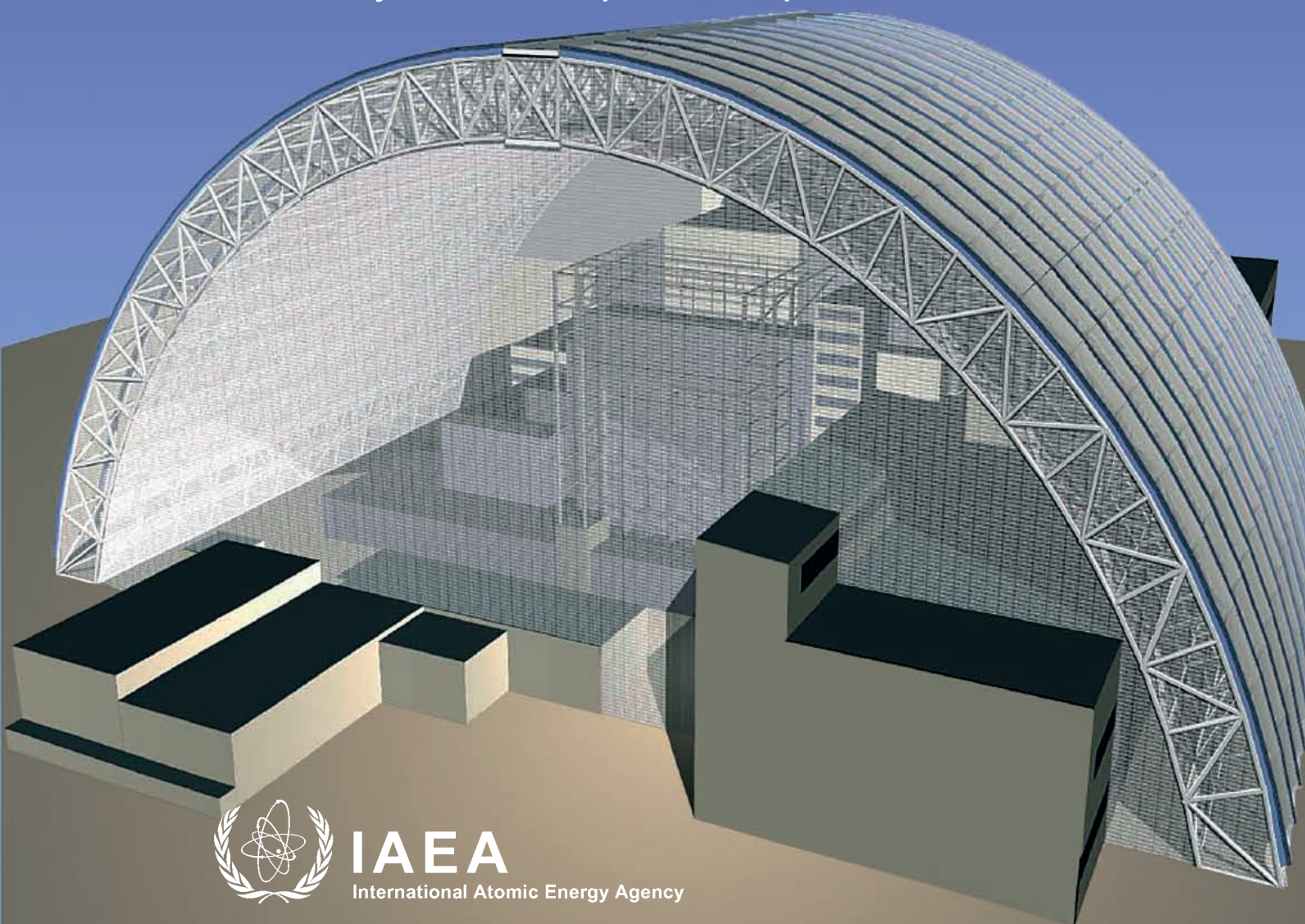


Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience

Report of the
Chernobyl Forum Expert Group 'Environment'



IAEA

International Atomic Energy Agency

ENVIRONMENTAL CONSEQUENCES
OF THE CHERNOBYL ACCIDENT
AND THEIR REMEDIATION:
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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2006

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FOREWORD

The explosion on 26 April 1986 at the Chernobyl nuclear power plant, which is located 100 km from Kiev in Ukraine (at that time part of the USSR), and the consequent reactor fire, which lasted for 10 days, resulted in an unprecedented release of radioactive material from a nuclear reactor and adverse consequences for the public and the environment.

The resulting contamination of the environment with radioactive material caused the evacuation of more than 100 000 people from the affected region during 1986 and the relocation, after 1986, of another 200 000 people from Belarus, the Russian Federation and Ukraine. Some five million people continue to live in areas contaminated by the accident. The national governments of the three affected countries, supported by international organizations, have undertaken costly efforts to remediate the areas affected by the contamination, provide medical services and restore the region's social and economic well-being.

The accident's consequences were not limited to the territories of Belarus, the Russian Federation and Ukraine, since other European countries were also affected as a result of the atmospheric transfer of radioactive material. These countries also encountered problems in the radiation protection of their populations, but to a lesser extent than the three most affected countries.

Although the accident occurred nearly two decades ago, controversy still surrounds the real impact of the disaster. Therefore the IAEA, in cooperation with the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO) and the World Bank, as well as the competent authorities of Belarus, the Russian Federation and Ukraine, established the Chernobyl Forum in 2003. The mission of the Forum was — through a series of managerial and expert meetings — to generate “authoritative consensual statements” on the environmental consequences and health effects attributable to radiation exposure arising from the accident, as well as to provide advice on environmental remediation and special health care programmes, and to suggest areas in which further research is required. The Forum was created as a contribution to the United Nations' ten year strategy for Chernobyl, launched in 2002 with the publication of Human Consequences of the Chernobyl Nuclear Accident — A Strategy for Recovery.

Over a two year period, two groups of experts from 12 countries, including Belarus, the Russian Federation and Ukraine, and from relevant international organizations, assessed the accident's environmental and health consequences. In early 2005 the Expert Group ‘Environment’, coordinated by the IAEA, and the Expert Group ‘Health’, coordinated by the WHO, presented their reports for the consideration of the Chernobyl Forum. Both reports were considered and approved by the Forum at its meeting on 18–20 April 2005. This meeting also decided, *inter alia*, “to consider the approved reports... as a common position of the Forum members, i.e., of the eight United Nations organizations and the three most affected countries, regarding the environmental and health consequences of the Chernobyl accident, as well as recommended future actions, i.e., as a consensus within the United Nations system.”

This report presents the findings and recommendations of the Chernobyl Forum concerning the environmental effects of the Chernobyl accident. The Forum's report considering the health effects of the Chernobyl accident is being published by the WHO. The Expert Group ‘Environment’ was chaired by L. Anspaugh of the United States of America. The IAEA technical officer responsible for this report was M. Balonov of the IAEA Division of Radiation, Transport and Waste Safety.

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1. SUMMARY

1.1. INTRODUCTION

This report provides an up to date evaluation of the environmental effects of the accident that occurred on 26 April 1986 at the Chernobyl nuclear power plant. Even though it is now nearly 20 years after the accident, there are still many conflicting reports and rumours concerning its consequences. For this reason the Chernobyl Forum was initiated by the IAEA in cooperation with the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO) and the World Bank, as well as the competent authorities of Belarus, the Russian Federation and Ukraine. The first organizational meeting of the Chernobyl Forum was held on 3–5 February 2003, at which time the decision was taken to establish the Forum as an ongoing entity of the above named organizations.

The Chernobyl Forum was established as a series of managerial, expert and public meetings with the purpose of generating authoritative consensual statements on the health effects attributable to radiation exposure arising from the accident and the environmental consequences induced by the released radioactive material, providing advice on remediation and special health care programmes and suggesting areas in which further research is required. The terms of reference of the Forum as approved at the meeting were:

- (a) To explore and refine the current scientific assessments on the long term health and environmental consequences of the Chernobyl accident, with a view to producing authoritative consensus statements focusing on:
 - (i) The health effects attributable to radiation exposure caused by the accident;
 - (ii) The environmental consequences induced by the radioactive material released due to the accident (e.g. contamination of foodstuffs);
- (iii) The consequences attributable to the accident but not directly related to the radiation exposure or radioactive contamination.
- (b) To identify gaps in scientific research relevant to the radiation induced or radioactive contamination induced health and environmental impacts of the accident, and to suggest areas in which further work is required based on an assessment of the work done in the past and bearing in mind ongoing work and projects.
- (c) To provide advice on, and to facilitate implementation of, scientifically sound programmes on mitigation of the accident consequences, including possible joint actions of the organizations participating in the Forum, such as:
 - (i) Remediation of contaminated land, with the aim of making it suitable for normal agricultural, economic and social life under safe conditions;
 - (ii) Special health care of the affected population;
 - (iii) Monitoring of long term human exposure to radiation;
 - (iv) Addressing the environmental issues pertaining to the decommissioning of the Chernobyl shelter and the management of radioactive waste originating from the Chernobyl accident.

The Chernobyl Forum is a high level organization of senior officials of United Nations agencies and the three most affected countries. The technical reports of the Forum were produced by two expert groups: Expert Group ‘Environment’ (EGE) and Expert Group ‘Health’ (EGH). The membership of the two groups comprised recognized international scientists and experts from the three most affected countries. Through the work of these two groups and their subworking groups, the technical documents were prepared. The EGE was coordinated by the IAEA and the EGH was coordinated by the WHO.

In all cases, the scientists of the EGE and EGH were able to reach consensus on the contents of their respective technical documents. The

technical reports were finally approved by the Chernobyl Forum itself. This report, on the environmental consequences, is published by the IAEA; the report on the health consequences will be published by the WHO.

1.2. RADIOACTIVE CONTAMINATION OF THE ENVIRONMENT

The Chernobyl accident caused a large regional release of radionuclides into the atmosphere and subsequent radioactive contamination of the environment. Many European countries were affected by the radioactive contamination; among the most affected were three former republics of the Soviet Union, now Belarus, the Russian Federation and Ukraine. The deposited radionuclides gradually decayed and moved within and among the environments — atmospheric, aquatic, terrestrial and urban.

1.2.1. Conclusions

1.2.1.1. Radionuclide release and deposition

Major releases from unit 4 of the Chernobyl nuclear power plant continued for ten days, and included radioactive gases, condensed aerosols and a large amount of fuel particles. The total release of radioactive substances was about 14 EBq¹ (as of 26 April 1986), which included 1.8 EBq of ¹³¹I, 0.085 EBq of ¹³⁷Cs and other caesium radioisotopes, 0.01 EBq of ⁹⁰Sr and 0.003 EBq of plutonium radioisotopes. The noble gases contributed about 50% of the total release of radioactivity.

Large areas of Europe were affected to some degree by the Chernobyl releases. An area of more than 200 000 km² in Europe was contaminated with radiocaesium (above 0.04 MBq of ¹³⁷Cs/m²), of which 71% was in the three most affected countries (Belarus, the Russian Federation and Ukraine). The deposition was highly heterogeneous; it was strongly influenced by rain when the contaminated air masses passed. In the mapping of the deposition, ¹³⁷Cs was chosen because it is easy to measure and is of radiological significance. Most of the strontium and plutonium radioisotopes were deposited close (less than 100 km) to the reactor, due to their being contained within larger particles.

Much of the release comprised radionuclides with short physical half-lives; long lived radionuclides were released in smaller amounts. Thus many of the radionuclides released by the accident have already decayed. The releases of radioactive iodines caused concern immediately after the accident. Owing to the emergency situation and the short half-life of ¹³¹I, few reliable measurements were made of the spatial distribution of deposited radioiodine (which is important in determining doses to the thyroid). Current measurements of ¹²⁹I may assist in estimating ¹³¹I deposition better and thereby improve thyroid dose reconstruction.

After the initial period, ¹³⁷Cs became the nuclide of greatest radiological importance, with ⁹⁰Sr being of less importance. For the first years ¹³⁴Cs was also important. Over the longer term (hundreds to thousands of years), the only radionuclides anticipated to be of interest are the plutonium isotopes and ²⁴¹Am.

1.2.1.2. Urban environment

In urban areas, open surfaces such as lawns, parks, streets, roads, squares, roofs and walls became contaminated with radionuclides. Under dry conditions, trees, bushes, lawns and roofs became more contaminated; under wet conditions, horizontal surfaces such as soil plots, lawns, etc., received the highest contamination. Particularly high ¹³⁷Cs activity concentrations were found around houses where rain had transported the radioactive material from the roofs to the ground. The deposition in urban areas in the nearest city of Pripjat and surrounding settlements could have initially given rise to substantial external radiation doses, but this was partially averted by the evacuation of the people. The deposited radioactive material in other urban areas has given rise to exposure of the public in the subsequent years and continues to do so.

Due to wind and rain and human activities, including traffic, street washing and cleanup, surface contamination by radioactive material was reduced significantly in inhabited and recreational areas during 1986 and afterwards. One of the consequences of these processes has been the secondary contamination of sewage systems and sludge storage areas.

At present, in most of the settlements subjected to radioactive contamination, the air dose rate above solid surfaces has returned to the pre-accident background level. The elevated air dose

¹ 1 EBq = 10¹⁸ Bq (becquerel).

rate remains mainly over undisturbed soil in gardens, kitchen gardens and parks.

1.2.1.3. Agricultural environment

In the early phase, direct surface deposition of many different radionuclides dominated the contamination of agricultural plants and the animals consuming them. The release and deposition of radioiodine isotopes caused the most immediate concern, but the problem was confined to the first two months, because of the short physical half-life (eight days) of the most important iodine isotope, ^{131}I . The radioiodine was rapidly transferred to milk at a high rate in Belarus, the Russian Federation and Ukraine, leading to significant thyroid doses to those consuming milk, especially children. In the rest of Europe the consequences of the accident varied; increased levels of radioiodine in milk were observed in some contaminated southern areas where dairy animals were already outdoors.

Different crop types, in particular green leafy vegetables, were also contaminated with radionuclides to varying degrees, depending on the deposition levels and the stage of the growing season. Direct deposition on to plant surfaces was of concern for about two months.

After the early phase of direct contamination, uptake of radionuclides through plant roots from soil became increasingly important and showed strong time dependence. Radioisotopes of caesium (^{137}Cs and ^{134}Cs) were the nuclides that led to the greatest problems, and after the decay of ^{134}Cs , ^{137}Cs remains to cause problems in some Belarusian, Russian and Ukrainian areas. In addition, ^{90}Sr causes problems in the near field of the reactor, but at longer distances the deposition levels were too low to be of radiological significance. Other radionuclides, such as plutonium isotopes and ^{241}Am , either were present at very low deposition levels or were not very available for root uptake, and therefore did not cause real problems in agriculture.

In general, there was an initial substantial reduction in the transfer of radionuclides to vegetation and animals, as would be expected, due to weathering, physical decay, migration of radionuclides down the soil column and reduction in radionuclide bioavailability in soil. Particularly in contaminated intensive agricultural systems, mostly in the former USSR, there was substantial reduction in the transfer of ^{137}Cs to plants and animals, especially in the first few years. However,

in the past decade there has been little further obvious decline, and long term effective half-lives have been difficult to quantify with precision.

The radiocaesium activity concentrations in foodstuffs after the early phase were influenced not only by deposition levels but also by soil types, management practices and types of ecosystem. The major and persistent problems in the affected areas occur in extensive agricultural systems with soils with a high organic content and where animals graze on unimproved pastures that are not ploughed or fertilized. In particular, this affects rural residents in the former USSR, who are commonly subsistence farmers with privately owned dairy cattle.

In the long term, ^{137}Cs in meat and milk, and to a lesser extent ^{137}Cs in vegetables, remains the most important contributor to human internal dose. As its activity concentration, in both vegetable and animal foods, has been decreasing during the past decade very slowly, at 3–7%/a, the contribution of ^{137}Cs to dose will continue to dominate for decades to come. The contribution of other long lived radionuclides, ^{90}Sr , plutonium isotopes and ^{241}Am , to human dose will remain insignificant.

1.2.1.4. Forest environment

Following the Chernobyl accident, vegetation and animals in forests and mountain areas showed a particularly high uptake of radiocaesium, with the highest recorded ^{137}Cs activity concentrations being found in forest products, due to the persistent recycling of radiocaesium in forest ecosystems. Particularly high ^{137}Cs activity concentrations have been found in mushrooms, berries and game, and these high levels have persisted since the accident. Thus, while there has been a general decline in the magnitude of exposures due to the consumption of agricultural products, there have been continued high levels of contamination in forest food products, which still exceed intervention limits in many countries. This can be expected to continue for several decades to come. Therefore, the relative importance of forests in contributing to the radiation exposures of the populations of several affected countries has increased with time. It will be, primarily, the combination of downward migration in the soil and the physical decay of ^{137}Cs that contribute to any further reduction in the contamination of forest food products.

The high transfer of radiocaesium in the lichen–reindeer meat–humans pathway was demonstrated after the Chernobyl accident in the Arctic

and sub-Arctic areas of Europe. The Chernobyl accident led to considerable contamination of reindeer meat in Finland, Norway, the Russian Federation and Sweden, and caused significant problems for the Sami people.

The use of timber and associated products makes only a small contribution to the exposure of the general public, although wood ash can contain high amounts of ^{137}Cs and could potentially give rise to higher doses than other uses of wood. Caesium-137 in timber is of minor importance, although doses in the wood pulp industry have to be considered.

Forest fires increased air activity concentrations in 1992, but not to a high extent. The possible radiological consequences of forest fires have been much discussed, but these are not expected to cause any problems of radionuclide transfer from contaminated forests, except, possibly, in the nearest surroundings of the fire.

1.2.1.5. Aquatic environment

Radionuclides from Chernobyl contaminated surface water systems not only in areas close to the site but also in many other parts of Europe. The initial contamination of water was due primarily to direct deposition of radionuclides on to the surfaces of rivers and lakes and was dominated by short lived radionuclides (most importantly ^{131}I). In the first few weeks after the accident, activity concentrations in drinking water from the Kiev reservoir were a particular concern.

The contamination of water bodies decreased rapidly during the weeks after fallout through dilution, physical decay and absorption of radionuclides by catchment soils. For lakes and reservoirs, the settling of suspended particles to the bed sediments also played an important role in reducing radionuclide levels in water. Bed sediments are an important long term sink for radionuclides.

The initial uptake of radioiodine by fish was rapid, but activity concentrations declined quickly, due primarily to physical decay. Bioaccumulation of radiocaesium in the aquatic food chain led to significant concentrations in fish in the most affected areas, and in some lakes as far away as Scandinavia and Germany. Owing to generally lower fallout and lower bioaccumulation, ^{90}Sr activity concentrations in fish were not a significant contributor to human dose in comparison with

radiocaesium, particularly since ^{90}Sr is accumulated in bone rather than in edible muscle.

In the long term, secondary contamination by wash-off of long lived ^{137}Cs and ^{90}Sr from contaminated soils and remobilization from bed sediments continues (at a much lower level) to the present day. Catchments with a high organic content (peat soils) release much more radiocaesium to surface waters than those with mostly mineral soils. At present, surface water activity concentrations are low; irrigation with surface water is therefore not considered to be a problem.

Fuel particles deposited in the sediments of rivers and lakes close to the Chernobyl nuclear power plant show significantly lower weathering rates than the same particles in terrestrial soils. The half-life of these particles is roughly the same as the physical half-life of the radionuclides ^{90}Sr and ^{137}Cs .

While ^{137}Cs and ^{90}Sr activity concentrations in the water and fish of rivers, open lakes and reservoirs are currently low, the most contaminated lakes are those few lakes with limited inflowing and outflowing streams ('closed' lakes) in Belarus, the Russian Federation and Ukraine that have a poor mineral nutrient status. Activity concentrations of ^{137}Cs in fish in some of these lakes will remain for a significant time into the future. In a population living next to a closed lake system (e.g. Lake Kozhanovskoe in the Russian Federation), consumption of fish has dominated the total ^{137}Cs ingestion for some people.

Owing to the large distance of the Black and Baltic Seas from Chernobyl, and the dilution in these systems, activity concentrations in sea water have been much lower than in fresh water. The low radionuclide concentrations in the water combined with the low bioaccumulation of radiocaesium in marine biota has led to activity concentrations in marine fish that are not of concern.

1.2.2. Recommendations for future research and monitoring

1.2.2.1. General

Various ecosystems considered in this report have been intensively monitored and studied during the years after the Chernobyl accident, and the transfer and bioaccumulation of the most important long term contaminants, ^{137}Cs and ^{90}Sr , are now generally well understood. There is, therefore, little urgent need for major new research programmes on radionuclides in ecosystems; there is, however, a

requirement for continued, but more limited, targeted monitoring of the environments, and for further research in some specific areas, as detailed below.

Long term monitoring of radionuclides (especially ^{137}Cs and ^{90}Sr) in various environmental compartments is required to meet the general practical and scientific needs described below.

1.2.2.2. Practical

The practical needs are to:

- (a) Assess current and predict future levels of human exposure and contamination of foods in order to justify remedial actions and long term countermeasures.
- (b) Inform the general public in affected areas about the persistence of radioactive contamination in food products and its seasonal and annual variability in natural food products gathered by themselves (such as mushrooms, game, freshwater fish from closed lakes, berries, etc.) and give advice on dietary and food preparation methods to reduce radionuclide intake by humans.
- (c) Inform the general public in affected areas about changing radiological conditions in order to relieve public concerns.

1.2.2.3. Scientific

The scientific needs are to:

- (a) Determine the parameters of the long term transfer of radionuclides in various ecosystems and different natural conditions in order to improve predictive models both for use in Chernobyl affected areas and for application to potential future radioactive releases.
- (b) Determine mechanisms of radionuclide behaviour in less studied ecosystems (e.g. the role of fungi in forests) in order to understand the mechanisms determining the persistence of radionuclides in these ecosystems and to explore possibilities for remediation, with special attention to be paid to processes of importance for contribution to human and biota doses.

As activity concentrations in environmental compartments are now in quasi-equilibrium and

changing slowly, the number and frequency of sampling and measurements performed in monitoring and research programmes can be substantially reduced compared with the early years after the Chernobyl accident.

The deposits of ^{137}Cs and a number of other long lived radionuclides in the 30 km zone should be used for radioecological studies of the various ecosystems located in this highly contaminated area. Such studies are, except for very small scale experiments, not possible or difficult to perform elsewhere.

1.2.2.4. Specific recommendations

Updated mapping of ^{137}Cs deposition in Albania, Bulgaria and Georgia should be performed in order to complete the study of the post-Chernobyl contamination of Europe.

Improved mapping of ^{131}I deposition, based both on historical environmental measurements carried out in 1986 and on recent measurements of ^{129}I in soil samples in areas where elevated thyroid cancer incidence has been detected after the Chernobyl accident, would reduce the uncertainty in thyroid dose reconstruction needed for the determination of radiation risks.

