Russian Federation, ‘natural’ foods contributed from 50% to 80% of ^{137}Cs intake. The average annual internal dose due to ^{137}Cs was estimated to be 1.2 mSv for men and 0.7 mSv for women.

(21) In most cases, aquatic pathways (drinking water, fish consumption and irrigation) make only a small contribution to the total dose from Chernobyl sources. At times of flooding of the Pripyat floodplain, dose rates increase somewhat due to washout of ^{90}Sr. Furthermore, in some closed lakes the concentration of ^{137}Cs remains high, and high levels of contamination are found in fish species. People who illegally catch and eat contaminated fish may receive internal doses in excess of 1 mSv/a from this source.

(22) Routine releases of radionuclides from operating nuclear reactors in the Dnieper River basin do not contribute significantly to radiation exposure of communities living in their vicinity.

(23) More data are required in order to make reliable estimates of exposures of people living in uranium affected areas. Estimates of exposure from the drinking water pathway suggest low dose rates, except in small areas that are unlikely sources of drinking water.

(24) Further work is needed to assess the potential short term and long term doses that might be received if uranium tailings impoundments adjacent to waterways in Ukraine were to fail and release tailings and/or contaminated water into adjacent rivers.

10.7. GENERAL

(25) Monitoring data are collected by various agencies for different purposes; different methodologies are used, some of which are outdated. There needs to be harmonization of results between the various organizations engaged in monitoring.

10.7.1. Classification of hot spots

Definitions appropriate to radiological assessment have been determined for hot spots, transboundary hot spots, national hot spots and local hot spots. Based on these definitions and assessments by the project team, the following hot spots have been identified.

Actual hot spots:

(a) The Pripyat floodplain area within the CEZ. This is assessed to be a transboundary hot spot with a current impact and a greater impact during times of high flooding.

(b) The radioactive waste dumps on the former Prydniprovsky chemical plant site in Dniprodzerzhinsk and of the uranium processing operations in Zhovti Vody. These are actual national hot spots with a potential for a major impact over a very long period if impoundment structures erode or fail catastrophically.

(c) Inhabited areas in the three countries with high levels of Chernobyl caused radioactive contamination, including closed lakes in which concentrations of ^{137}Cs in fish or drinking water exceed the permissible levels. These are local hot spots but occur in all three countries.

Potential hot spots:

(i) The Chernobyl shelter in the event of its collapse (transboundary hot spot).

(ii) The Chernobyl cooling pond in the event of a dam failure (national hot spot).

(iii) The Ecores and RADON facilities at Kiev and Dnipropetrovsk, until reconstruction is complete (local hot spots).

10.8. POSSIBLE ACCIDENTS

In addition to these actual and potential hot spots, an accident at a nuclear power plant was considered. A major accident at a nuclear power plant is considered to be of very low probability, having regard for major and ongoing improvements at nuclear power plants in the Russian Federation and Ukraine. However, a large release would have considerable transboundary impacts, especially in the Black Sea if the source were in the south of Ukraine.

11. RECOMMENDATIONS TO THE GOVERNMENTS OF BELARUS, THE RUSSIAN FEDERATION AND UKRAINE FOR THE STRATEGIC ACTION PLAN AND NATIONAL ACTION PLANS

11.1. CHERNOBYL AFFECTED AREAS

Within the CEZ:

(1) The engineering works on the right bank of the Pripyat river within the CEZ should be completed. The works were started in 1998 but were suspended due to lack of funding.

(1) A diversionary canal should be constructed along the Belarus–Ukraine border between the settlements of Krasne and Zimovische to prevent inundation of the heavily contaminated areas on the Pripyat River's left bank.

(2) After 2007 the heavily contaminated Chernobyl cooling pond should be safely decommissioned.

(3) Appropriate measures need to be taken to monitor and prevent releases of radioactivity from the Chernobyl shelter.

(4) Technical measures should be taken to prevent significant radionuclide dispersion from the sites of temporary radioactive waste storage in the floodplain of the Pripyat River.

(5) The monitoring system for surface and underground waters in the CEZ should be improved and optimized.

Within inhabited areas:

(6) In order to reduce population exposure in the most contaminated areas, the following measures should be considered:
   (i) Restrict consumption of local foods (wild game, fish, berries, mushrooms, etc.);
   (ii) Restrict grazing and use of vegetation on floodplains;
   (iii) Provide safe water to rural communities.