Long term monitoring of ^{137}Cs and ^{90}Sr activity concentrations in agricultural plant and animal products produced in areas with various soil and climate conditions and different agricultural practices should be performed in the next decades, in the form of limited target research programmes on selected sites, to determine parameters for the modelling of long term transfer.

Studies of the distribution of ^{137}Cs and plutonium radionuclides in the urban environment (Pripyat, Chernobyl and some other contaminated towns) at long times after the accident would improve modelling of human external exposure and inhalation of radionuclides in the event of a nuclear or radiological accident or malicious action.

Continued long term monitoring of specific forest products, such as mushrooms, berries and game, should be carried out in those areas in which forests were significantly contaminated and where the public consumes wild foods. The results from such monitoring are being used by the relevant authorities in the affected countries to provide advice to the general public on the continued use of forests for recreation and the gathering of wild foods.

In addition to the general monitoring of forest products, required for radiation protection, more detailed, scientifically based, long term monitoring of specific forest sites is required to provide an ongoing and improved understanding of the mechanisms, long term dynamics and persistence of radiocaesium contamination and its variability. It is desirable to explore further the key organisms, for example fungi, and their role in radiocaesium mobility and long term behaviour in forest ecosystems. Such monitoring programmes are being carried out in the more severely affected countries, such as Belarus and the Russian Federation, and it is important that these continue into the foreseeable future if the current uncertainties on long term forecasts are to be reduced.

Aquatic systems have been intensively monitored and studied during the years after the Chernobyl accident, and transfers and bioaccumulation of the most important long term contaminants, ^{90}Sr and ^{137}Cs , are now well understood. There is, however, a requirement for continued (but perhaps more limited) monitoring of the aquatic environment, and for further research in some specific areas, as detailed below.

Although there is currently no need for major new research programmes on radioactivity in aquatic systems, predictions of future contamination of aquatic systems by ^{90}Sr and ^{137}Cs would be improved by continued monitoring of radioactivity in key systems (the Pripyat–Dnieper system, the seas, and selected rivers and lakes in the most affected areas and western Europe). This would continue the excellent existing time series measurements of activity concentrations in water, sediments and fish, and enable the refinement of predictive models for these radionuclides.

Although they are currently of minor radiological importance in comparison with ^{90}Sr and ^{137}Cs , further studies of transuranic elements in the Chernobyl zone would help to improve predictions of environmental contamination in the very long term (hundreds to thousands of years). Further empirical studies of transuranic radionuclides and ^{99}Tc are unlikely to have direct implications for radiological protection in the Chernobyl affected areas, but would add to knowledge of the environmental behaviour of these very long lived radionuclides.

Future plans to reduce the water level of the Chernobyl cooling pond will have significant implications for its ecology and the behaviour of radionuclides/fuel particles in newly exposed

sediments. Specific studies on the cooling pond should therefore continue. In particular, further study of fuel particle dissolution rates in aquatic systems such as the cooling pond would improve knowledge of these processes.

1.3. ENVIRONMENTAL COUNTERMEASURES AND REMEDATION

After the Chernobyl accident, the authorities in the USSR introduced a range of short term and long term countermeasures to reduce the effects of the environmental contamination. The countermeasures consumed a great amount of human, economic and scientific resources. Unfortunately, there was not always openness and transparency in the actions of the authorities, and information was withheld from the public. This can, in part, explain some of the problems experienced later in communication with the public, and the public's mistrust of the authorities. Similar behaviour in many other countries outside the Russian Federation, Belarus and Ukraine led to a distrust in authority that, in many countries, prompted investigations on how to deal with such major accidents in an open and transparent way and on how the affected people can be involved in decision making processes.

The unique experience of countermeasure application after the Chernobyl accident has already been widely used both at the national and international levels in order to improve preparedness against future nuclear and radiological emergencies.

1.3.1. Conclusions

1.3.1.1. Radiological criteria

At the time of the Chernobyl accident, well developed international and national guidance on general radiation protection of the public and specific guidance applicable to major nuclear emergencies was in place. The basic methodology of the guidance used in the former USSR was different from that of the international system, but the dose limits of the radiation safety standards were similar. The then available international and national standards were widely applied for the protection of the populations of the European countries affected by the accident.

The scale and long term consequences of the Chernobyl accident required the development of some additional national and international radiation safety standards as a result of changing radiological conditions.

1.3.1.2. Urban countermeasures

Decontamination of settlements was widely applied as a countermeasure in the contaminated regions of the USSR during the first years after the Chernobyl accident as a means of reducing the external exposure of the public and the inhalation of resuspended radioactive substances.

Decontamination was cost effective with regard to reduction of external dose when its planning and implementation were preceded by a remediation assessment based on cost-benefit techniques and external dosimetry data. Since the areas have been cleaned up, no secondary contamination of cleaned up plots has been observed.

The decontamination of urban environments has produced a considerable amount of low level radioactive waste, which, in turn, has created a problem of disposal.

Numerous experimental studies and associated modelling have been used as the scientific basis for developing improved recommendations for decontamination of the urban environment. Such recommendations could be used in the event of any future large scale radioactive contamination of urban areas.

1.3.1.3. Agricultural countermeasures

Countermeasures applied in the early phase of the Chernobyl accident were only partially effective in reducing radioiodine intake via milk, because of the lack of timely information about the accident and guidance on recommended actions, particularly for private farmers. This led to significant radioiodine exposure of some people in the affected countries.

The most effective countermeasures in the early phase were exclusion of contaminated pasture grasses from animals' diets and the rejection of milk. Feeding animals with clean fodder was effectively implemented in some countries; however, this countermeasure was not widely applied in the USSR, due to a lack of uncontaminated feeds. Slaughtering of cattle was often carried out, but it was unjustified from a radiological point

of view and caused significant hygienic, practical and economic problems.

Several months after the accident, long term agricultural countermeasures against radiocaesium and radiostrontium were effectively implemented in all contaminated regions; these countermeasures included feeding animals with clean fodder and obligatory milk processing. This enabled most farming practices to continue in affected areas and resulted in a large reduction in dose. The most important precondition was the radiation monitoring of agricultural lands, feeds and foodstuffs, including in vivo monitoring of caesium activity concentrations in the muscle of cattle.

The greatest long term problem has been radiocaesium contamination of milk and meat. In the USSR, and later in the three independent countries, this was addressed by the treatment of land used for fodder crops, clean feeding and the application of caesium binders to animals. Clean feeding is one of the most important and effective measures used in countries where animal products have ^{137}Cs activity concentrations exceeding the action levels. In the long term, environmental radiation conditions are changing only slowly; however, the efficiency of environmental countermeasures remains at a constant level.

The application of agricultural countermeasures in the three most affected countries has substantially decreased since the mid-1990s, because of economic problems. Within a short time this resulted in an increase of radionuclide content in plant and animal agricultural products.

There are still agricultural areas in the three countries that remain out of use. This land could be used after appropriate remediation, but at present legal, economic and social constraints make this difficult.

Where social and economic factors, along with radiological factors, have been taken into account during the planning and application of countermeasures, better acceptability of the countermeasures by the public has been achieved.

In western Europe, because of the high and prolonged uptake of radiocaesium in the affected extensive systems, a range of countermeasures is still being used for animal products from uplands and forests.

For the first time, practical, long term agricultural countermeasures have been developed, tested and implemented on a large scale; these include radical improvement of meadows, pre-slaughter clean feeding, the application of caesium binders,

and soil treatment and cultivation. Their implementation on more than three billion hectares of agricultural land has made it possible to minimize the amount of products with radionuclide activity concentrations above the action levels in all three countries.

1.3.1.4. Forest countermeasures

The principal forest related countermeasures applied after the Chernobyl accident were management based countermeasures (restrictions of various activities normally carried out in forests) and technology based countermeasures.

Restrictions widely applied in the three most affected countries, and partially in Scandinavia, included the following actions that have reduced human exposure due to residence in radioactively contaminated forests and the use of forest products:

- (a) Restrictions on public and forest worker access, as a countermeasure against external exposure.
- (a) Restrictions on the harvesting of food products such as game, berries and mushrooms. In the three most affected countries mushrooms are widely consumed, and therefore this restriction has been particularly important.
- (b) Restrictions on the collection of firewood by the public, in order to prevent external exposures in the home and garden when the wood is burned and the ash is disposed of or used as a fertilizer.
- (c) Alteration of hunting practices, aimed at avoiding the consumption of meat with high seasonal levels of radiocaesium.
- (d) Fire prevention, especially in areas with large scale radionuclide deposition, aimed at the avoidance of secondary contamination of the environment.

However, experience in the three most affected countries has shown that such restrictions can also result in significant negative social consequences, and advice from the authorities to the general public may be ignored as a result. This situation can be offset by the provision of suitable educational programmes targeted at the local scale to emphasize the relevance of suggested changes in the use of some forest areas.

It is unlikely that any technology based forest countermeasures (i.e. the use of machinery and/or

chemical treatments to alter the distribution or transfer of radiocaesium in the forest) will be practicable on a large scale.

1.3.1.5. Aquatic countermeasures

Numerous countermeasures were put in place in the months and years after the accident to protect water systems from the transfer of radionuclides from contaminated soils. In general, these measures were ineffective and expensive and led to relatively high exposures of the workers implementing the countermeasures.

The most effective countermeasure was the early restriction of drinking water abstraction and the change to alternative supplies. Restrictions on the consumption of freshwater fish have proved effective in Scandinavia and Germany; however, in Belarus, the Russian Federation and Ukraine such restrictions may not always have been adhered to.

It is unlikely that any future countermeasures to protect surface waters would be justifiable in terms of economic cost per unit of dose reduction. It is expected that restrictions on the consumption of fish will remain in a few cases (in closed lakes) for several more decades.

Future efforts in this area should be focused on public information, because there are still public misconceptions concerning the perceived health risks due to radioactively contaminated waters and fish.

1.3.2. Recommendations

1.3.2.1. Countries affected by the Chernobyl accident

Long term remediation measures and countermeasures should be applied in the areas contaminated with radionuclides if they are radiologically justified and optimized.

Members of the general public should be informed, along with the authorities, about the existing radiation risk factors and the technological possibilities to reduce them in the long term via remediation and countermeasures, and be involved in discussions and decision making.

In the long term, remediation measures and countermeasures remain efficient and justified — mainly in the agricultural areas with poor (sandy and peaty) soils, where high radionuclide transfer from soil to plants can occur.

Particular attention must be given to private farms in several hundred settlements and to about 50 intensive farms in Belarus, the Russian Federation and Ukraine, where radionuclide concentrations in milk still exceed the national action levels.

Among long term remediation measures, radical improvement of pastures and grasslands, as well as the draining of wet peaty areas, is highly efficient. The most efficient agricultural countermeasures are pre-slaughter clean feeding of animals accompanied by in vivo monitoring, application of Prussian blue to cattle and enhanced application of mineral fertilizers in plant cultivation.

Restricting harvesting by the public of wild food products such as game, berries, mushrooms and fish from closed lakes may still be needed in areas where radionuclide activity concentrations exceed the national action levels.

Advice should continue to be given on individual diets, as a way of reducing consumption of highly contaminated wild food products, and on simple cooking procedures to remove radioactive caesium.

It is necessary to identify sustainable ways of making use of the most affected areas, but also to revive the economic potential of such areas for the benefit of the community. Such strategies should take into account the associated radiation hazard.

1.3.2.2. Worldwide

The unique experience of countermeasure application after the Chernobyl accident should be carefully documented and used for the preparation of international and national guidance for authorities and experts responsible for radiation protection of the public and the environment.

Practically all the long term agricultural countermeasures implemented on a large scale in contaminated lands of the three most affected countries can be recommended for use in the event of future accidents. However, the effectiveness of soil based countermeasures varies at each site. Analysis of soil properties and agricultural practice before the application of countermeasures is therefore of great importance.

Recommendations on the decontamination of the urban environment in the event of large scale radioactive contamination should be distributed to the management of nuclear facilities that have the

potential for substantial accidental radioactive release (nuclear power plants and reprocessing plants) and to authorities in adjacent regions.

1.3.2.3. Research

Generally, the physical and chemical processes involved in environmental countermeasures and remediation technologies, both of a mechanical nature (radionuclide removal, mixing with soil, etc.) or of a chemical nature (soil liming, fertilization, etc.), or their combinations, are understood well enough to be modelled and applied in similar circumstances worldwide. Much less well understood are the biological processes that could be used in environmental remediation (e.g. reprofiling of agricultural production, bioremediation, etc.). These processes require more research.

An important issue that requires more sociological research is the perception by the public of the introduction, performance and withdrawal of countermeasures in the event of an emergency, as well as the development of social measures aimed at involving the public in these processes at all stages, beginning with the decision making process.

There is still substantial diversity in the international and national radiological criteria and safety standards applicable to the remediation of areas affected by environmental contamination with radionuclides. The experience of radiological protection of the public after the Chernobyl accident has clearly shown the need for further international harmonization of appropriate radiological criteria and safety standards.

1.4. HUMAN EXPOSURE

Following the Chernobyl accident, both workers and the general public were affected by radiation that resulted, or can result, in adverse health effects. In this report consideration is given primarily to the exposure patterns of members of the general public exposed to radionuclides released to the environment. Information on doses received by members of the general public, both those evacuated from the accident area and those who live permanently in contaminated areas, is required for the following health related purposes:

- (a) Substantiation of countermeasures and remediation programmes;

- (b) Forecast of expected adverse health effects and justification of corresponding health protection measures;
- (c) Information for the public and the authorities;
- (d) Epidemiological and other medical studies of radiation induced adverse health effects.

The results of post-accident environmental monitoring indicate that the most affected countries were Belarus, the Russian Federation and Ukraine. Much of the information on doses from the Chernobyl accident relates to these countries.

There were four main mechanisms for delivering radiation dose to the public: external dose from cloud passage, internal dose from inhalation of the cloud and resuspended material, external dose from radioactive material deposited on soil and other surfaces, and internal dose from the ingestion of food products and water. Except for unusual circumstances, the latter two pathways were the more important. External dose and internal dose tended to be approximately equally important, although this general conclusion is subject to large variation, due to the shielding afforded by buildings and the soil from which crops were grown.

Estimates of doses to individual members of population groups were based on millions of measurements of concentrations of radioactive material in air, soil, foods, water, human thyroids and the whole body contents of humans. In addition, many measurements were made of the external gamma exposure rate over undisturbed and disturbed fields, and external doses to humans were measured with individual thermoluminescent dosimeters. Thus the results of estimated doses are firmly based upon measurements and tend to be realistic rather than conservative.

As the major health effect of the Chernobyl accident for the general public was an elevated thyroid cancer incidence in children and adolescents, much attention has been paid to the dosimetry of the thyroid gland. The assessment of thyroid doses resulting from the intake of ^{131}I is based on the results of 350 000 human measurements and a few thousand measurements of ^{131}I in milk performed in Belarus, the Russian Federation and Ukraine within a few weeks of the accident.

Doses to humans were reduced significantly by a number of countermeasures. Official countermeasures included evacuation and relocation of persons, the blockage of contaminated food supplies, the removal of contaminated soil, the

treatment of agricultural fields to reduce the uptake of radionuclides, the substitution of foods and the prohibition of the use of wild foods. Unofficial countermeasures included the self-initiated avoidance of foods judged to be contaminated.

1.4.1. Conclusions

The collective effective dose (not including dose to the thyroid) received by about five million residents living in the areas of Belarus, the Russian Federation and Ukraine contaminated by the Chernobyl accident (^{137}Cs deposition on soil $>37 \text{ kBq/m}^2$) was approximately 40 000 man Sv during the period 1986–1995. The groups of exposed persons within each country received an approximately equal collective dose. The additional amount of collective effective dose projected to be received between 1996 and 2006 is about 9000 man Sv.

The collective dose to the thyroid was nearly 2×10^6 man Gy, with nearly half received by persons exposed in Ukraine.

The main pathways leading to human exposure were external exposure from radionuclides deposited on the ground and the ingestion of contaminated terrestrial food products. Inhalation and ingestion of drinking water, fish and products contaminated with irrigation water were generally minor pathways.

The range in thyroid dose in different settlements and in all age–gender groups is large, between less than 0.1 Gy and more than 10 Gy. In some groups, and especially in younger children, doses were high enough to cause both short term functional thyroid changes and thyroid cancer in some individuals.

The internal thyroid dose from the intake of ^{131}I was mainly due to the consumption of fresh cow's milk and, to a lesser extent, of green vegetables; children, on average, received a dose that was much higher than that received by adults, because of their small thyroid masses and consumption rates of fresh cow's milk that were similar to those of adults.

For populations permanently residing in contaminated areas and exposed predominantly via ingestion, the contribution of short lived radioiodines (i.e. ^{132}I , ^{133}I and ^{135}I) to thyroid dose was minor (i.e. about 1% of the ^{131}I thyroid dose), since short lived radioiodines decayed during transport of the radioiodines along the food chains. The highest relative contribution (20–50%) to the thyroid doses to the public from short lived radionuclides was

received by the residents of Pripyat through inhalation; these residents were evacuated before they could consume contaminated food.

Both measurement and modelling data show that the urban population was exposed to a lower external dose by a factor of 1.5–2 compared with 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. Also, as the urban population depends less on local agricultural products and wild foods than the rural population, both effective and thyroid internal doses caused predominantly by ingestion were lower by a factor of two to three in the urban than in the rural population.

The initial high rates of exposure declined rapidly due to the decay of short lived radionuclides and to the movement of radiocaesium into the soil profile. The latter caused a decrease in the rate of external dose due to increased shielding. In addition, as caesium moves into the soil column it binds to soil particles, which reduces the availability of caesium to plants and thus to the human food chain.

The great majority of dose from the accident has already been accumulated.

Persons who received effective doses (not including dose to the thyroid) higher than the average by a factor of two to three were those who lived in rural areas in single storey homes and who ate large amounts of wild foods such as game meats, mushrooms and berries.

The long term internal doses to residents of rural settlements strongly depend on soil properties. Contributions due to internal and external exposure are comparable in areas with light sandy soil, and the contribution of internal exposure to the total (external and internal) dose does not exceed 10% in areas with predominantly black soil. The contribution of ^{90}Sr to the internal dose, regardless of natural conditions, is usually less than 5%.

The long term internal doses to children caused by ingestion of food containing caesium radionuclides are usually lower by a factor of about 1.1–1.5 than those to adults and adolescents.

Both accumulated and predicted mean doses in settlement residents vary in the range of two orders of magnitude, depending on the radioactive contamination of the area, predominant soil type and settlement type. In the period 1986–2000 the accumulated dose ranged from 2 mSv in towns located in black soil areas up to 300 mSv in villages

located in areas with podzol sandy soil. The doses expected in the period 2001–2056 are substantially lower than the doses already received (i.e. in the range of 1–100 mSv).

If countermeasures had not been applied, the populations of some of the more contaminated villages could have received lifetime (70 years) effective doses of up to 400 mSv. Intensive application of countermeasures such as settlement decontamination and agricultural countermeasures has substantially reduced the doses. For comparison, a worldwide average lifetime dose from natural background radiation is about 170 mSv, with a typical range of 70–700 mSv in various regions of the world.

The vast majority of the approximately five million people residing in the contaminated areas of Belarus, the Russian Federation and Ukraine currently receive annual effective doses of less than 1 mSv (equal to the national action levels in the three countries). For comparison, a worldwide average annual dose from natural background radiation is about 2.4 mSv, with a typical range of 1–10 mSv in various regions of the world.

The number of residents of the contaminated areas in the three most affected countries that currently receive more than 1 mSv annually can be estimated to be about 100 000 persons. As the future reduction of both the external dose rate and the radionuclide (mainly ^{137}Cs) activity concentrations in food is predicted to be rather slow, the reduction in the human exposure levels is also expected to be slow (i.e. about 3–5%/a with current countermeasures).

Based upon available information, it does not appear that the doses associated with hot particles were significant.

The assessment of the Chernobyl Forum agrees with that of UNSCEAR [1.1] in terms of the dose received by the populations of the three most affected countries: Belarus, the Russian Federation and Ukraine.

1.4.2. Recommendations

Large scale monitoring of foodstuffs, whole body counting of individuals and provision of thermoluminescent dosimeters to members of the general public are no longer necessary. The critical groups in areas of high contamination and/or high transfer of radiocaesium to foods are known. Representative members of these critical groups should be monitored with dosimeters for external

dose and with whole body counting for internal dose.

Sentinel or marker individuals in more highly contaminated areas not scheduled for further remediation might be identified for continued periodic whole body counting and monitoring for external dose. The goal would be to follow the expected continued decrease in external and internal dose rate and to determine whether such decreases are due to radioactive decay alone or to further ecological elimination.

1.5. RADIATION INDUCED EFFECTS ON PLANTS AND ANIMALS

The biological effects of radiation on plants and animals have long been of interest to scientists; in fact, much of the information on the effects on humans has evolved from experimental studies on plants and animals. Additional research followed the development of nuclear energy and concerns about the possible impacts of radioactive releases into the terrestrial and aquatic environments. By the mid-1970s, a large amount of information had been accrued on the effects of ionizing radiation on plants and animals.

The Chernobyl nuclear accident in April 1986 occurred not in a desert or ocean but in a territory with a temperate climate and flourishing flora and fauna. Both acute radiation effects (radiation death of plants and animals, loss of reproduction, etc.) and long term effects (change of biodiversity, cytogenetic anomalies, etc.) have been observed in the affected areas. Biota located in the area nearest to the source of the radioactive release, the 30 km zone or Chernobyl exclusion zone (CEZ), were most affected. As a result, in this area population and ecosystem effects on biota, caused, on the one hand, by high radiation levels, and, on the other hand, by plant succession and animal migration due to intraspecific and interspecific competition, have occurred.

The plant and animal conditions in the CEZ changed rapidly during the first months and years after the accident and later arrived at a quasi-stationary equilibrium. At present, traces of adverse radiation effects on biota can hardly be found in the near vicinity of the radiation source (a few kilometres from the damaged reactor), and on the rest of the territory both wild plants and animals are flourishing because of the removal of the major natural stressor: humans.

1.5.1. Conclusions

Radiation from radionuclides released by the Chernobyl accident caused numerous acute adverse effects in the biota located in the areas of highest exposure (i.e. up to a distance of a few tens of kilometres from the release point). Beyond the CEZ, no acute radiation induced effects on biota have been reported.

The environmental response to the Chernobyl accident was a complex interaction among radiation dose, dose rate and its temporal and spatial variations, and the radiosensitivities of the different taxons. Both individual and population effects caused by radiation induced cell death have been observed in plants and animals as follows:

- (a) Increased mortality of coniferous plants, soil invertebrates and mammals;
- (b) Reproductive losses in plants and animals;
- (c) Chronic radiation syndrome in animals (mammals, birds, etc.).

No adverse radiation induced effects have been reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy during the first month after the radionuclide fallout.

Following the natural reduction of exposure levels due to radionuclide decay and migration, populations have been recovering from the acute radiation effects. By the next growing season after the accident, the population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from the major radiation induced adverse effects in plants and animals.

The acute radiobiological effects observed in the Chernobyl accident area are consistent with radiobiological data obtained in experimental studies or observed in natural conditions in other areas affected by ionizing radiation. Thus rapidly developing cell systems, such as meristems of plants and insect larvae, were predominantly affected by radiation. At the organism level, young plants and animals were found to be the most sensitive to the acute effects of radiation.

Genetic effects of radiation, in both somatic and germ cells, were observed in plants and animals in the CEZ during the first few years after the accident. Both in the CEZ and beyond, different cytogenetic anomalies attributable to radiation continue to be reported from experimental studies

performed on plants and animals. Whether the observed cytogenetic anomalies have any detrimental biological significance is not known.

The recovery of affected biota in the CEZ has been confounded by the overriding response to the removal of human activities (e.g. termination of agricultural and industrial activities and the accompanying environmental pollution in the most affected area). As a result, the populations of many plants and animals have expanded, and the present environmental conditions have had a positive impact on the biota in the CEZ.

1.5.2. Recommendations for future research

In order to develop a system of environmental protection against radiation, the long term impact of radiation on plant and animal populations should be further investigated in the CEZ; this is a globally unique area for radioecological and radiobiological research in an otherwise natural setting.

In particular, multigenerational studies of radiation effects on the genetic structure of plant and animal populations might bring fundamentally new scientific information.

There is a need to develop standardized methods for biota-dose reconstruction, for example in the form of a unified dosimetric protocol.

1.5.3. Recommendations for countermeasures and remediation

Protective actions for farm animals in the event of a nuclear or radiological emergency should be developed and internationally harmonized based on modern radiobiological data, including the experience gained in the CEZ.

It is likely that any technology based remediation actions aimed at improving the radiological conditions for plants and animals in the CEZ would have adverse impacts on biota.

1.6. ENVIRONMENTAL AND RADIOACTIVE WASTE MANAGEMENT ASPECTS OF THE DISMANTLING OF THE CHERNOBYL SHELTER

1.6.1. Conclusions

The accidental destruction of unit 4 of the Chernobyl nuclear power plant resulted in extensive radioactive contamination and the

generation of large amounts of radioactive waste in the unit, the Chernobyl nuclear power plant site and the surrounding area (CEZ). Construction of the shelter between May and November 1986 was aimed at environmental containment of the damaged reactor, reduction of radiation levels on the site and the prevention of further release of radionuclides off the site.

The shelter was erected in an extremely short period of time under conditions of severe radiation exposure of personnel. As a result, the measures taken to save time and reduce dose during the construction led to imperfection in the newly constructed shelter as well as to a lack of comprehensive data on the stability of the damaged unit 4 structures. In addition to uncertainties on stability at the time of its construction, structural elements of the shelter have degraded as a result of moisture induced corrosion during the two decades that have passed since the shelter was erected. The main potential hazard associated with the shelter is a possible collapse of its top structures and release of radioactive dust into the environment.

In order to avoid the potential collapse of the shelter in the future, measures are planned to strengthen the unstable structures of the shelter. In addition, a new safe confinement (NSC) with more than 100 years of service life is planned to be built as a cover over the existing shelter as a longer term solution. The construction of the NSC is expected to allow for the dismantlement of the current shelter, removal of highly radioactive fuel-containing material (FCM) from unit 4 and eventual decommissioning of the damaged reactor.

In the course of remediation activities, both at the Chernobyl nuclear power plant site and in its vicinity, large volumes of radioactive waste were generated as a result of the cleanup of contaminated areas and placed in temporary near surface waste storage and disposal facilities. Facilities of the trench and landfill type were created from 1986 to 1987 in the CEZ at distances of 0.5–15 km from the nuclear power plant site with the intention of avoiding dust spread, reducing the radiation levels and enabling better working conditions at unit 4 and in its surroundings. These facilities were established without proper design documentation, engineered barriers or hydrogeological investigations and do not meet current waste safety requirements.

During the years following the accident, large resources were expanded to provide a systematic analysis and an acceptable strategy for the management of the existing radioactive waste.

However, to date, a broadly accepted strategy for radioactive waste management at the Chernobyl nuclear power plant site and the CEZ, and especially for high level and long lived waste, has not been developed. The main reason for this is the large number of radioactive waste storage and disposal facilities, of which only half are well studied and inventoried. This results in large uncertainties on the radioactive waste inventories.

More radioactive waste is expected in the years to come, generated during the construction of the NSC, the possible shelter dismantling, FCM removal and the decommissioning of unit 4. This waste, belonging to different categories, must be properly managed.

According to the Ukrainian national programme on radioactive waste management, there are different options for the different waste categories. The planned options for low level radioactive waste are to sort the waste according to its physical characteristics (e.g. soil, concrete, metal) and possibly decontaminate and/or condition it for beneficial reuse (reuse of soil for NSC foundations, melting of metal pieces, etc.), or send it for disposal.

The long lived waste is planned to be placed in interim storage. Different storage options are being considered, and a decision has not yet been made. After construction of the NSC and decommissioning of the shelter facilities, it is envisaged that shelter dismantling and further removal of FCM will occur. High level radioactive waste is planned to be partially processed in place and then stored at a temporary storage site until a deep geologic disposal site is ready.

Such a strategic approach is foreseen by the Comprehensive Programme on Radioactive Waste Management, which was approved by the Ukrainian Government in 1996 and confirmed in 2004. According to this concept, it is considered reasonable to begin a specific investigation for exploring the most appropriate geological site in this area in 2006. Following such planning, the construction of a deep geologic disposal facility might be completed before 2035–2040.

The future development of the CEZ as an industrial site or nature reserve depends on the future strategy for the conversion of unit 4 into an ecologically safe system (i.e. the development of the NSC, the dismantlement of the current shelter, the removal of FCM and the eventual decommissioning of the unit 4 reactor site). Currently units 1, 2 and 3 (1000 MW RBMK (high power channel type) reactors) are shut down with a view to being decom-

missioned, and two additional reactors (units 5 and 6) that had been near completion were abandoned in 1986 following the accident.

There are uncertainties related to the current radioactive material inventory at the shelter and also at the waste storage and disposal sites within the CEZ. This situation affects not only safety assessments and environmental analyses but also the design of remediation actions and the criteria for new facilities.

1.6.2. Recommendations for future actions

Recognizing the ongoing effort on improving safety and addressing the aforementioned uncertainties in the existing input data, the following main recommendations are made regarding the dismantling of the shelter and the management of the radioactive waste generated as a result of the accident.

Since individual safety and environmental assessments have been performed only for individual facilities at and around the Chernobyl nuclear power plant, a comprehensive safety and environmental impact assessment, in accordance with international standards and recommendations, that encompasses all activities inside the entire CEZ, should be performed.

During the preparation and construction of the NSC and soil removal, special monitoring wells are expected to be destroyed. Therefore, it is important to maintain and improve the environmental monitoring strategies, methods, equipment and staff qualification needed for the adequate performance of monitoring of the conditions at the Chernobyl nuclear power plant site and the CEZ.

Development of an integrated radioactive waste management programme for the shelter, the Chernobyl nuclear power plant site and the CEZ is needed to ensure application of consistent management approaches and sufficient facility capacity for all waste types. Specific emphasis needs to be given to the characterization and classification of waste (in particular waste with transuranic elements) from all remediation and decommissioning activities, as well as to the establishment of sufficient infrastructure for the safe long term management of long lived and high level waste. Therefore, development of an appropriate waste management infrastructure is needed in order to ensure sufficient waste storage capacity; at present, the rate and continuity of remediation activities at

the Chernobyl nuclear power plant site and in the CEZ are being limited.

A coherent and comprehensive strategy for the rehabilitation of the CEZ is needed, with particular focus on improving the safety of the existing waste storage and disposal facilities. This will require development of a prioritization approach for remediation of the sites, based on safety assessment results, aimed at making decisions about those sites at which waste will be retrieved

and disposed of and those sites at which the waste will be allowed to decay in situ.

REFERENCE TO SECTION 1

- [1.1] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly, with Scientific Annexes), Vol. II, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).

2. INTRODUCTION

2.1. BACKGROUND

The Chernobyl Forum was initiated by the IAEA in cooperation with the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO) and the World Bank, as well as the competent authorities of Belarus, the Russian Federation and Ukraine. The organizational meeting for the Chernobyl Forum was held on 3–5 February 2003, at which time the decision was taken to establish the Forum as an ongoing entity of the above named organizations.

The background for the establishment of the Forum dates back to 2000, when UNSCEAR published its 2000 report to the United Nations General Assembly [2.1]. In this report it was stated that, apart from the very early deaths due to extreme overexposure, the only clearly indicated health effect on the population that could be attributed to radiation exposure was an increased rate in the diagnosis of thyroid cancer among persons who were young children at the time of exposure. The political representatives of Belarus, the Russian Federation and Ukraine had strong reservations regarding the report. These reservations seem to have had two bases:

- (a) The statement on health effects was widely divergent from what was being reported in the popular press and even by some other members of the United Nations family;
- (b) The political representatives felt that the views of scientists from the three affected countries had not been considered by UNSCEAR.

Subsequently, during his visit to Belarus and in meetings with the Belarusian authorities and its scientific community, the Director General of the IAEA, M. ElBaradei, noted that “a lack of trust still prevails among the people of the region..., due in part to the contradictory data and reports — on the

precise environmental and health impacts of the accident — among national authorities, as well as among the relevant international organizations.” This was in general agreement with the stated views of the political authorities of the three countries. It was evident that the authorities desired a new opportunity for an exchange of views and for the discussion of issues such as optimization of activities related to the remediation of contaminated land and the provision of health care to those affected by the accident. During meetings with these representatives, the Director General of the IAEA indicated his support for the concept of a Chernobyl Forum as a joint activity of the United Nations family and the three affected countries.

2.2. OBJECTIVES OF THE CHERNOBYL FORUM

At the organizational meeting of the Forum it was decided to establish the Chernobyl Forum as a series of managerial, expert and public meetings for the purpose of generating authoritative consensual statements on the health effects attributable to radiation exposure arising from the accident and on the environmental consequences induced by the released radioactive material, to provide advice on remediation and special health care programmes, and to suggest areas in which further research is required.

Participants at the organization meeting accepted the terms of reference of the Forum as being:

- (a) To explore and refine the current scientific assessments on the long term health and environmental consequences of the Chernobyl accident, with a view to producing authoritative consensus statements focusing on:
 - (i) The health effects attributable to radiation exposure caused by the accident;
 - (ii) The environmental consequences induced by the radioactive material released due to the accident (e.g. contamination of foodstuffs);

- (iii) The consequences attributable to the accident but not directly related to the radiation exposure or radioactive contamination.
- (b) To identify gaps in scientific research relevant to the radiation induced or radioactive contamination induced health and environmental impacts of the accident, and to suggest areas in which further work is required based on an assessment of the work done in the past and bearing in mind the ongoing work and projects.
- (c) To provide advice on, and to facilitate implementation of, scientifically sound programmes on mitigation of the accident consequences, including possible joint actions of the organizations participating in the Forum, such as:
 - (i) Remediation of contaminated land, with the aim of making it suitable for normal agricultural, economic and social life under safe conditions;
 - (ii) Special health care of the affected population;
 - (iii) Monitoring of long term human exposure to radiation;
 - (iv) Addressing the environmental issues pertaining to the decommissioning of the Chernobyl shelter and the management of radioactive waste originating from the Chernobyl accident.

2.3. METHOD OF OPERATION AND OUTPUT OF THE CHERNOBYL FORUM

The Chernobyl Forum is a high level organization of senior officials of United Nations agencies and the three affected countries. The technical reports of the Forum were produced by two expert groups: Expert Group 'Environment' (EGE) and Expert Group 'Health' (EGH). The membership of the two groups comprised recognized international scientists and experts from the three affected countries. Through the work of these two groups and their subworking groups, the technical documents were prepared. The EGE was coordinated by the IAEA and the EGH was coordinated by the WHO.

The documents were produced through meetings of groups of experts on specific topics. The groups considered in detail the data available from the literature as well as unpublished data from the three most affected countries. The documents were

used as the basis for the final reports of the Chernobyl Forum, which were approved by the Forum itself.

This report is the Chernobyl Forum's report on the environmental consequences of the Chernobyl accident. The Chernobyl Forum's report on the health effects of the Chernobyl accident will be published by the WHO [2.2].

2.4. STRUCTURE OF THE REPORT

This report consists of seven sections. Following the Introduction, Section 3 describes the processes and patterns of radioactive contamination of the urban, agricultural, forest and aquatic environments as a result of the deposition of the Chernobyl release. Section 4 identifies the major environmental countermeasures and remediation measures applied to the aforementioned four environments in order to mitigate the accident's consequences and, specifically, to reduce human exposure. Section 5 deals with an assessment of human exposure to radiation within the affected areas, based on data on environmental radioactive contamination and the countermeasures presented in Sections 3 and 4. Section 6 presents an overview of experimental data on the radiation induced effects in plants and animals observed predominantly in the near zone of radioactive contamination. Finally, Section 7 discusses the environmental aspects of the dismantling of the shelter facility at the Chernobyl site and radioactive waste management in the CEZ.

Each section is completed with relevant conclusions and recommendations for future environmental remediation actions, monitoring and research. The entire report is preceded by Section 1, the Summary.

REFERENCES TO SECTION 2

- [2.1] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly, with Scientific Annexes), Vol. II, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000) 451-566.
- [2.2] WORLD HEALTH ORGANIZATION, Health Effects of the Chernobyl Accident and Special Health Care Programmes, Report of the Chernobyl Forum Expert Group "Health" (EGH), WHO, Geneva (in press).

3. RADIOACTIVE CONTAMINATION OF THE ENVIRONMENT

The accident at the Chernobyl nuclear power plant resulted in a substantial release of radionuclides to the atmosphere and caused extensive contamination of the environment. A number of European countries were subjected to radioactive contamination; among the most affected were three former republics of the USSR, now Belarus, the Russian Federation and Ukraine. The activity levels of the radionuclides in the environment gradually declined due to radioactive decay. At the same time, there was movement of the radionuclides within the environments — atmospheric, aquatic, terrestrial and urban — and among the environments. The processes that determined the patterns of radioactive contamination in those environments are presented in this section.

The focus of this section is mainly on radioactive contamination of the off-site environment. Significant attention is given in Section 7 to the Chernobyl nuclear power plant site, the CEZ and the Chernobyl shelter.

3.1. RADIONUCLIDE RELEASE AND DEPOSITION

3.1.1. Radionuclide source term

The accident at unit 4 of the Chernobyl nuclear power plant took place shortly after midnight on 26 April 1986. Prior to the accident, the reactor had been operated for many hours in non-design configurations in preparation for an experiment on recovery of the energy in the turbine in the event of an unplanned shutdown. The cause of the accident is rather complicated, but can be considered as a runaway surge in the power level that caused the water coolant to vaporize inside the reactor. This in turn caused a further increase in the power level, with a resulting steam explosion that destroyed the reactor. After the initial explosion, the graphite in the reactor caught fire. Despite the heroic efforts of the staff to control the fire, the graphite burned for many days, and releases of radioactive material continued until 6 May 1986. The reconstructed time course of the release of radioactive material is shown in Fig. 3.1 [3.1–3.3].

The occurrence of the accident was not immediately announced by the authorities of the then USSR. However, the releases were so large that the presence of fresh fission products was soon detected in Scandinavian countries, and retrospective calculations of possible trajectories indicated that the accident had occurred in the former USSR. Further details of the accident and its immediate consequences are available in reports by the International Nuclear Safety Advisory Group [3.1], the International Advisory Committee [3.4] and UNSCEAR [3.5, 3.6].

An early estimate of the amount of ^{137}Cs released by the accident and deposited in the former USSR was made based on an airborne radiometric measurement of the contaminated parts of the former USSR; this estimate indicated that about 40 PBq (1×10^6 Ci) was deposited. Estimates of the releases have been refined over the years, and the current estimate of the total amount of ^{137}Cs deposited in the former USSR is about twice the earlier estimate (i.e. 80 PBq). Current estimates of the amounts of the more important radionuclides released are shown in Table 3.1. Most of the radionuclides for which there were large releases have short physical half-lives, and the radionuclides with long half-lives were mostly released in small

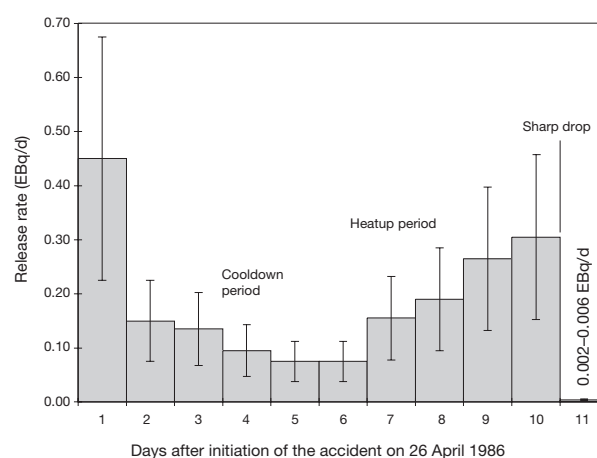


FIG. 3.1. Daily release rate to the atmosphere of radioactive material, excluding noble gases, during the Chernobyl accident. The values are decay corrected to 6 May 1986 and are uncertain by $\pm 50\%$ [3.1].

TABLE 3.1. REVISED ESTIMATES OF THE PRINCIPAL RADIONUCLIDES RELEASED DURING THE COURSE OF THE CHERNOBYL ACCIDENT^a

	Half-life	Activity released (PBq)
<i>Inert gases</i>		
Krypton-85	10.72 a	33
Xenon-133	5.25 d	6500
<i>Volatile elements</i>		
Tellurium-129m	33.6 d	240
Tellurium-132	3.26 d	~1150
Iodine-131	8.04 d	~1760
Iodine-133	20.8 h	910
Caesium-134	2.06 a	~47 ^b
Caesium-136	13.1 d	36
Caesium-137	30.0 a	~85
<i>Elements with intermediate volatility</i>		
Strontium-89	50.5 d	~115
Strontium-90	29.12 a	~10
Ruthenium-103	39.3 d	>168
Ruthenium-106	368 d	>73
Barium-140	12.7 d	240
<i>Refractory elements (including fuel particles)^c</i>		
Zirconium-95	64.0 d	84
Molybdenum-99	2.75 d	>72
Cerium-141	32.5 d	84
Cerium-144	284 d	~50
Neptunium-239	2.35 d	400
Plutonium-238	87.74 a	0.015
Plutonium-239	24 065 a	0.013
Plutonium-240	6 537 a	0.018
Plutonium-241	14.4 a	~2.6
Plutonium-242	376 000 a	0.00004
Curium-242	18.1 a	~0.4

^a Most of the data are from Refs [3.6, 3.7].

^b Based on ¹³⁴Cs/¹³⁷Cs ratio of 0.55 as of 26 April 1986 [3.8].

^c Based on fuel particle release of 1.5% [3.9].

amounts. In the early period after the accident, the radionuclide of most radiological concern was ¹³¹I; later, the emphasis shifted to ¹³⁷Cs.

By 2005 most of the radionuclides released by the accident had already decayed below levels of concern. Interest over the next few decades will

continue to be on ¹³⁷Cs and, to a lesser extent, ⁹⁰Sr; the latter remains more important in the near zone of the Chernobyl nuclear power plant. Over the longer term (hundreds to thousands of years), the only radionuclides anticipated to be of interest are the plutonium isotopes. The only radionuclide

expected to increase in its levels in the coming years is ^{241}Am , which arises from the decay of ^{241}Pu ; it takes about 100 years for the maximum amount of ^{241}Am to form from ^{241}Pu .

3.1.2. Physical and chemical forms of released material

Radionuclides in the releases from the stricken reactor were in the form of gases, condensed particles and fuel particles. The presence of the latter was an important characteristic of the accident. The oxidation of nuclear fuel was the basic mechanism of fuel particle formation. Less oxidized fuel particles were formed as a result of the initial explosion and were released primarily towards the western direction. More oxidized and soluble particles predominated in the remaining fallout, which was deposited in many other areas.

During oxidation and dispersal of the nuclear fuel, volatilization of some radionuclides took place. After the initial cloud cooled, the more volatile of the released radionuclides remained in the gas phase, whilst the less volatile radionuclides condensed on particles of construction material, soot and dust. Thus the chemical and physical forms of the radionuclides in the Chernobyl release were determined by the volatility of their compounds and the conditions inside the reactor. Radioactive compounds with relatively high vapour pressure (primarily isotopes of inert gases and iodine in different chemical forms) were transported in the atmosphere in the gas phase. Isotopes of refractory elements (e.g. cerium, zirconium, niobium and plutonium) were released into the atmosphere primarily in the form of fuel particles. Other radionuclides (isotopes of caesium, tellurium, antimony, etc.) were found in both fuel and condensed particles. The relative contributions of condensed and fuel components in the deposition at a given site can be estimated from the activity ratios of radionuclides of different volatility classes.

Fuel particles made up the most important part of the fallout in the vicinity of the release source. Radionuclides such as ^{95}Zr , ^{95}Nb , ^{99}Mo , $^{141,144}\text{Ce}$, $^{154,155}\text{Eu}$, $^{237,239}\text{Np}$, $^{238-242}\text{Pu}$, $^{241,243}\text{Am}$ and $^{242,244}\text{Cm}$ were released in a matrix of fuel particles only. More than 90% of $^{89,90}\text{Sr}$ and $^{103,106}\text{Ru}$ activities was also released in fuel particles. The release fraction of ^{90}Sr , ^{154}Eu , ^{238}Pu , $^{239,240}\text{Pu}$ and ^{241}Am , and, therefore, of the nuclear fuel itself, deposited outside the Chernobyl nuclear power plant industrial site has been recently estimated to be

only $1.5\% \pm 0.5\%$ [3.9], which is half that of earlier estimates [3.1].

The chemical and radionuclide composition of fuel particles was close to that of irradiated nuclear fuel, but with a lower fraction of volatile radionuclides, a higher oxidation state of uranium and the presence of various admixtures, especially in the surface layer. In contrast, the chemical and radionuclide composition of condensed particles varied widely. The specific activity of the radionuclides in these particles was determined by the duration of the condensation process and the process temperature, as well as by the particle characteristics. The radionuclide content of some of the particles was dominated by just one or two nuclides, for example $^{103,106}\text{Ru}$ or $^{140}\text{Ba}/^{140}\text{La}$ [3.10].