(7) The monitoring system for surface and underground waters should be optimized. In particular, screening studies on closed lakes in the most contaminated areas should be performed and their impact on population exposure assessed.

(8) The radiological criteria in the Chernobyl affected countries should be harmonized.

11.2. NUCLEAR POWER PLANTS

(9) Rules and regulations should be harmonized within the Dnieper River basin and made consistent with international best practice.

(10) Cooperation and information exchange between regulatory organizations should be strengthened to make use of experience gained in implementing safety upgrade programmes.

(11) To improve preparedness for a possible nuclear accident, technical measures (early warning systems, decision support systems), institutional measures (logistics) and links between nuclear power plants and regional administrative units should be improved.

(12) The scope of safety analysis reports should be compliant with national requirements and consistent with the IAEA safety standards and current international practice.

(13) Comprehensive plant specific probabilistic safety assessments need to be finalized for all nuclear power plants in the region and subjected to thorough regulatory review. The countries with nuclear power plants would benefit from participation in activities organized by the IAEA on comparison of probabilistic safety assessment studies for similar reactors.

(14) Plans established for safety improvements should be carried out as a matter of urgency.

11.3. URANIUM MINING AND PROCESSING

(15) An ongoing system for radioecological monitoring of the environment (water, soil, vegetation, air and food products) in the affected regions (Zhovti Vody, mining areas and Dniprodzerzhinsk) needs to be

established. This should involve provision of appropriate equipment and coordination of the efforts of the external monitoring organizations.

(16) The pollution resulting from past and present operations in the Dniprodzerzhinsk industrial complex needs to be considered holistically in order to understand its respective contribution to pollution of the Dnieper River basin and the effects of interactions between the major waste storage areas. Essentially, there needs to be an overall plan for the site, which will include rehabilitation of sites along with possible further industrial development.

(17) Rehabilitation of non-operational uranium tailings impoundments at Zhovti Vody and Dniprodzerzhinsk needs to be completed in order to ensure that they provide long term containment. In any rehabilitation plan, particular attention should be given to tailings D and to the Konoplyanka River, which is acting as a conduit for the transfer of pollutants from the tailings impoundment into the Dnieper River.

(18) Current and future operations need to be carried out in accordance with an environmental plan that includes funding provisions to ensure progressive rehabilitation of closed mines, dumps and other facilities.

11.4. GENERAL

(19) Existing laws, regulations and guidelines should be reviewed and revised:
   - (i) To ensure that radiation safety provisions are consistent within the region and compliant with the latest international standards;
   - (ii) To apply risk assessment methodologies to account for radioactive, chemical and biological contamination.

(20) More detailed impact analysis of actual and potential hot spots should be undertaken within the framework of a specialized project.

(21) Monitoring of the environmental radioactive contamination in the Dnieper River basin should be improved and harmonized among Belarus, the Russian Federation and Ukraine.

(22) Scientific research that contributes to the assessment, understanding and solution of radiological problems in the Dnieper River basin should be supported.

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Consultants Meetings

Vienna, Austria: 15–19 April 2002, 7–11 October 2002

Fact finding missions

Radiation and waste safety issues: Moscow and Obninsk, Russian Federation; Minsk, Belarus;
Kiev, Chernobyl, Dnipropetrovsk and Dniprodzerzhinsk, Ukraine: 1–12 July 2002
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Workshops

UNDP Hot Spots Workshop, Kiev: 9–10 September 2002
UNDP Workshop on TDA Methodology and Causal Chain Analysis, Kharkiv, Ukraine: 8 November 2002

In 1986 the Chernobyl nuclear power plant accident in Ukraine destroyed a high power nuclear reactor and resulted in the release of large amounts of radionuclides into the environment. Uranium mining and milling facilities have been in operation since 1948 in the areas of the Ukraine adjacent to the middle reaches of the Dnieper River; these facilities have left substantial tailings containing naturally occurring radioactive material. These, together with the accident, resulted in the contamination of substantial areas with radioactive residues. This report was prepared in 2002–2003 by an IAEA project team within the framework of the Dnieper Basin Environmental Programme carried out under the United Nations Development Programme — Global Environment Facility. It includes the findings and conclusions of the IAEA project team on radioactive contamination in the Dnieper River basin and its radiological consequences, as well as recommendations to the Governments of Belarus, the Russian Federation and Ukraine in the area of radiation and environmental protection.

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