The form of a radionuclide in the release determined the distance of its atmospheric transport. Even the smallest fuel particles consisting of a single grain of nuclear fuel crystallite had a relatively large size (up to $10\text{ }\mu\text{m}$) and high density ($8\text{--}10\text{ g/cm}^3$). Owing to their size, they were transported only a few tens of kilometres. Larger aggregates of particles were found only within distances of several kilometres from the power plant. For this reason, the deposition of refractory radionuclides strongly decreased with distance from the damaged reactor, and only traces of refractory elements could be found outside the industrial site of the power plant. In contrast, significant deposition of gaseous radionuclides and sub-micrometre condensed particles took place thousands of kilometres from Chernobyl. Ruthenium particles, for example, were found throughout Europe [3.11]. At distances of hundreds of kilometres from Chernobyl the deposition of ^{137}Cs was as high as 1 MBq/m^2 [3.12, 3.13].

Another important characteristic of fallout is related to its solubility in aqueous solutions. This determines the mobility and bioavailability of deposited radionuclides in soils and surface waters during the initial period after deposition. In fallout sampled at the Chernobyl meteorological station from 26 April to 5 May 1986 with a 24 h sampling period, the water soluble and exchangeable (extractable with $1\text{M CH}_3\text{COONH}_4$) forms of ^{137}Cs varied from 5% to more than 30% [3.14]. The water soluble and exchangeable forms of ^{90}Sr in deposits on 26 April accounted for only about 1% of the total; this value increased to 5–10% in subsequent days.

The low solubility of deposited ^{137}Cs and ^{90}Sr near the nuclear power plant indicates that fuel particles were the major part of the fallout, even at

20 km from the source. At shorter distances the portion of water soluble and exchangeable forms of ^{137}Cs and ^{90}Sr was, obviously, lower, due to the presence of larger particles; at longer distances the fraction of soluble condensed particles increased. As one example, almost all the ^{137}Cs deposited in 1986 in the United Kingdom was water soluble and exchangeable [3.15].

3.1.3. Meteorological conditions during the course of the accident

At the time of the accident the weather in most of Europe was dominated by a vast anti-cyclone. At the 700–800 m and 1500 m altitudes, the area of the Chernobyl nuclear power plant was at the south-west periphery of a high atmospheric pressure zone with air masses moving north-west with a velocity of 5–10 m/s [3.12].

At daybreak, the altitude of the air mixing layer was about 2500 m. This resulted in rapid mixing of the airborne debris throughout the mixing layer and dispersion of the cloud at different layers of the mixing height. Further dissemination of the particles originating from the time of the accident within the 700–1500 m layer occurred as the air mass moved towards the north-east, with a subsequent turn to the north; this plume was detected in Scandinavian countries.

Ground level air on 26 April was transported to the west and north-west and reached Poland and the Scandinavian countries by 27–29 April. In southern and western Ukraine, the Republic of Moldova, Romania, Slovakia and Poland the weather was influenced by a low gradient pressure field. In the following days the cyclone moved slowly south-east and the low gradient pressure field with several poorly defined pressure areas dispersed over the major part of the European sector of the former USSR. One of the pressure areas was a small near surface cyclone located on the morning of 27 April south of Gomel.

Later, the releases from the reactor were carried predominantly in the south-western and southern directions until 7–8 May. During the first five days after the accident commenced, the wind pattern had changed through all directions of the compass [3.12].

Within a few days after the accident, measurements of radiation levels in air over Europe, Japan and the USA showed the presence of radionuclides at altitudes of up to 7000 m. The force of the explosion, rapid mixing of air layers due to

thunderstorms near the Chernobyl nuclear power plant and the presence of warm frontal air masses between the Chernobyl nuclear power plant and the Baltic Sea all contributed to the transport of radionuclides to such heights.

To understand the complex meteorological situation better, Borzilov and Klepikova [3.16] carried out calculations with assumed input pulses of unit activity at various times of the accident. The height of the source was selected to be 1000 m until 14:00 (GMT) on 28 April, and later 500 m. The results of calculations are presented in Fig. 3.2 for six time periods (GMT time) with differing long range transport conditions as follows:

- (1) From the start of the accident to 12:00 (GMT) on 26 April: towards Belarus, Lithuania, the Kaliningrad region (of the Russian Federation), Sweden and Finland.
- (2) From 12:00 on 26 April to 12:00 on 27 April: to Polesye, then Poland and then south-west.
- (3) From 12:00 on 27 April to 29 April: to the Gomel (Belarus) region, the Bryansk (Russian Federation) region and then the east.
- (4) 29 April to 30 April: to the Sumy and Poltava regions (Ukraine) and towards Romania.
- (5) 1–3 May: to southern Ukraine and across the Black Sea to Turkey.
- (6) 4–5 May: to western Ukraine and Romania, and then to Belarus.

Atmospheric precipitation plays an important role in determining whether an area might receive heavy contamination, as the processes of rainout (entrainment in a storm system) and washout (rain falling through a contaminated air mass) are important mechanisms in bringing released material to the ground. In particular, significant heterogeneity in the deposition of radioactive material is related to the presence or absence of precipitation during passage of the cloud. Also, there are differences in behaviour regarding how effectively different radionuclides, or chemical forms of the same radionuclide, are rained or washed out.

There were many precipitation events during the course of the accident, and these events produced some areas of high ground deposition at distances far from the reactor. An example of the complex precipitation situation during the accident is shown in Fig. 3.3, which is a map of average daily precipitation intensity on 29 April for the parts of Belarus, the Russian Federation and Ukraine most heavily affected by the accident.

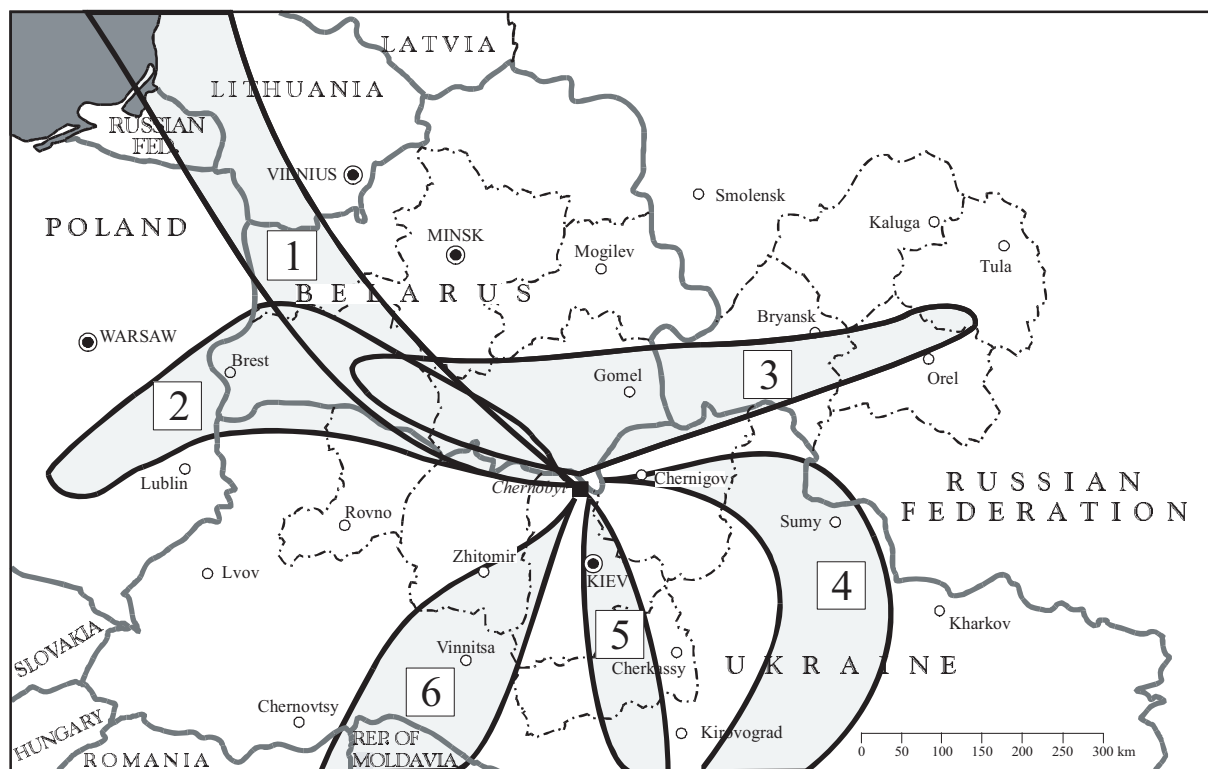


FIG. 3.2. Calculated plume formation according to the meteorological conditions for instantaneous releases on the following dates and times (GMT): (1) 26 April 1986, 00:00; (2) 27 April, 00:00; (3) 27 April, 12:00; (4) 29 April, 00:00; (5) 2 May, 00:00; and (6) 4 May, 12:00 [3.16].

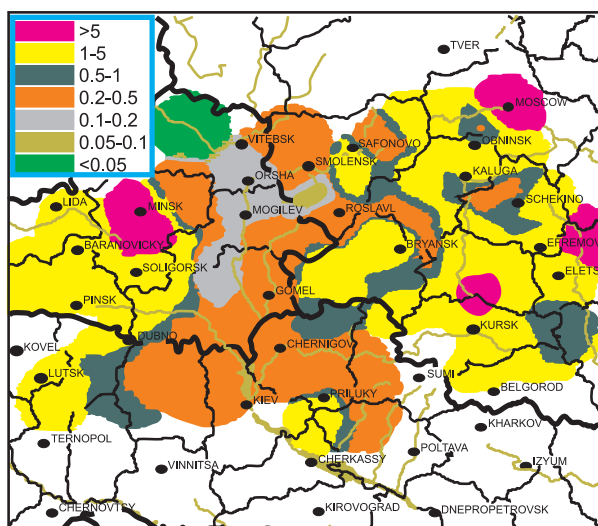


FIG. 3.3. Map of average precipitation intensity (mm/h) on 29 April 1986 in the area near the Chernobyl nuclear power plant [3.12].

In the case of dry deposition, the contamination levels were lower, but the radionuclide mixture intercepted by vegetation was substantially enriched with radioiodine isotopes; in the case of wet deposition, the radionuclide content in the fallout was similar to that in the radioactive cloud.

As a result, both the levels and ratios of radionuclides in areas with different deposition types varied.

3.1.4. Concentration of radionuclides in air

The activity concentrations of radioactive material in air were measured at many locations in the former USSR and throughout the world. Examples of such activity concentrations in air are shown in Fig. 3.4 for two locations: Chernobyl and Baryshevka, Ukraine. The location of the Chernobyl sampler was the meteorological station in the city of Chernobyl, which is more than 15 km south-east of the Chernobyl nuclear power plant. The initial concentrations of airborne material were very high, but dropped in two phases. There was a rapid fall over a few months, and a more gradual decrease over several years. Over the long term, the sampler at Chernobyl records consistently higher activity concentrations than the sampler at Baryshevka (about 150 km south-east of the Chernobyl nuclear power plant), presumably due to resuspension [3.17].

Even with the data smoothed by a rolling average, there are some notable features in the data

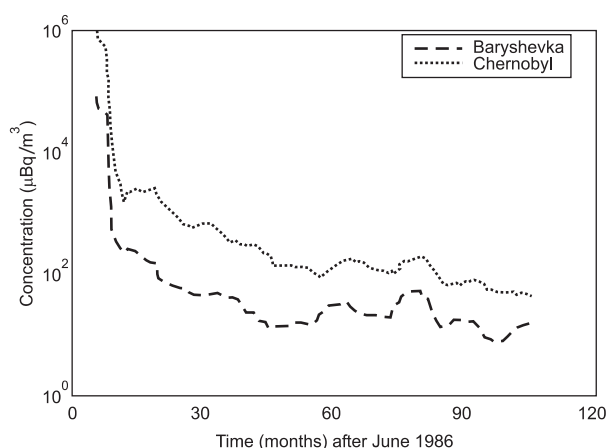


FIG. 3.4. Rolling seven month mean atmospheric concentration of ^{137}Cs at Baryshevka and Chernobyl (June 1986–August 1994) [3.17].

collected over the long term. The clearly discernible peak that occurred during the summer of 1992 (month 78) was due to widespread forest fires in Belarus and Ukraine.

3.1.5. Deposition of radionuclides on soil surfaces

As already mentioned, surveys with airborne spectrometers over large areas were undertaken soon after the accident to measure the deposition of ^{137}Cs (and other radionuclides) on the soil surface in

several countries. In the mapping of the deposition, ^{137}Cs was chosen because it is easy to measure and is of radiological significance. Soil deposition of ^{137}Cs equal to 37 kBq/m^2 (1 Ci/km^2) was chosen as a provisional minimum contamination level, because: (a) this level was about ten times higher than the ^{137}Cs deposition in Europe from global fallout; and (b) at this level the human dose during the first year after the accident was about 1 mSv and was considered to be radiologically important. Knowledge of the extent and spatial variation of deposition is critical in defining the magnitude of the accident, predicting future levels of external and internal dose, and determining what radiation protection measures are necessary. In addition, many soil samples were collected and analysed at radiological laboratories.

Thus massive amounts of data were collected and subsequently published in the form of an atlas that covers essentially all of Europe [3.13]. Another atlas produced in the Russian Federation [3.12] covers the European part of the former USSR. An example is shown in Fig. 3.5.

It is clear from Fig. 3.5 and Table 3.2 that the three countries most heavily affected by the accident were Belarus, the Russian Federation and Ukraine. From the total ^{137}Cs activity of about 64 TBq (1.7 MCi) deposited on European territory in 1986, Belarus received 23%, the Russian Federation 30% and Ukraine 18%. However, due

TABLE 3.2. AREAS IN EUROPE CONTAMINATED BY CHERNOBYL FALLOUT IN 1986 [3.6, 3.13]

	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	—	—	—

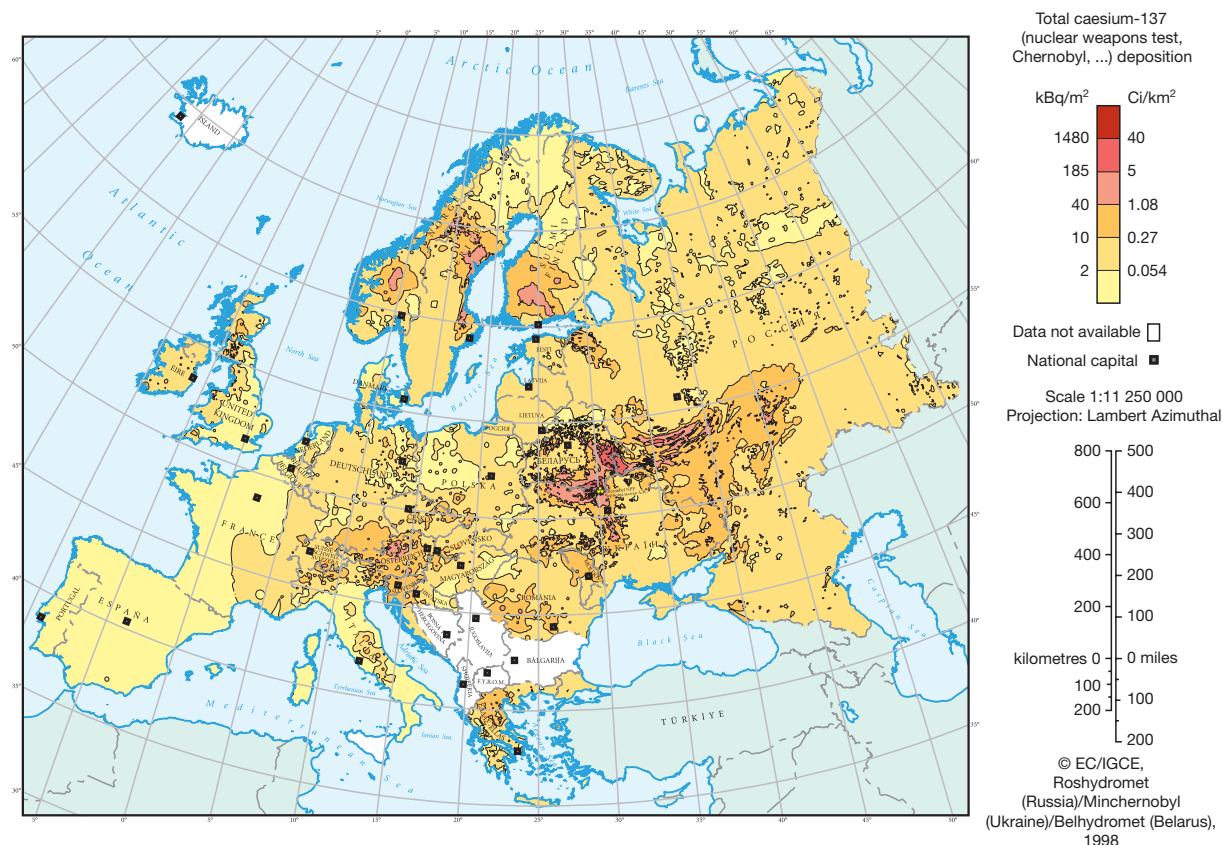


FIG. 3.5. Surface ground deposition of ^{137}Cs throughout Europe as a result of the Chernobyl accident [3.13].

to the wet deposition processes discussed above, there were also major contaminated areas in Austria, Finland, Germany, Norway, Romania and Sweden. A more detailed view of the nearby heavily contaminated areas is shown in Fig. 3.6 [3.4].

Water and wind erosion of soil may lead to ^{137}Cs transfer and redistribution on a local scale at relatively short distances. Wind erosion may also lead to ^{137}Cs transfer with soil particles on a regional scale.

Soon after the accident, a 30 km radius exclusion zone (the CEZ) was established around the reactor. Further relocations of populations took place in subsequent months and years in Belarus, the Russian Federation and Ukraine; eventually, 116 000 persons were evacuated or relocated.

The total area with ^{137}Cs soil deposition of 0.6 MBq/m^2 (15 Ci/km^2) and above in 1986 was $10\,300 \text{ km}^2$, including 6400 km^2 in Belarus, 2400 km^2 in the Russian Federation and 1500 km^2 in Ukraine. In total, 640 settlements with about 230 000 inhabitants were located on these contaminated territories. Areas with ^{137}Cs depositions of more than 1 Ci/km^2 (37 kBq/m^2) are classified as radioactively contaminated according to the laws on social protection in the three most affected countries. The

number of people who were living in such contaminated areas in 1995 is shown in Table 3.3.

Immediately after the accident, most concern was focused on contamination of food with ^{131}I . The broad pattern of the deposition of ^{131}I is shown in Fig. 3.7. Unfortunately, due to the rapid decay of ^{131}I after its deposition, there was not enough time to collect a large number of samples for detailed analysis. At first, it was assumed that a strong correlation could be assumed between depositions of ^{131}I and ^{137}Cs . However, this has not been found to be consistently valid. More recently, soil samples have been collected and analysed for ^{129}I , which has a physical half-life of 16×10^6 years and can only be measured at very low levels by means of accelerator mass spectrometry. Straume et al. [3.19] have reported the successful analysis of samples taken in Belarus, from which they have established that, at the time of the accident, there were 15 ± 3 atoms of ^{129}I for each atom of ^{131}I . This estimated ratio enables better estimates of the deposition of ^{131}I for the purpose of reconstructing radiation doses received by people.

Similar maps can be drawn for the other radionuclides of interest shown in Table 3.1. The deposition of ^{90}Sr is shown in Fig. 3.8. In comparison

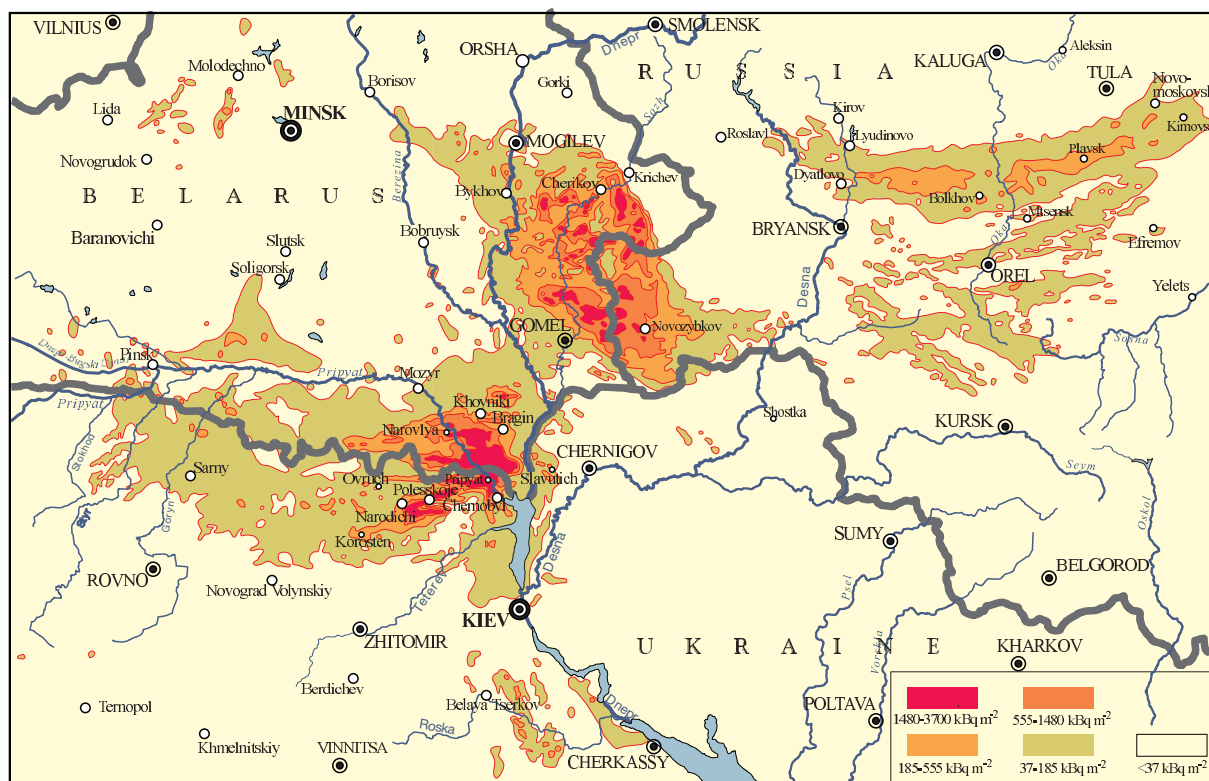


FIG. 3.6. Surface ground deposition of ^{137}Cs in areas of Belarus, the Russian Federation and Ukraine near the accident site [3.4].

with ^{137}Cs , (a) there was less ^{90}Sr released from the reactor and (b) strontium is less volatile than caesium. Thus the spatial extent of ^{90}Sr deposition was much more confined to areas close to the Chernobyl nuclear power plant than that of ^{137}Cs . The amounts of plutonium deposited on soil have also been measured (see Fig. 3.9). Nearly all areas with plutonium deposits above 3.7 kBq/m^2 (0.1 Ci/km^2) are within the CEZ.

3.1.6. Isotopic composition of the deposition

The most extensive measurements of surface activity concentrations have been performed for ^{137}Cs . Values for other radionuclides, especially ^{134}Cs , ^{136}Cs , ^{131}I , ^{133}I , $^{140}\text{Ba}/^{140}\text{La}$, $^{95}\text{Zr}/^{95}\text{Nb}$, ^{103}Ru , ^{106}Ru , ^{132}Te , ^{125}Sb and ^{144}Ce , have been expressed as ratios to the reference radionuclide, ^{137}Cs . These ratios depend on the location, because of (a) the

TABLE 3.3. DISTRIBUTION OF INHABITANTS LIVING IN AREAS CONSIDERED TO BE RADIO-ACTIVELY CONTAMINATED IN BELARUS, THE RUSSIAN FEDERATION AND UKRAINE IN 1995 [3.6]

Caesium-137 deposition density (kBq/m^2)	Thousands of inhabitants ^a			
	Belarus	Russian Federation	Ukraine	Total
37–185	1543	1654	1189	4386
185–555	239	234	107	580
555–1480	98	95	0.3	193
Total	1880	1983	1296	5159

^a For social and economic reasons, some people living in areas of contamination of less than 37 kBq/m^2 are also included.

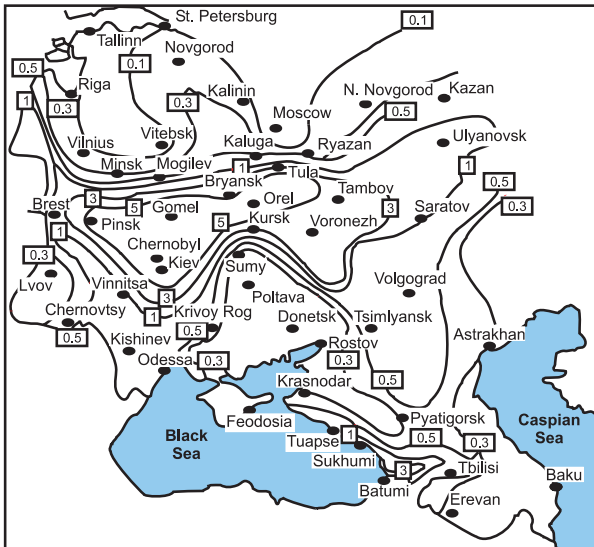


FIG. 3.7. Surface ground deposition of ^{131}I [3.18] (Ci/km^2 on 15 May 1986).



FIG. 3.8. Surface ground deposition of ^{90}Sr [3.4].

different deposition behaviour of fuel particles, aerosols and gaseous radionuclides and (b) the variation in radionuclide composition with time of release. In fact, these ratios are not necessarily

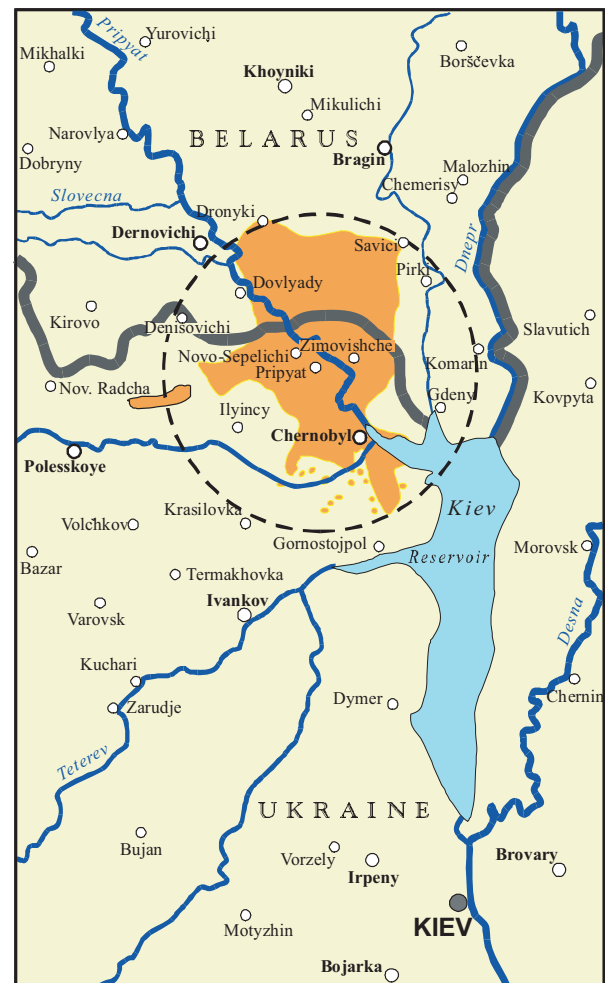


FIG. 3.9. Areas (orange) where the surface ground deposition of $^{239,240}\text{Pu}$ exceeds $3.7 \text{ kBq}/\text{m}^2$ [3.4].

constant with time. Depending on the time of release and the corresponding release characteristics (e.g. temperature of the core), significant variations in the release ratios were observed after the Chernobyl accident [3.2, 3.20].

The first plume, which moved to the west, carried the release that occurred during the explosive phase, when the exposed core was not as hot as in the later phases. The second plume, which moved north to north-east, carried releases from a core that was becoming increasingly hot, while the third plume, moving mainly south, was characterized by releases from a core heated to temperatures above 2000°C ; at such temperatures the less volatile radionuclides, such as molybdenum, strontium, zirconium, ruthenium and barium, are readily released. During this phase, releases of iodine radioisotopes also increased.

Caesium hot spots occurred in the far zone of Belarus and in the Kaluga, Tula and Orel regions of

the Russian Federation. The composition of the deposited radionuclides in each of these highly contaminated areas was similar. The ratios of different radionuclides to ^{137}Cs as observed in ground deposits in the different release vectors are shown in Table 3.4.

The activity ratios for the western and northern plumes were similar and in many cases identical, in contrast to the ratios for the southern plume. All activity ratios show, with the exception of $^{132}\text{Te}/^{137}\text{Cs}$, a decrease with increasing distance from the nuclear power plant. The decrease is less profound for ^{95}Zr and ^{144}Ce (about a factor of three) than with ^{99}Mo and ^{140}Ba (two orders of magnitude) or ^{90}Sr and ^{103}Ru (one order of magnitude). For the ratio $^{131}\text{I}/^{137}\text{Cs}$ only a slight decrease, by about a factor of four, was observed over a 1000 km distance. Within the first 200 km virtually no variation in the ratio was observed.

3.2. URBAN ENVIRONMENT

3.2.1. Deposition patterns

Radioactive fallout resulted in long term contamination of thousands of settlements in the USSR and some other European countries and in

the irradiation of their inhabitants due to both external gamma radiation and internal exposure due to consumption of contaminated food. Near to the Chernobyl nuclear power plant, the towns of Pripyat and Chernobyl and some other smaller settlements were subjected to substantial contamination from an 'undiluted' radioactive cloud under dry meteorological conditions, whereas more distant settlements were significantly affected because of precipitation at the time of cloud passage.

When the radioactive fallout was deposited on settlements, exposed surfaces such as lawns, parks, streets, roofs and walls became contaminated with radionuclides. Both the activity level and elemental composition of the radioactive fallout was significantly influenced by the type of deposition mechanism, namely wet deposition with precipitation or dry deposition influenced by atmospheric mixing, diffusion and chemical adsorption. Surfaces such as trees, bushes, lawns and roofs become relatively more contaminated under dry conditions than when there is precipitation. Under wet conditions, horizontal surfaces, including soil plots and lawns (see Fig. 3.10), receive the highest levels of contamination. Particularly high ^{137}Cs activity concentrations have been found around houses where rain has transported radioactive material from roofs to the ground.

TABLE 3.4. ESTIMATED RELATIVE SURFACE ACTIVITY CONCENTRATION OF DIFFERENT RADIONUCLIDES AFTER RELEASE FROM THE CHERNOBYL NUCLEAR POWER PLANT (26 APRIL 1986) [3.2]

	Half-life	Activity per unit area relative to ^{137}Cs			
		Western plume (near zone)	Northern plume (near zone)	Southern plume (near zone)	At caesium hot spots (far zone)
Strontium-90	28.5 a	0.5	0.13	1.5	0.014
Zirconium-95	64.0 d	5	3	10	0.06
Molybdenum-99	66.0 h	8	3	25	0.11
Ruthenium-103	39.35 d	4	2.7	12	1.9
Tellurium-132	78.0 h	15	17	13	13
Iodine-131	8.02 d	18	17	30	10
Caesium-137	30.0 a	1.0	1.0	1.0	1.0
Barium-140	12.79 d	7	3	20	0.7
Cerium-144	284.8 d	3	2.3	6	0.07
Neptunium-239	2.355 d	25	7	140	0.6
Plutonium-239	24 400 a	0.0015	0.0015	—	—

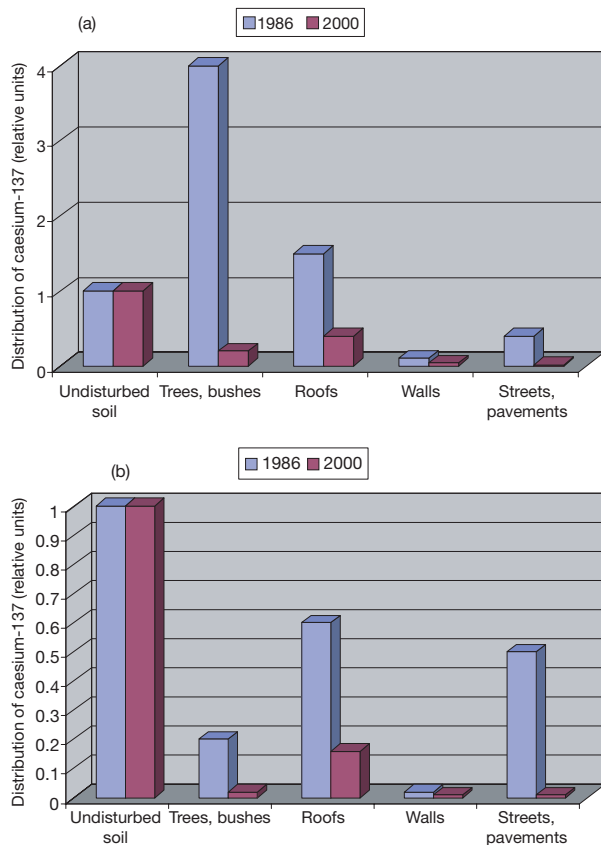


FIG. 3.10. Typical distribution of ^{137}Cs on different surfaces within settlements in 1986 and 14 years after deposition of the Chernobyl fallout. (a) Dry deposition; (b) wet deposition [3.23].

3.2.2. Migration of radionuclides in the urban environment

Due to natural weathering processes such as the effects of rainfall and snow melting, and to human activities such as traffic movement and street washing and cleaning, radionuclides became detached from the surfaces on which they were deposited and were transported within settlements. Contaminated leaves and needles from trees and bushes are removed from settlements after seasonal defoliation and radionuclides deposited on asphalt and concrete pavements are eroded or washed off and removed via sewage systems. These natural processes and human activities significantly reduced dose rates in inhabited and recreational areas during 1986 and in successive years [3.21].

In general, vertical surfaces of houses are not subjected to the same degree of weathering through rain as horizontal surfaces such as roofs. The loss of contamination from walls after 14 years has been

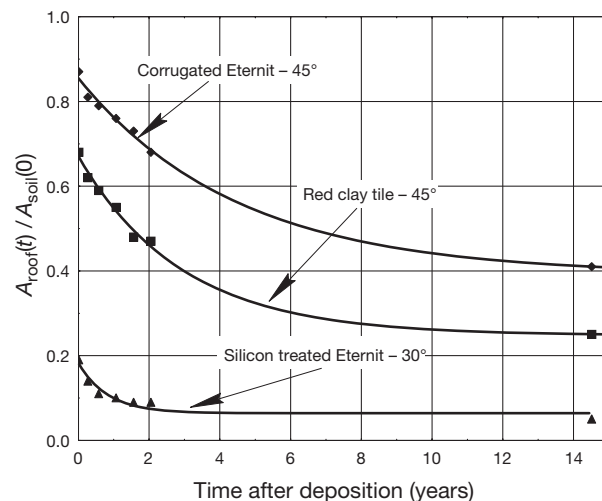


FIG. 3.11. Measured ^{137}Cs contamination levels (relative to the initial soil contamination) on three types of roof at Risø, Denmark [3.22].

typically 50–70% of the initial deposit. Roof contamination levels in Denmark decreased after 14 years by 60–95% of those originally present, due to natural processes (see Fig. 3.11) [3.22].

In contrast, the level of radiocaesium on asphalt surfaces has decreased substantially, such that, generally, less than 10% of the initially retained radiocaesium is now left. Only a small fraction of the radiocaesium contamination is associated with the bitumen fraction of the asphalt; most is associated with a thin layer of street dust, which will eventually be weathered off.

Measurements made in 1993 in the city of Pripjat near the Chernobyl nuclear power plant showed high residual levels of radiocaesium on the roads. However, this town was evacuated in the early accident phase, and therefore traffic there has been limited. Some 5–10% of the initially deposited radiocaesium seems to be firmly fixed to concrete paved surfaces, and no significant decrease has been recorded over the past few years. The weathering on horizontal hard surfaces was, as expected, generally faster in the areas with more traffic.

One of the consequences of these processes has been secondary contamination of sewage systems and sludge storage areas, which has necessitated special cleanup measures. Generally, radionuclides in soil have not been transferred to other urban areas but have migrated down into the soil column due to natural processes or due to mixing during the digging of gardens, kitchen gardens and parks.

3.2.3. Dynamics of the exposure rate in urban environments

Gamma radiation from radionuclides deposited in the urban environment has contributed to human external exposure. Compared with the dose rate in open fields (see Section 5.2.2), the dose rate within a settlement is significantly lower, because of photon absorption in building structures, especially those made of brick and concrete. The lowest dose rates have been observed inside buildings, and especially on the upper floors of multistorey buildings. Due to radioactive decay of the initial radionuclide mixture, wash-off from solid surfaces and soil migration, dose rates in air have been gradually decreasing with time in typical urban areas.

Another relevant parameter is the time dependence of the ratio of the dose rate in air at an urban location to that in an open field (the 'location factor') due to radionuclide migration processes. The dependence of urban location factors on time after the Chernobyl accident, as derived from measurements performed in the town of Novozybkov in the Russian Federation, is shown in Fig. 3.12 [3.24]. While for virgin sites such as parks or grassy plots the location factors are relatively constant, values for hard surfaces such as asphalt decrease considerably with time. Similar time dependences have been found in other countries [3.25, 3.26].

At present, in most of the settlements subjected to radioactive contamination after the Chernobyl accident, the air dose rate above solid

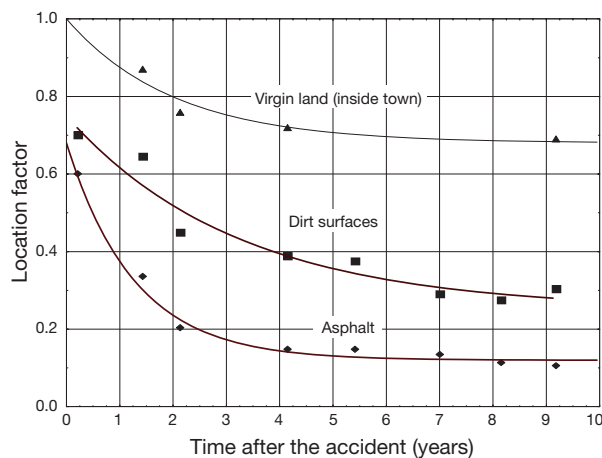


FIG. 3.12. Ratio of the radiation dose rate above different surfaces to that in open fields in the town of Novozybkov, Russian Federation, after the Chernobyl accident [3.24].

surfaces has returned to the pre-accident background level. Some elevated air dose rates can be measured, mainly in areas of undisturbed soil. The highest level of urban radioactive contamination is found in Pripyat, which is 3 km from the Chernobyl nuclear power plant; its inhabitants were resettled to non-contaminated areas within 1.5 days of the accident.

3.3. AGRICULTURAL ENVIRONMENT

3.3.1. Radionuclide transfer in the terrestrial environment

Radioactive elements behave differently in the environment; some, such as caesium, iodine and strontium, are environmentally mobile and transfer readily, under certain environmental conditions, to foodstuffs. In contrast, radionuclides with low solubility, such as the actinides, are relatively immobile and largely remain in the soil. The main routes for the cycling of radionuclides and the possible pathways to humans are shown in Fig. 3.13.

Many factors influence the extent to which radionuclides are transferred through terrestrial pathways. If transfer is high in a particular environment it is said to be radioecologically sensitive, because such transfer can lead to relatively high radiological exposure [3.28].

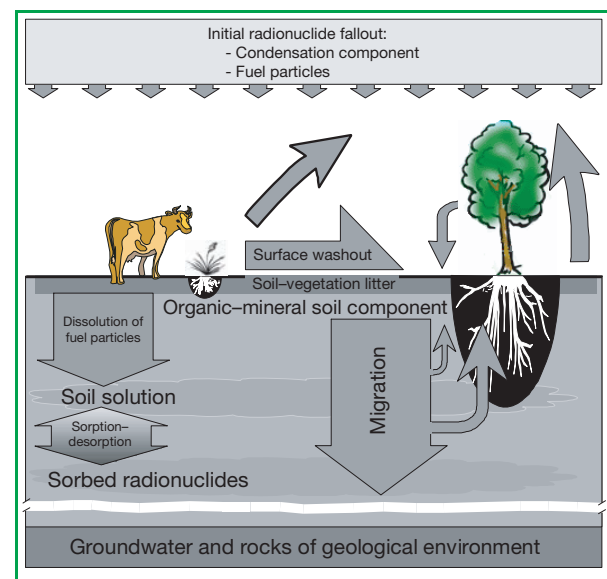


FIG. 3.13. Main transfer pathways of radionuclides in the terrestrial environment [3.27].

Of the radionuclides deposited after the Chernobyl accident, during the short initial phase (zero to two months) those of iodine were the most important with regard to human exposure via agricultural food chains. In the longer term, radio-caesium has been the most important (and, to a much lesser extent, radiostrontium).

Radioecological sensitivity to radiocaesium is generally higher in seminatural ecosystems than in agricultural ecosystems, sometimes by a few orders of magnitude [3.29]. This difference is caused by a number of factors, the more important being in some natural ecosystems the different physico-chemical behaviour in soils (lack of competition between caesium and potassium, resulting in higher transfer rates of radiocaesium in nutrient-poor ecosystems) and the presence of specific food chain pathways, leading to highly contaminated produce from seminatural ecosystems. Also, forest soils are fundamentally different from agricultural soils; they have a clear multilayered vertical structure characterized mainly by a clay-poor mineral layer, which supports a layer rich in organic matter. In contrast, agricultural soils generally contain less organic matter and higher amounts of clay.

3.3.2. Food production systems affected by the accident

The radioactive material released by the Chernobyl accident contaminated large areas of the terrestrial environment and had a major impact on both agricultural and natural ecosystems not only within the former USSR but also in many other countries in Europe.

In the former USSR countries, the food production system that existed at the time of the accident can be divided into two types: large collective farms and small private farms. Collective farms routinely apply land rotation combined with ploughing and fertilization to improve productivity. Traditional small private farms, in contrast, seldom apply artificial fertilizers and often use manure for improving yield. Typically they have one or, at most, a few cows, and produce milk mainly for private consumption. The grazing regime of private farms was initially limited to the utilization of marginal land not used by the collective farms, but nowadays includes some better quality pasture.

In western Europe, poor soils are used extensively for agriculture, mainly for grazing of ruminants (e.g. sheep, goats, reindeer and cattle). Such areas include alpine meadows and upland

regions in western and northern Europe that have organic soils.

3.3.3. Effects on agriculture in the early phase

At the time of the Chernobyl nuclear power plant accident, vegetation in the affected areas was at different stages of growth, depending on latitude and elevation. Initially, interception on plant leaves of dry deposition and atmospheric washout with precipitation were the main mechanisms by which vegetation became contaminated. In the medium and long term, root uptake predominated. The highest activity concentrations of radionuclides in most foodstuffs occurred in 1986.

In the initial phase, ^{131}I was the radionuclide of most concern and milk was the main contributor to internal dose. This is because radioiodine was released in large amounts and intercepted by plant surfaces that were then grazed by dairy cows. The ingested radioiodine was completely absorbed in the gut of the cow [3.31] and then rapidly transferred to the animal's thyroid and milk (within about one day). Thus peak values occurred rapidly after deposition in late April or early May 1986, depending on when deposition occurred in different countries. During this period, in the former USSR and some other European countries, ^{131}I activity concentrations in milk exceeded the national and regional (European Union (EU)) action levels of a few hundred to a few thousand becquerels per litre (see Section 4.1).

There are no time trend data available for ^{131}I activity concentrations in milk in the first few days after the accident in the heavily affected areas of the USSR, for the obvious and understandable reason that the authorities were dealing with other immediate accident response priorities. Nevertheless, data are available for the period starting two weeks after the accident from the Tula region of the Russian Federation, and the data in Fig. 3.14(a) show an exponential decline in ^{131}I activity concentration in milk normalized to ^{137}Cs deposition, which can be extrapolated back to the first days to estimate the initial ^{131}I activity concentration in milk. Furthermore, a direct comparison of ^{131}I activity in milk in early May with ^{137}Cs deposition shows the contribution of dry deposition to ^{131}I in milk, because the linear relationship line shown does not go through the zero deposition point (Fig. 3.14(b)). In the early spring in northern Europe, dairy cows and goats were not yet on pasture, therefore there was very little milk

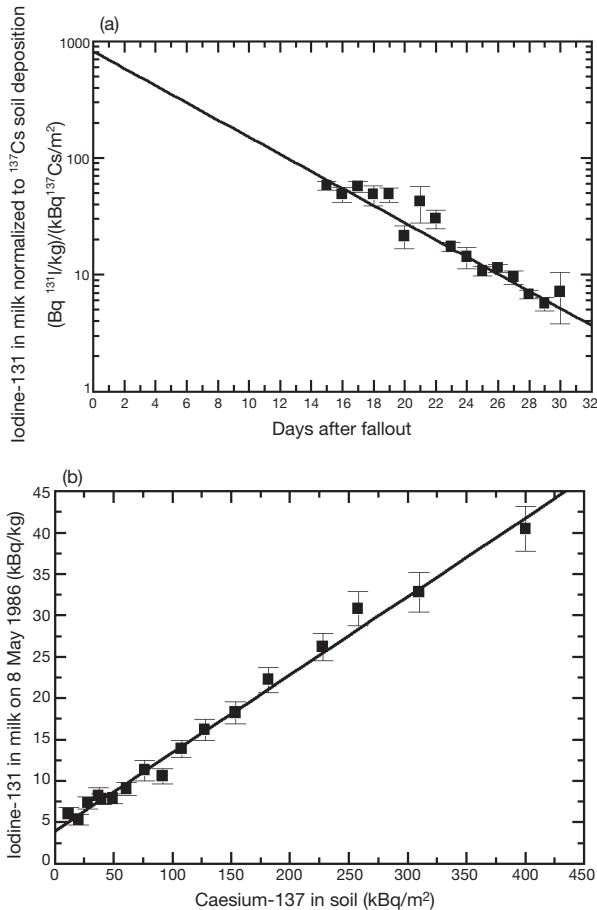


FIG. 3.14. Variation in ^{131}I activity concentration in milk in the Tula region of the Russian Federation (a) with time after deposition, standardized by ^{137}Cs soil deposition, and (b) with ^{137}Cs soil deposition (time corrected to 8 May 1986) [3.30].

contamination. In contrast, in the southern regions of the USSR, as well as in Germany, France and southern Europe, dairy animals were already grazing outdoors and some contamination of cow, goat and sheep milk occurred. The ^{131}I activity concentration in milk decreased with an effective half-life of four to five days [3.32], due to its short physical half-life and the reduction in iodine activity concentrations on plants due to atmospheric removal processes from leaf surfaces (Fig. 3.15). This removal occurred with a mean weathering half-life on grass of nine days for radioiodine and 11 days for radiocaesium [3.33]. Leafy vegetables were also contaminated on their surfaces and also made a contribution to the radiation dose to humans via the food chain (Fig. 3.15).

Both plants and animals were also contaminated with radiocaesium and, to a lesser extent, radiostrontium. From June 1986 radiocaesium was the dominant radionuclide in most environmental

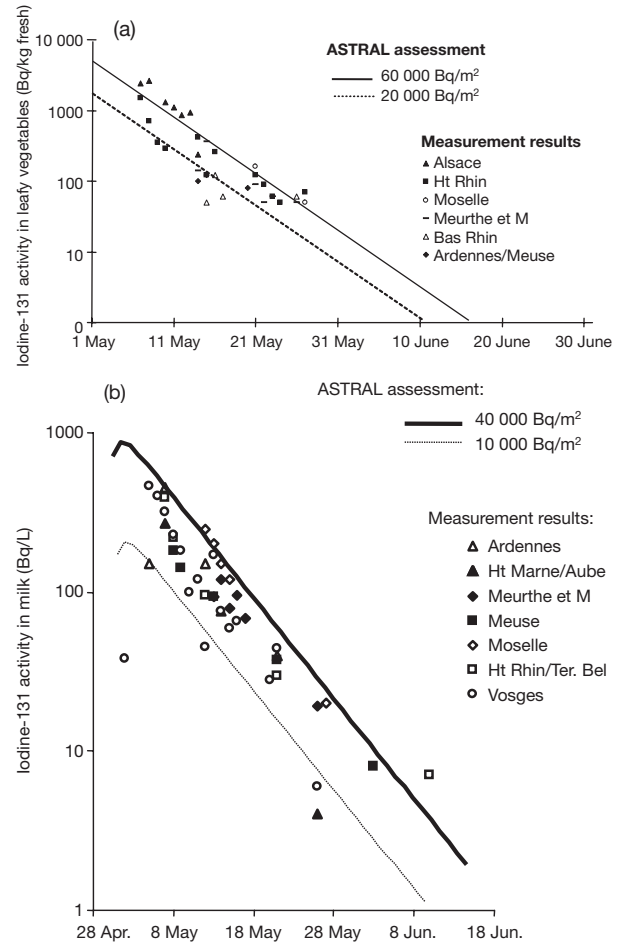


FIG. 3.15. Changes with time of ^{131}I activity concentrations in (a) leafy vegetables and (b) cow's milk in different regions of France, May–June 1986 [3.34].

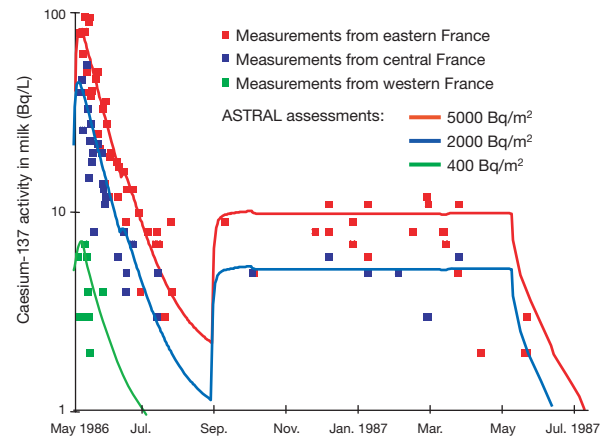


FIG. 3.16. Changes with time of ^{137}Cs activity concentrations in cow's milk in France in 1986–1987 as observed and simulated by the ASTRAL model [3.34].

samples (except in the CEZ) and in food products. As shown in Fig. 3.16, the contamination of milk with radiocaesium decreased during spring 1986 with an effective half-life of about two weeks, due to

weathering, biomass growth and other natural processes. However, radiocaesium activity concentrations increased again during winter 1986/1987, due to the feeding of cows with contaminated hay harvested in spring/summer 1986. This phenomenon was observed in the winter period in many countries after the accident.

The transfer to milk of many of the other radionuclides present in the terrestrial environment during the early phase of the accident was low. This was because of low inherent transfer in the gut of those elements, compounded by low bioavailability due to their association within the matrix of fuel particles [3.35]. Nevertheless, some high transfers occurred, notably that of ^{110m}Ag to the liver of ruminants [3.36].

3.3.4. Effects on agriculture in the long term

Since 1987, the radionuclide content of both plants and animals has been largely determined by the interaction between radionuclides and different soil components, as soil is the main reservoir of long lived radionuclides deposited on terrestrial ecosystems. This process controls radionuclide availability [3.37, 3.38] for uptake into plants and animals and also influences radionuclide migration down the soil column.

3.3.4.1. Physicochemistry of radionuclides in the soil-plant system

Plants take up nutrients and pollutants from the soil solution. The activity concentration of radionuclides in the soil solution is the result of physicochemical interactions with the soil matrix, of which competitive ion exchange is the dominant mechanism. The concentration and composition of the major and competitive elements present in the soil are thus of prime importance for determining the radionuclide distribution between the soil and the soil solution. Many data obtained after the Chernobyl accident demonstrate that the amount and nature of clay minerals present in soil are key factors in determining radioecological sensitivity with regard to radiocaesium. These features are crucially important for understanding radiocaesium behaviour, especially in areas distant from the Chernobyl nuclear power plant, where ^{137}Cs was initially deposited mainly in condensed, water soluble forms.

Close to the nuclear power plant, radionuclides were deposited in a matrix of fuel particles

that have slowly dissolved with time; this process is not complete today. The more significant factors influencing the fuel particle dissolution rate in soil are the acidity of the soil solution and the physicochemical properties of the particles (notably the degree of oxidation) (see Fig. 3.17). In a low pH of pH4, the time taken for 50% dissolution of particles was about one year, whereas for a higher pH of pH7 up to 14 years were needed [3.39–3.41]. Thus in acid soils most of the fuel particles have already dissolved. In neutral soils, the amount of mobile ^{90}Sr released from the fuel particles is now increasing, and this will continue over the next 10–20 years.

In addition to soil minerals, microorganisms can significantly influence the fate of radionuclides in soils [3.42, 3.43]. They can interact with minerals and organic matter and consequently affect the bioavailability of radionuclides. In the specific case of mycorrhizal fungi, soil microorganisms may even act as a carrier, transporting radionuclides from the soil solution to the associated plant.

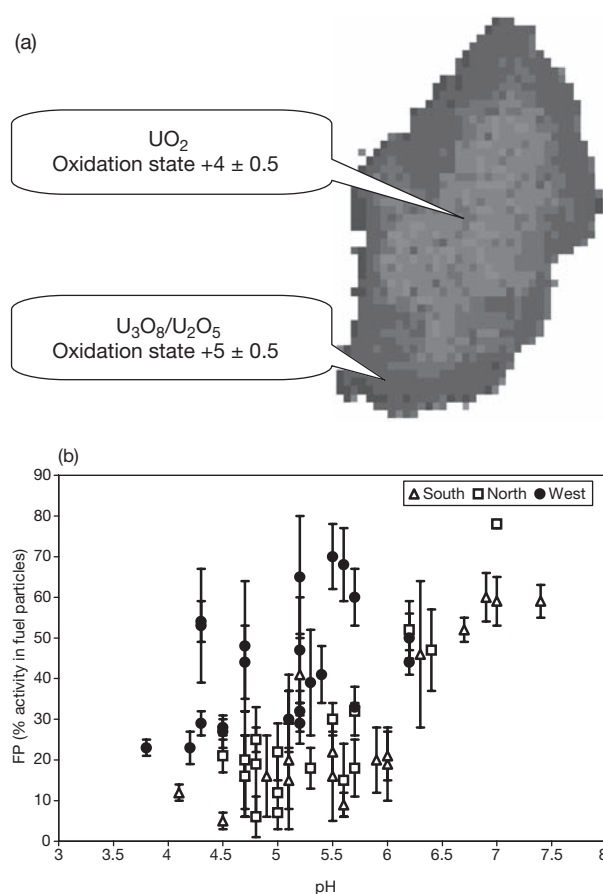


FIG. 3.17. (a) Variation in the oxidation within a Chernobyl fuel particle [3.40]; (b) fraction of ^{90}Sr present in fuel particles (FP) ten years after the Chernobyl accident as a function of soil acidity [3.39].

A traditional approach of characterizing the mobility and bioavailability of a radioactive contaminant in soil is by applying sequential extraction techniques. A number of experimental protocols have been developed that use a sequence of progressively aggressive chemicals, each of which is assumed to selectively leach a fraction of the contaminant bound to a specific soil constituent. An example of the results available from this procedure is presented in Fig. 3.18, which shows that a much higher proportion of radiocaesium was fixed in the soil than of radiostrontium. The selectivity and reproducibility of chemical extraction procedures varies and therefore often should be considered to give only qualitative estimates of bioavailability.

By use of sequential extraction techniques, the fraction of exchangeable ^{137}Cs was found to decrease by a factor of three to five within a decade after 1986 [3.44, 3.45]. This time trend, which resulted in a reduction of plant contamination, may be due to progressive fixation of radiocaesium in interlayer positions of clay minerals and to its slow diffusion and binding to the frayed edge sites of clay minerals. This process reduces the exchangeability

of radiocaesium so that is not then available to enter the soil solution from which plants take up most of the radiocaesium via the roots. For ^{90}Sr an increase with time of the exchangeable fraction has been observed, which is attributed to the leaching of the fuel particles [3.39].

3.3.4.2. Migration of radionuclides in soil

The vertical migration of radionuclides down the soil column can be caused by various transport mechanisms, including convection, dispersion, diffusion and biological mixing. Root uptake of radionuclides into plants is correlated with vertical migration. Typically, the rate of movement of radionuclides varies with soil type and physicochemical form. As an example, Fig. 3.19 shows the change with time of the depth distributions of ^{90}Sr and ^{137}Cs measured in the Gomel region of Belarus. Although there has been a significant downward migration of both radionuclides, much of the radionuclide activity has remained within the rooting zone of plants. At such sites, where contamination occurred through atmospheric deposition, there is a low risk of radionuclide migration to groundwater.

The rate of downward migration in different types of soil varies for radiocaesium and radiostrontium. Low rates of ^{90}Sr vertical migration are observed in peat soils, whereas ^{137}Cs migrates at the highest rate in these (highly organic) soils, but moves much more slowly in soddy podzolic sandy soils. In dry meadows, the migration of ^{137}Cs below the root-containing zone (0–10 cm) was hardly detectable in the ten years after the fallout deposition. Thus the contribution of vertical migration to the decrease of ^{137}Cs activity concentrations in the root-containing zone of mineral soils

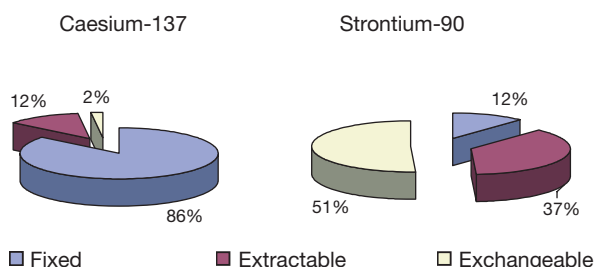


FIG. 3.18. Forms of radionuclides in soddy podzolic loam sand soil of the Gomel region of Belarus in 1998 [3.46].

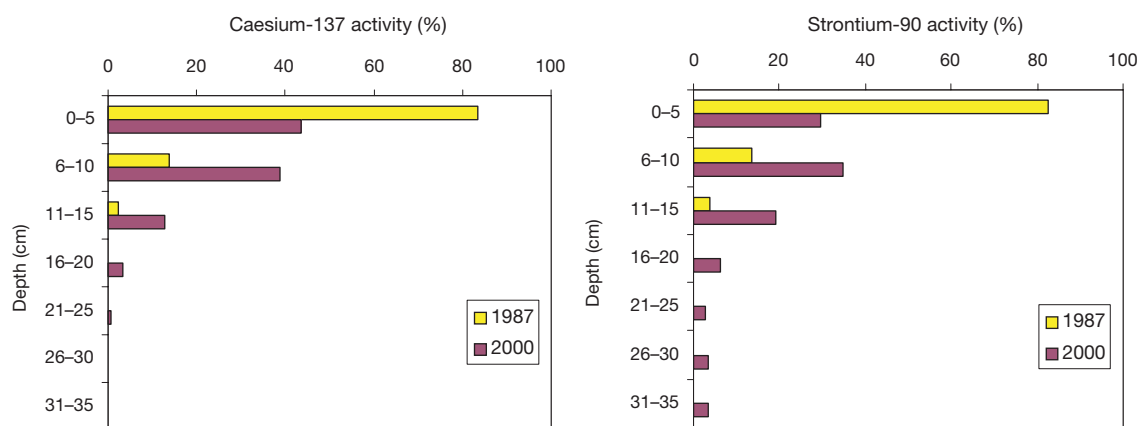


FIG. 3.19. Depth distributions of ^{137}Cs and ^{90}Sr measured in 1987 and 2000 in a soddy gley sandy soil (in per cent of total activity) in the Gomel region of Belarus [3.46].

is negligible. In contrast, in wet meadows and in peatland, downward migration can be an important factor in reducing the availability of ^{137}Cs for plants [3.48].

The higher rates of ^{90}Sr vertical migration are observed in low humified sandy soil (Fig. 3.20), soddy podzolic sandy soil and sandy loam soil with an organic content of less than 1% [3.27]. Generally, the highest rate of ^{90}Sr vertical migration occurs where there are completely non-equilibrium soil conditions. This occurs in the floodplains of rivers, where the soil is not structurally formed (light humified sands), in arable lands in a non-equilibrium state and in soils in which the organic layers have been removed, for example at sites of forest fires and sites with deposited sand with a low content of organic matter (<1%). In such conditions there is a high rate of radiostrontium vertical migration to groundwater with convective moisture flow, and high activity levels can occur in localized soil zones. Thus the spatial distribution of ^{90}Sr can be particularly heterogeneous in soils in which there have been changes in sorption properties.

Agricultural practices have a major impact on radionuclide behaviour. Depending on the type of

soil tillage and on the tools used, a mechanical redistribution of radionuclides in the soil may occur. In arable soils, radionuclides are distributed fairly uniformly down the whole depth of the tilled layer.

The lateral redistribution of radionuclides in catchments, which can be caused by both water and wind erosion, is significantly less than their vertical migration into the soil and the underlying geological layers [3.27]. The type and density of plant cover may significantly affect erosion rates. Depending on the intensity of erosive processes, the content of radionuclides in the arable layer on flat land with small slopes may vary by up to 75% [3.49].

3.3.4.3. Radionuclide transfer from soil to crops

The uptake of radionuclides, as well as of other trace elements, by plant roots is a competitive process [3.50]. For radiocaesium and radiostrontium the main competing elements are potassium and calcium, respectively. The major processes influencing radionuclide transport processes within the rooting zone are schematically represented in Fig. 3.21, although the relative importance of each component varies with the radionuclide and soil type.

The fraction of deposited radionuclides taken up by plant roots differs by orders of magnitude, depending primarily on soil type. For radiocaesium and radiostrontium, the radioecological sensitivity of soils can be broadly divided into the categories listed in Table 3.5. For all soils and plant species, the root uptake of plutonium is negligible compared with the direct contamination of leaves via rain splash or resuspension.

Transfer from soil to plants is commonly quantified using either the transfer factor (TF,

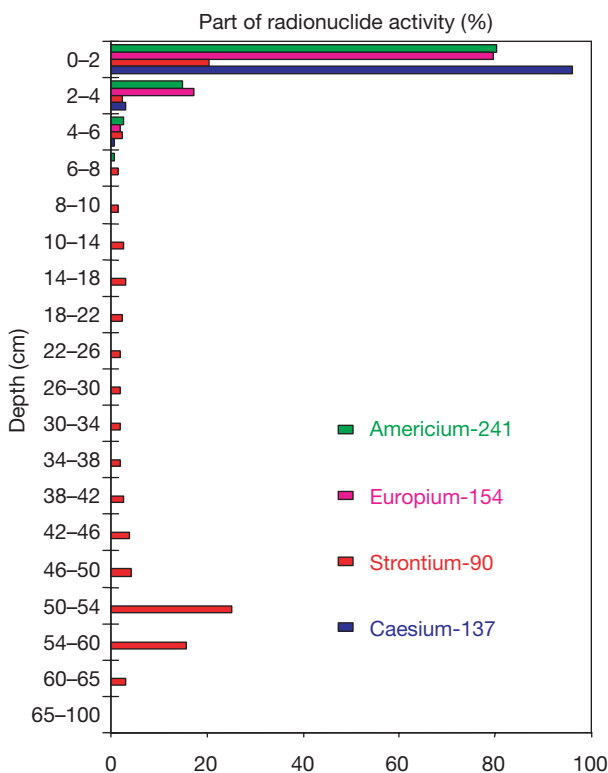


FIG. 3.20. Depth distributions of radionuclides in low humified sandy soil (in per cent of total activity) measured in 1996 [3.47].

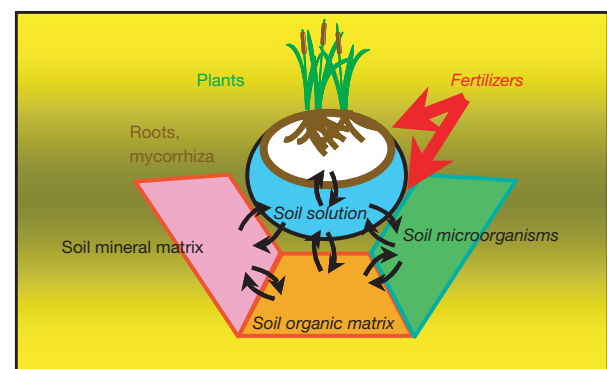


FIG. 3.21. Radionuclide pathways from soil to plants with consideration of biotic and abiotic processes [3.43].

dimensionless, equal to plant activity concentration, Bq/kg, divided by soil activity concentration, Bq/kg) or the aggregated transfer coefficient (T_{ag} , m²/kg, equal to plant activity concentration, Bq/kg, divided by activity deposition on soil, Bq/m²).

The highest ¹³⁷Cs uptake by roots from soil to plants occurs in peaty, boggy soils, and is one to two orders of magnitude higher than in sandy soils; this uptake often exceeds that of plants grown on fertile agricultural soils by more than three orders of magnitude. The high radiocaesium uptake from peaty soils became important after the Chernobyl accident because in many European countries such soils are vegetated by natural unmanaged grassland used for the grazing of ruminants and the production of hay.

The amount of radiocaesium in agricultural products in the medium to long term depends not only on the density of contamination but also on the soil type, moisture regime, texture, agrochemical properties and plant species. Agricultural activity often reduces the transfer of radionuclides from soil to plants by physical dilution (e.g. ploughing) or by adding competitive elements (e.g. fertilizing). There are also differences in radionuclide uptake between plant species. Although among species variations in uptake may exceed one or more orders of

magnitude for radiocaesium, the impact of differing radioecological sensitivities of soils is often more important in explaining the spatial variation in transfer in agricultural systems.

The influence of other factors that have been reported to influence plant root uptake of radionuclides (e.g. soil moisture) is less clear or may be explained by the basic mechanisms discussed above; for example, the accumulation of radiocaesium in crops and pastures is related to soil texture. In sandy soils the uptake of radiocaesium by plants is approximately twice as high as in loam soils, but this effect is mainly due to the lower concentrations of its main competing element, potassium, in sand.

The main process controlling the root uptake of radiocaesium into plants is the interaction between the soil matrix and solution, which depends primarily on the cation exchange capacity of the soil. For mineral soils this is influenced by the concentrations and types of clay minerals and the concentrations of competitive major cations, especially potassium and ammonium. Examples of these relationships are shown in Fig. 3.22 for both radiocaesium and radiostrontium. The modelling of soil solution physicochemistry, which takes account of these major factors, enables prediction of the root uptake of both radionuclides [3.51, 3.52].

TABLE 3.5. CLASSIFICATION OF RADIOECOLOGICAL SENSITIVITY FOR SOIL-PLANT TRANSFER OF RADIOCAESIUM AND RADIOSTRONTIUM

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

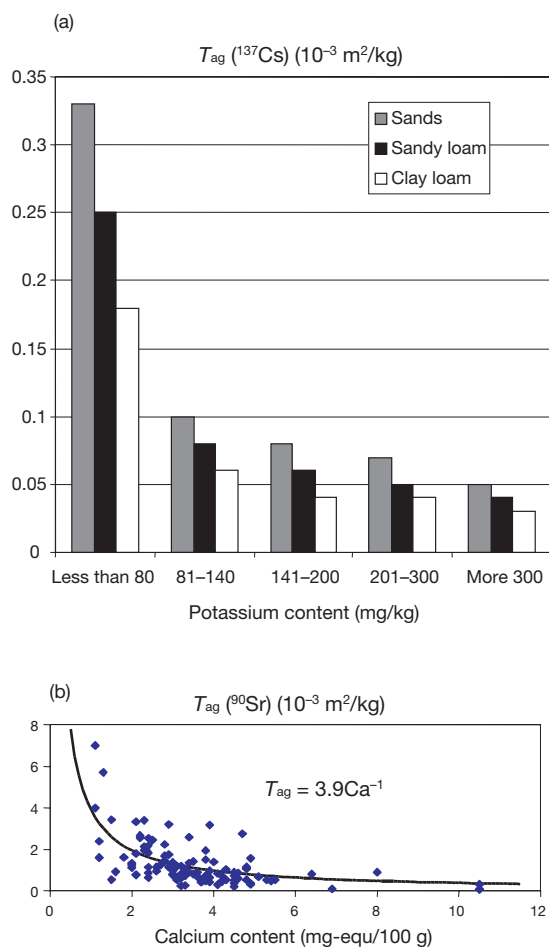


FIG. 3.22. (a) Transfer of ^{137}Cs into oat grain in soddy podzolic soils of various textures with varying potassium contents [3.61] and (b) transfer of ^{90}Sr into seeds of winter rye with varying concentrations of exchangeable calcium in different soils [3.53].

Thus differences in radioecological sensitivities of soils explain why in some areas of low deposition high concentrations of radiocaesium are found in plants and mushrooms harvested from seminatural ecosystems and, conversely, why areas of high deposition can show only low to moderate concentrations of radiocaesium in plants. This is illustrated in Fig. 3.23, in which the variability in activity concentrations of radiocaesium and radiostrontium in plants is shown for a normalized concentration in soil.

3.3.4.4. Dynamics of radionuclide transfer to crops

In 1986 the ^{137}Cs content in plants, which was at its maximum in that year, was primarily determined by aerial contamination. During the first post-accident year (1987), the ^{137}Cs content in

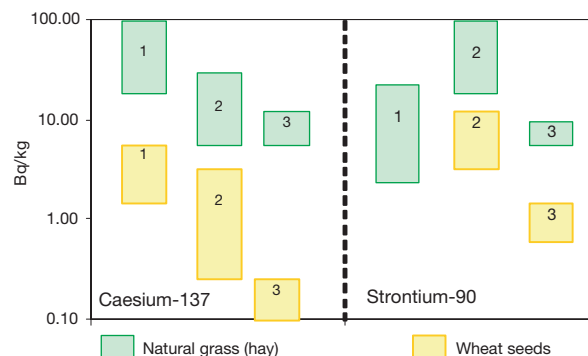


FIG. 3.23. Variation in the concentrations of ^{137}Cs and ^{90}Sr in two plant species with soil type; the data refer to a soil deposition of 1 kBq/m^2 [3.54]. 1: peat soil; 2: soddy podzolic soil; 3: chernozem soil.

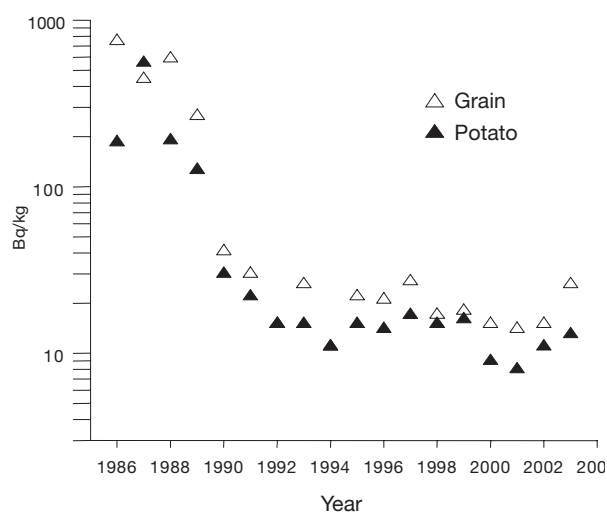


FIG. 3.24. Changes with time of ^{137}Cs concentrations in grain and potato produced in contaminated districts of the Bryansk region of the Russian Federation (Bq/kg) [3.55].

plants dropped by a factor of three to one hundred (depending on soil type) as roots became the dominant contamination route.

For meadow plants in the first years after deposition, ^{137}Cs behaviour was considerably influenced by the radionuclide distribution between soil and mat. In this period, ^{137}Cs uptake from mat significantly exceeded (up to eight times) that from soil. Further, as a result of mat decomposition and radionuclide transfer to soil, the contribution of mat decreased rapidly, and in the fifth year after the deposition it did not exceed 6% for automorphous soils and 11% for hydromorphous soils [3.41].

In most soils the transfer rate of ^{137}Cs to plants has continued to decrease since 1987, although the rate of decrease has slowed, as can be seen from Fig. 3.24 [3.55]. A decrease with time similar to that shown in Fig. 3.24 has been observed in many

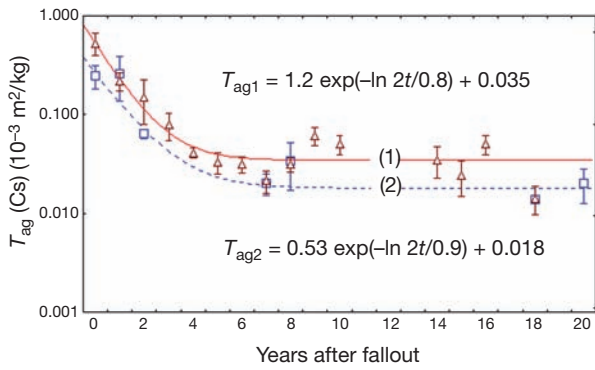


FIG. 3.25. Dynamics of the ^{137}Cs T_{ag} for cereals. 1: sandy and sandy loam soil, Bryansk region, Russian Federation; 2: chernozem soil, Tula and Orel regions, Russian Federation [3.56].

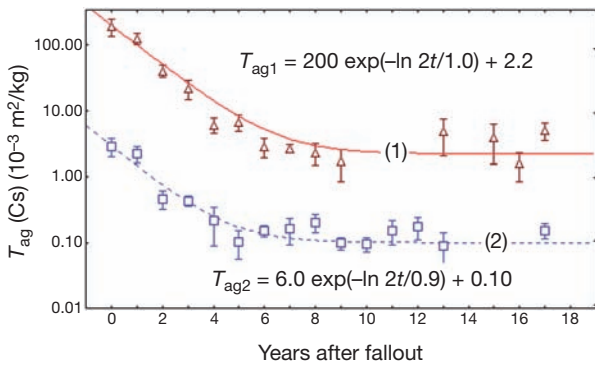


FIG. 3.26. Dynamics of the ^{137}Cs T_{ag} (dry weight) for natural grasses. 1: sandy and sandy loam soil, Bryansk region, Russian Federation; 2: chernozem soil, Tula and Orel regions, Russian Federation [3.56].

studies of plant root uptake in different crops, as can be seen in Figs 3.25 and 3.26 for cereals and natural grasses, respectively, growing in two different soil types [3.56]. Two experimental points for chernozem soil (18 and 20 years) were obtained from the measurements made in 1980–1985 (i.e. after ^{137}Cs global fallout and before the Chernobyl accident) (Fig. 3.25). Values of ^{137}Cs TFs for cereals as well as for potato and cow's milk obtained about 20 years following global fallout do not differ significantly from those observed eight to nine years and later after the Chernobyl fallout in remote areas with dominant sandy, sandy loam and chernozem soils [3.56, 3.57]. The difference between T_{ag} values relevant to cereals grown on fertilized soil is much lower than the difference for natural grasses.

For the transfer of radiocaesium from soil to plants, a decrease with time is likely to reflect: (a) physical radionuclide decay; (b) the downward

migration of the radionuclide out of the rooting zone; and (c) physicochemical interactions with the soil matrix that result in decreasing bioavailability. In many soils, the ecological half-lives of the plant root uptake of radiocaesium can be characterized by two components: (a) a relatively fast decrease, with a half-life between 0.7 and 1.8 years, dominating for the first four to six years, leading to a reduction of concentration in plants by about an order of magnitude compared with 1987; and (b) a slower decrease with a half-life of between seven and 60 years [3.45, 3.55, 3.57, 3.58]. The dynamics of the decrease of ^{137}Cs availability in the soil–plant system are considerably influenced by soil properties, and as a result the rates of decreasing ^{137}Cs uptake by plants can differ by a factor of three to five [3.41].

Some caution should be exercised, however, in generalizing these observations, because some data indicate almost no decrease in the root uptake of radiocaesium with time beyond the first four to six years, which suggests that there is no reduction in bioavailability in soil within the time period of observation. Furthermore, the prediction of ecological half-lives that exceed the period of observation can be highly uncertain. The application of countermeasures aimed at reducing the concentration of radiocaesium in plants will also modify the ecological half-life.

Compared with radiocaesium, the uptake of ^{90}Sr by plants has usually not shown such a marked decrease with time. In the areas close to the Chernobyl nuclear power plant, the gradual dissolution of fuel particles has enhanced the bioavailability of ^{90}Sr , and therefore there has been an increase with time in ^{90}Sr uptake by plants (Fig. 3.27 [3.39]).

In remote areas, where strontium radionuclides were predominantly deposited in condensed form and in lesser amounts as fine dispersed fuel particles, the dynamics of long term transfer of ^{90}Sr to plants were similar to those of radiocaesium, but with different ecological half-lives for plant root uptake. This difference is associated with various mechanisms of soil transfer for these two elements. The fixation of strontium by soil components depends less on the clay content of the soil than that of caesium (see Table 3.5). More generally, the values of ^{90}Sr transfer parameters from soil to plants depend less on the soil properties than the transfer parameters for radiocaesium [3.37]. An example of the time dependence of ^{90}Sr uptake by plants is given in Fig. 3.28 [3.56].

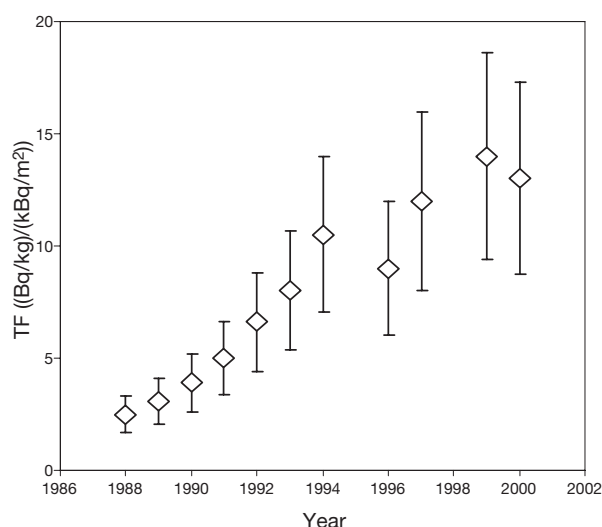


FIG. 3.27. Dynamics of the ^{90}Sr TF into natural grass from soddy podzolic soil in the CEZ [3.39].

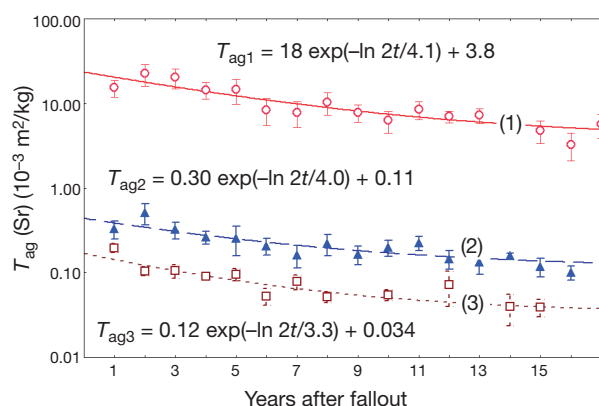


FIG. 3.28. Dynamics of the ^{90}Sr aggregated TF for natural grasses (1: sandy and sandy loam soil, Bryansk region, Russian Federation) and cow's milk (2: sandy and sandy loam soil, Bryansk region, Russian Federation; 3: chernozem soil, Tula and Orel regions, Russian Federation) [3.56].

3.3.4.5. Radionuclide transfer to animals

Animals take up radionuclides through contaminated forage and direct soil ingestion. Milk and meat were major contributors to the internal radiation dose to humans after the Chernobyl accident, both in the short term, due to ^{131}I , and in the long term, due to radiocaesium. In intensively managed agricultural ecosystems, high levels of contamination of animal food products can be expected only for a few weeks, or at most a few months, after a pulse of fallout. In these circumstances the extent of interception and retention on plant surfaces largely determines both the duration

and the level of contamination of animal derived food products. An exception is found where very high deposition occurs or where plant uptake is high and sustained, both of which occurred in some areas after the Chernobyl accident.

The levels of radiocaesium in animal food products can be high and persist for a long time, even though the original deposition may not have been very high. This is because: (a) soils often allow significant uptake of radiocaesium; (b) some plant species accumulate relatively high levels of radiocaesium, for example ericaceous species and fungi; and (c) areas with poor soils are often grazed by small ruminants, which accumulate higher caesium activity concentrations than larger ruminants [3.35].

The contamination of animal products by radionuclides depends on their behaviour in the plant-soil system, the absorption rate and metabolic pathways in the animal and the rate of loss from the animal (principally in urine, faeces and milk). Although absorption can occur through the skin and lungs, oral ingestion of radionuclides in feed, and subsequent absorption through the gut, is the major route of uptake of most radionuclides. Absorption of most nutrients takes place in the rumen or the small intestine at rates that vary from almost negligible, in the case of actinides, to 100% for radioiodine, and varying from 60% to 100% for radiocaesium, depending on the form [3.31].

After absorption, radionuclides circulate in the blood. Some accumulate in specific organs; for example, radioiodine accumulates in the thyroid, and many metal ions, including ^{144}Ce , ^{106}Ru and $^{110\text{m}}\text{Ag}$, accumulate in the liver. Actinides and especially radiostrontium tend to be deposited in the bone, whereas radiocaesium is distributed throughout the soft tissues [3.36, 3.37, 3.50, 3.59, 3.60].

The transfer of radionuclides to animal products is often described by transfer coefficients defined as the equilibrium ratio between the radionuclide activity concentration in milk, meat or eggs divided by the daily dietary radionuclide intake. Transfer coefficients for radioiodine and radiocaesium to milk, and for radiocaesium to meat, are generally lower for large animals such as cattle than for small animals such as sheep, goats and chickens. The transfer of radiocaesium to meat is higher than that to milk.

The long term time trend of radiocaesium contamination levels in meat and milk, an example of which is displayed in Fig. 3.29, follows that for

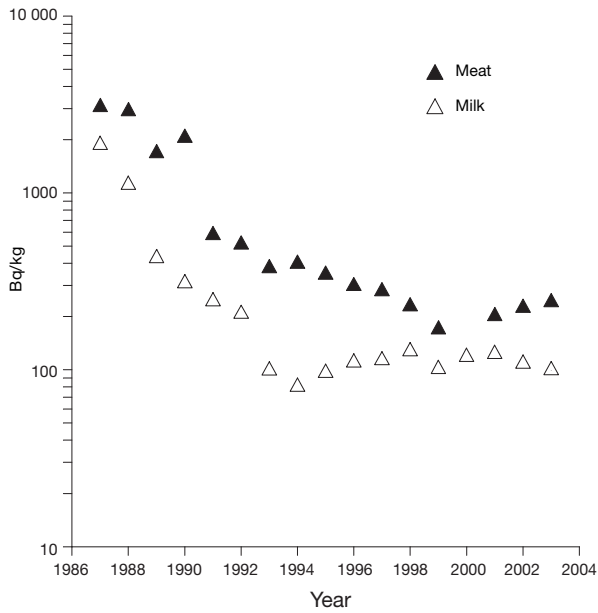


FIG. 3.29. Changes with time in mean ^{137}Cs activity concentrations in meat and milk produced in contaminated districts of the Bryansk region of the Russian Federation (Bq/kg) [3.55].

vegetation and can be divided into two phases [3.55, 3.57, 3.58]. For the first four to six years after the deposition of the radiocaesium there was an initial fast decrease with an ecological half-life of between 0.8 and 1.2 years. For later times, only a small decrease has been observed [3.55, 3.56].

There are differing rates of ^{137}Cs transfer to milk in areas with different soil types, as demonstrated over nearly two decades after the accident (Fig. 3.30) in milk from the Bryansk, Tula and Orel regions of the Russian Federation, where few countermeasures have been used. The transfer of ^{137}Cs to milk is illustrated using the T_{ag} , which normalizes the data for different levels of soil contamination; this makes comparison among soil types easier. The transfer to milk declines in the order peat bog > sandy and sandy loam > chernozem and grey forest soils. Both the dynamics of ^{137}Cs activity concentration in milk and its dependence on soil type are similar to those in natural grasses (see Fig. 3.26) sampled in areas where cattle graze.

Similar long term data are available for comparing the transfer of ^{137}Cs to beef in the Russian Federation for different soil types. They also show higher transfer in areas with sandy/sandy loam soils compared with chernozem soils (Fig. 3.31); there has been little decline in ^{137}Cs transfer over the past decade.

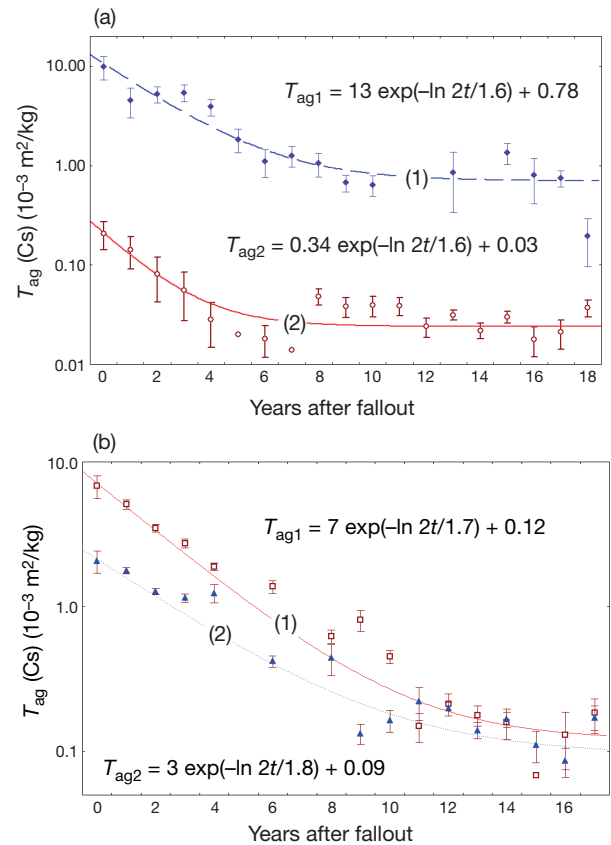


FIG. 3.30. (a) Dynamics of the ^{137}Cs aggregated TF for cow's milk. 1: peat bog soil, Bryansk region, Russian Federation; 2: chernozem soil, Tula and Orel regions, Russian Federation [3.56]. (b) Dynamics of ^{137}Cs aggregated TF for cow's milk (sandy and sandy loam soil, Bryansk region, Russian Federation). 1: ^{137}Cs soil deposition <370 kBq/m²; 2: ^{137}Cs soil deposition >370 kBq/m² [3.56].

The long term dynamics of ^{90}Sr in cow's milk sampled in Russian areas with dominant soddy podzolic and chernozem soils (see Fig. 3.28) are different from those of ^{137}Cs . The graphs for ^{90}Sr in milk do not contain the initial decreasing portion with an ecological half-life of about one year, as shown in the graphs for ^{137}Cs , which are presumed to reflect fixation of caesium in the soil matrix. In contrast, the ^{90}Sr activity concentration in cow's milk gradually decreases with an ecological half-life of three to four years; the second component (if any) has not yet been identified. The physical and chemical processes responsible for these time dynamics obviously include diffusion and convection with vertical transfer of ^{90}Sr into soil, as well as its radioactive decay. However, the chemical interactions with the soil components may differ significantly from those known for caesium.

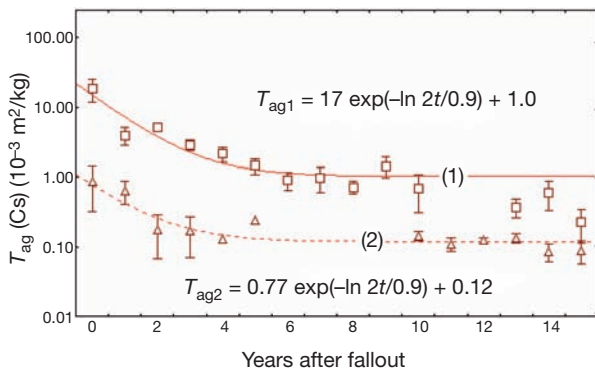


FIG. 3.31. Dynamics of ^{137}Cs aggregated TF for beef. 1: sandy and sandy loam soil; 2: chernozem soil [3.56].

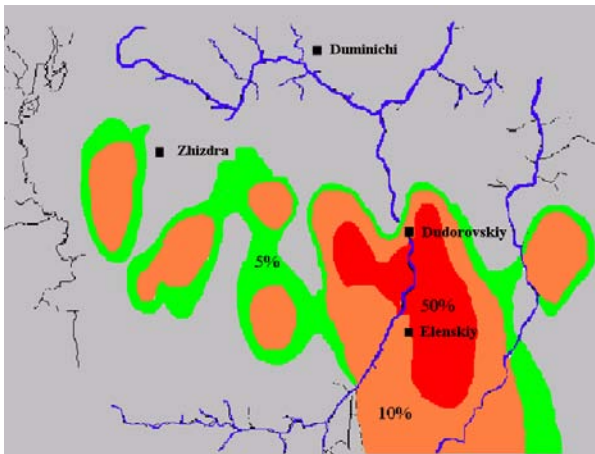


FIG. 3.32. Isolines of different levels of probability of exceeding 100 Bq/L of ^{137}Cs in milk (for 1991) in the Kaluga region, Russian Federation [3.54]. The red colour indicates a high probability, the pink and green colours indicate medium and low probabilities, respectively.

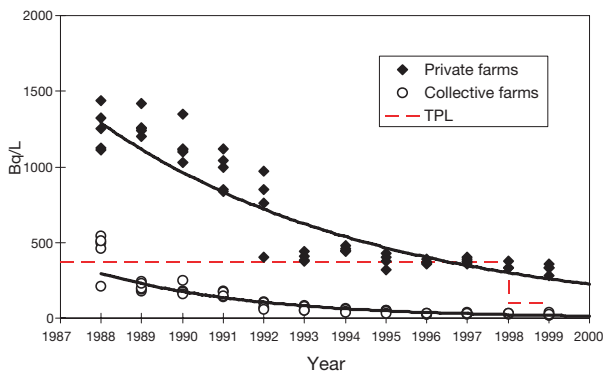


FIG. 3.33. Typical dynamics of ^{137}Cs activity concentrations in milk produced on private and collective farms in the Rovno region of Ukraine with a comparison with the temporary permissible level (TPL) [3.62].

By combining information on radionuclide transfer with spatially varying information in geographic information systems, it is possible to identify zones in which a specified average activity concentration in milk is likely to be exceeded. An example is shown in Fig. 3.32.

A significant amount of production in the former USSR is confined to the grazing of privately owned cows on poor, unimproved meadows. Owing to the poor productivity of these areas, radiocaesium uptake is relatively high compared with that on land used by collective farms. As an example of the difference between farming systems, changes in ^{137}Cs activity concentrations in milk from private and collective farms in the Rovno region of Ukraine are shown in Fig. 3.33. The activity concentrations in milk from private farms exceeded the action levels until 1991, when countermeasures were implemented that resulted in a radical improvement.

3.3.5. Current contamination of foodstuffs and expected future trends

Table 3.6 shows summarized data of measured current (2000–2003) activity concentrations of radiocaesium in grain, potato, milk and meat produced in highly and less highly contaminated areas covering many different types of soil with widely differing radioecological sensitivities in Belarus, the Russian Federation and Ukraine. Caesium-137 activity concentrations are consistently higher in animal products than in plant products.

Currently, due to natural processes and agricultural countermeasures, radiocaesium activity concentrations in agricultural food products produced in areas affected by the Chernobyl fallout are generally below national, regional (EU) and international action levels [3.64, 3.65]. However, in some limited areas with high radionuclide contamination (parts of the Gomel and Mogilev regions in Belarus and the Bryansk region in the Russian Federation) or poor organic soils (the Zhytomyr and Rovno regions in Ukraine), radiocaesium activity concentrations in food products, especially milk, still exceed the national action levels of about 100 Bq/kg. In these areas remediation may still be warranted (see Section 4).

Contaminated milk from privately owned cows with ^{137}Cs activity concentrations exceeding 100 Bq/L (the current permissible level for milk) was being produced in more than 400, 200 and 100 Ukrainian, Belarusian and Russian settlements,

respectively, 15 years after the accident. Levels of milk contamination higher than 500 Bq/L occur in six Ukrainian, five Belarusian and five Russian settlements (in 2001).

The concentrations and transfer coefficients shown in the above mentioned figures and tables show that there has been only a slow decrease in radiocaesium activity concentrations in most plant and animal foodstuffs during the past decade. This indicates that radionuclides must be close to equilibrium within the agricultural ecosystems, although continued reductions with time are expected, due to continuing radionuclide migration down the soil profile and to radioactive decay (even if there was an equilibrium established between ^{137}Cs in the labile and non-labile pools of soil). Given the slow current rates of decline, and the difficulties in quantifying long term effective half-lives from currently available data because of high uncertainties, it is not possible to conclude that there will be any further substantial decrease over the next decades, except due to the radioactive decay of both ^{137}Cs and ^{90}Sr , which have half-lives of about 30 years.

Radionuclide activity concentrations in foodstuffs can increase through fuel particle disso-

lution, changes in the water table as a consequence of change of management of currently abandoned land or cessation of the application of counter-measures.

3.4. FOREST ENVIRONMENT

3.4.1. Radionuclides in European forests

Forest ecosystems were one of the major seminatural ecosystems contaminated as a result of fallout from the Chernobyl plume. The primary concern from a radiological perspective is the long term contamination of the forest environment and its products with ^{137}Cs , owing to its 30 year half-life. In the years immediately following contamination, the shorter lived ^{134}Cs isotope was also significant. In forests, other radionuclides such as ^{90}Sr and the plutonium isotopes are of limited significance for humans, except in relatively small areas in and around the CEZ. As a result, most of the available environmental data concern ^{137}Cs behaviour and the associated radiation doses.

Forests provide economic, nutritional and recreational resources in many countries.

TABLE 3.6. MEAN AND RANGE OF CURRENT CAESIUM-137 ACTIVITY CONCENTRATIONS IN AGRICULTURAL PRODUCTS ACROSS CONTAMINATED AREAS OF BELARUS [3.49], THE RUSSIAN FEDERATION [3.55] AND UKRAINE [3.63]
(data are in Bq/kg fresh weight for grain, potato and meat and in Bq/L for milk)

Caesium-137 soil deposition range	Grain	Potato	Milk	Meat
<i>Belarus</i>				
>185 kBq/m ² (contaminated districts of the Gomel region)	30 (8–80)	10 (6–20)	80 (40–220)	220 (80–550)
37–185 kBq/m ² (contaminated districts of the Mogilev region)	10 (4–30)	6 (3–12)	30 (10–110)	100 (40–300)
<i>Russian Federation</i>				
>185 kBq/m ² (contaminated districts of the Bryansk region)	26 (11–45)	13 (9–19)	110 (70–150)	240 (110–300)
37–185 kBq/m ² (contaminated districts of the Kaluga, Tula and Orel regions)	12 (8–19)	9 (5–14)	20 (4–40)	42 (12–78)
<i>Ukraine</i>				
>185 kBq/m ² (contaminated districts of the Zhytomyr and Rovno regions)	32 (12–75)	14 (10–28)	160 (45–350)	400 (100–700)
37–185 kBq/m ² (contaminated districts of the Zhytomyr and Rovno regions)	14 (9–24)	8 (4–18)	90 (15–240)	200 (40–500)

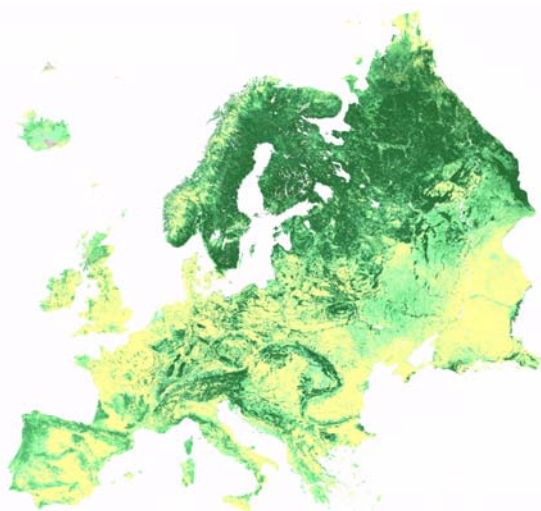


FIG. 3.34. Forest map of Europe. The darkest colour, green, indicates a proportion of 88% forest in the area, while yellow indicates less than 10% [3.69].

Figure 3.34 shows the wide distribution of forests across the European continent. Following the Chernobyl accident, substantial radioactive contamination of forests occurred in Belarus, the Russian Federation and Ukraine, and in countries beyond the borders of the former USSR, notably Finland, Sweden and Austria (see Fig. 3.5). The degree of forest contamination with ^{137}Cs in these countries ranged from $>10 \text{ MBq/m}^2$ in some locations to between 10 and 50 kBq/m^2 , the latter range being typical of ^{137}Cs deposition in several countries of western Europe.

Since the Chernobyl accident it has become apparent that the natural decontamination of forests is proceeding extremely slowly. The net export of ^{137}Cs from forest ecosystems was less than $1\%/a$ [3.66, 3.67], so it is likely that, without artificial intervention, it is the physical decay rate of ^{137}Cs that will largely influence the duration over which forests continue to be affected by the Chernobyl fallout. Despite the fact that the absolute natural losses of ^{137}Cs from forests are small, recycling of radiocaesium within forests is a dynamic process in which reciprocal transfers occur on a seasonal, or longer term, basis between biotic and abiotic components of the ecosystem. To facilitate appropriate long term management of forests, a reliable understanding of these exchange processes is required. Much information on such processes has been obtained from experiments and field measurements, and many of these data have been used to develop predictive mathematical models [3.68].

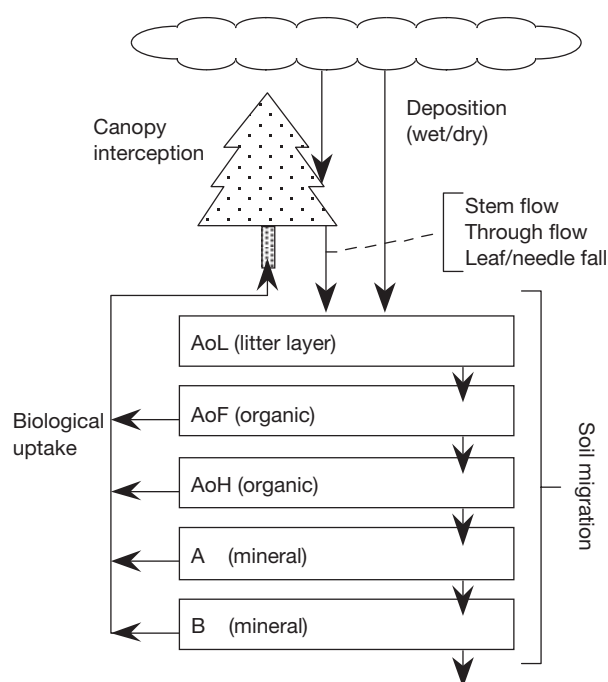


FIG. 3.35. Major storages and fluxes in radionuclides of contaminated forest ecosystems [3.70].

3.4.2. Dynamics of contamination during the early phase

Forests in the USSR located along the trajectory of the first radioactive plume were contaminated primarily as a result of dry deposition, while further away, in countries such as Austria and Sweden, wet deposition occurred and resulted in significant hot spots of contamination. Other areas in the USSR, such as the Mogilev region in Belarus and Bryansk and some other regions in the Russian Federation, were also contaminated by deposition with rain.

Tree canopies, particularly at forest edges, are efficient filters of atmospheric pollutants of all kinds. The primary mechanism of tree contamination after the Chernobyl accident was direct interception of radiocaesium by the tree canopy, which intercepted between 60% and 90% of the initial deposition [3.66]. Within a 7 km radius of the reactor this led to very high levels of contamination on the canopies of pine trees, which, as a consequence, received lethal doses of radiation from the complex mixture of short and long lived radionuclides released in the accident. Gamma dose rates in the days and weeks immediately following the accident were in excess of 5 mGy/h in the area close

to the reactor. The calculated absorbed gamma dose amounted to 80–100 Gy in the needles of pine trees. This small area of forest became known as the Red Forest, as the trees died and became a reddish brown colour, which was the most readily observable effect of radiation damage on organisms in the area (see Section 6).

The contamination of tree canopies was reduced rapidly over a period of weeks to months due to wash-off by rainwater and the natural process of leaf/needle fall (Fig. 3.35). Absorption of radiocaesium by leaf surfaces also occurred, although this was difficult to measure directly. By the end of the summer of 1986, approximately 15% of the initial radiocaesium burden in the tree canopies remained, and by the summer of 1987 this had been further reduced to approximately 5%. Within this roughly one year period, therefore, the bulk of radiocaesium was transferred from the tree canopy to the underlying soil.

During the summer of 1986 radiocaesium contamination of forest products such as mushrooms and berries increased, which led to increased contamination of forest animals such as deer and moose. In Sweden activity concentrations of ^{137}Cs in moose exceeded 2 kBq/kg fresh weight, while those in roe deer were even higher [3.71].

3.4.3. Long term dynamics of radiocaesium in forests

Within approximately one year after the initial deposition, the soil became the major repository of radiocaesium contamination within forests. Subsequently, trees and understorey plants became contaminated due to root uptake, which has continued as radiocaesium has migrated into the soil profile. Just as for potassium, the nutrient analogue rate of radiocaesium cycling within forests is rapid and a quasi-equilibrium is reached a few years after atmospheric fallout [3.72]. The upper, organic rich, soil layers act as a long term sink but also as a general source of radiocaesium for contamination of forest vegetation, although individual plant species differ greatly in their ability to accumulate radiocaesium from this organic soil (Fig. 3.36).

Release of radiocaesium from the system via drainage water is generally limited due to its fixation on micaceous clay minerals [3.67]. An important role of forest vegetation in the recycling of radiocaesium is the partial and transient storage of radiocaesium, particularly in perennial woody

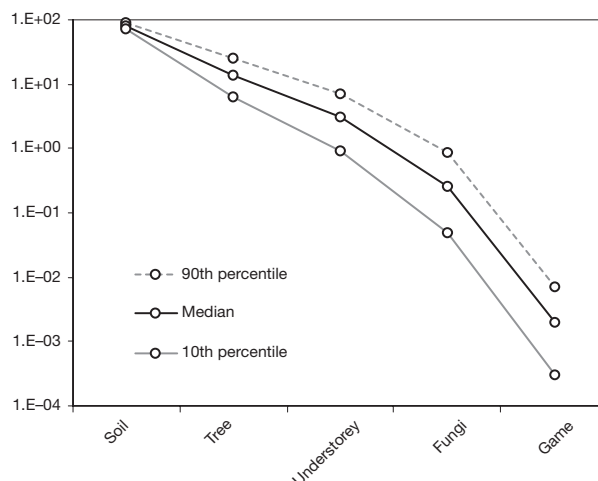


FIG. 3.36. Calculated percentage distributions of radiocaesium in specified components of coniferous forest ecosystems [3.73].

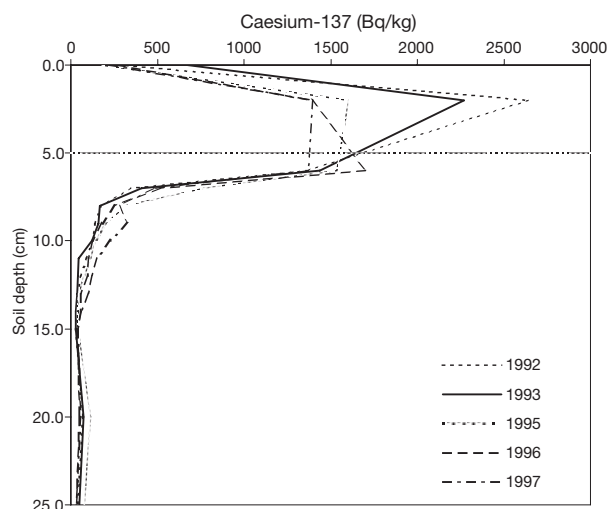


FIG. 3.37. Soil profiles of radiocaesium in a Scots pine forest near Gomel in Belarus, 1992–1997 [3.74]. The horizontal line indicates the boundary between organic and mineral soil layers.

components such as tree trunks and branches, which can have a large biomass. A portion of radiocaesium taken up by vegetation from the soil, however, is recycled annually through leaching and needle/leaf fall, resulting in the long lasting biological availability of radiocaesium in surface soil. The stored amount of radiocaesium in the standing biomass of forests is approximately 5% of the total activity in a temperate forest ecosystem, with the bulk of this activity residing in trees.

Due to biological recycling and storage of radiocaesium, migration within forest soils is limited and the bulk of contamination in the long term resides in the upper organic horizons (Fig. 3.37). Slow downward migration of radiocaesium

continues to take place, however, although the rate of migration varies considerably with soil type and climate.

The hydrological regime of forest soils is an important factor governing radionuclide transfer in forest ecosystems [3.75]. Depending on the hydrological regime, the radiocaesium T_{ag} for trees, mushrooms, berries and shrubs can vary over a range of more than three orders of magnitude. The minimum T_{ag} values were found for automorphic (dry) forests and soils developed on even slopes under free surface runoff conditions. The maximum T_{ag} values are related to hydromorphic forests developed under prolonged stagnation of surface waters. Among other factors influencing radionuclide transfer in forests, the distribution of root systems (mycelia) in the soil profile and the capacity of different plants for radiocaesium accumulation are of importance [3.76].

The vertical distribution of radiocaesium within soil has an important influence on the dynamics of uptake by herbaceous plants, trees and mushrooms. It also influences the change in external gamma dose rate with time. The upper soil layers provide increasing shielding from radiation as the peak of the contamination migrates downwards (Fig. 3.38). The most rapid downward vertical transfer was observed for hydromorphic forests [3.75].

Once forests become contaminated with radiocaesium, any further redistribution is limited. Processes of small scale redistribution include resuspension [3.78], fire [3.79] and erosion/runoff, but none of these processes are likely to result in any significant migration of radiocaesium beyond the location of initial deposition.

3.4.4. Uptake into edible products

Edible products obtained from forests include mushrooms, fruits and game animals. In forests affected by the Chernobyl deposition, each of these products became contaminated. The highest levels of contamination with radiocaesium have been observed in mushrooms, due to their great capacity to accumulate some mineral nutrients as well as radiocaesium. Mushrooms provide a common and significant food source in many of the affected countries, particularly in the countries of the former USSR. Changes with time in the contamination of mushrooms reflect the bioavailability of ^{137}Cs in the various relevant nutrient sources utilized by the different mushroom species.

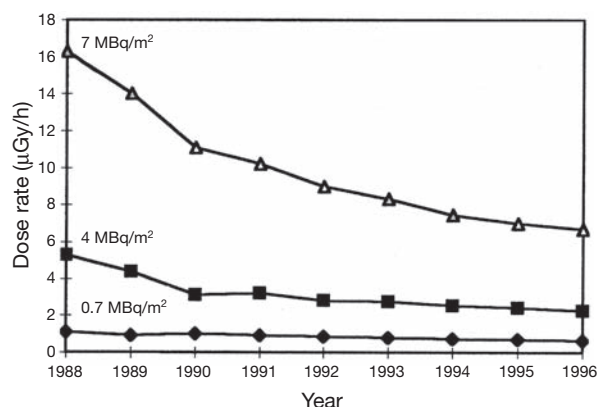


FIG. 3.38. Gamma dose rates in air at three forest locations with different ^{137}Cs soil depositions in the Bryansk region of the Russian Federation, 150 km north-east of Chernobyl [3.77].

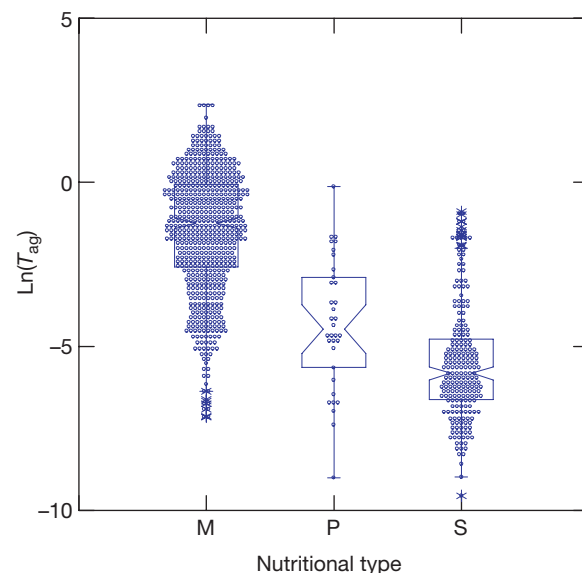


FIG. 3.39. Variation in the logarithm of T_{ag} with different nutritional types of mushroom [3.82]. M: mycorrhizal; P: parasitic; S: saprotrophic nutritional type.

Some mushroom species exploit specific soil layers for their nutrition, and the dynamics of contamination of such species have been related to the contamination levels of these layers [3.80]. The high levels of contamination in mushroom species are reflected in generally high soil to mushroom transfer coefficients. However, these transfer coefficients (T_{ag}) are also subject to considerable variability and can range from 0.003 to 7 m²/kg (i.e. by a factor of approximately 2000 [3.81]). There are significant differences in the accumulation of radiocaesium in different species of mushroom (see Fig. 3.39) [3.82]. In general, the saprotrophs and wood degrading fungi, such as the honey fungus

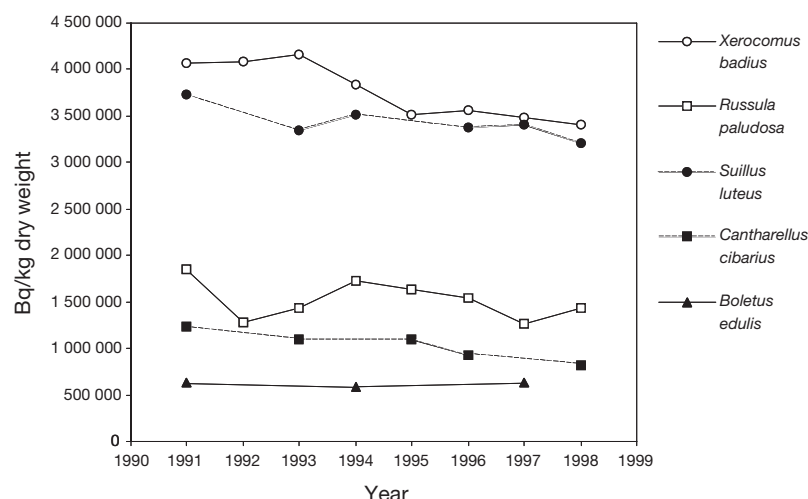


FIG. 3.40. Caesium-137 activity concentrations (Bq/kg dry weight) in selected mushroom species harvested in a pine forest in the Zhytomyr region of Ukraine, approximately 130 km south-west of Chernobyl. The soil deposition of ^{137}Cs at this site in 1986 was 555 kBq/m^2 . From Ref. [3.68].

(*Armillaria mellea*), have a low level of contamination, while those fungi forming symbioses with tree roots (mycorrhizal fungi such as *Xerocomus* and *Lactarius*) have a high uptake. The degree of variability of mushroom contamination is illustrated in Fig. 3.40, which also indicates the tendency for a slow decrease in contamination during the 1990s.

Contamination of mushrooms in forests is often much higher than that of forest fruits such as bilberries. This is reflected in the T_{ag} for forest berries, which ranges from 0.02 to $0.2 \text{ m}^2/\text{kg}$ [3.81]. Due to the generally lower radiocaesium levels and the relative masses consumed, forest berries pose a smaller radiological hazard to humans than do mushrooms. However, both products contribute significantly to the diet of grazing animals and therefore provide a second route of exposure of humans via game. Animals grazing in forests and other seminatural ecosystems often produce meat with high radiocaesium levels. Such animals include wild boar, roe deer, moose and reindeer, but also domestic animals such as cattle and sheep, which may graze marginal areas of forests.

Most data on the contamination of game animals such as deer and moose have been obtained from western European countries in which the hunting and eating of game is commonplace. Significant seasonal variations occur in the body content of radiocaesium in these animals due to the seasonal availability of foods such as mushrooms and lichens, the latter being particularly important as a component of the diet of reindeer. Good time

series measurements have been obtained from the Nordic countries and Germany. Figure 3.41 shows a complete time series of annual average radiocaesium activities for moose from 1986 to 2003 for one hunting area in Sweden, and Fig. 3.42 shows individual measurements of ^{137}Cs activity concentrations in the muscle of roe deer in southern Germany. A major factor for the contamination of game, and roe deer in particular, is the high concentration of radiocaesium in mushrooms. The T_{ag} for moose ranges from 0.006 to $0.03 \text{ m}^2/\text{kg}$ [3.81]. The mean T_{ag} for moose in Sweden has been falling since the period of high initial contamination, indicating that the ecological half-life of radiocaesium in moose is less than 30 years (i.e. less than the physical half-life of ^{137}Cs).

3.4.5. Contamination of wood

Most forests in Europe and the former USSR affected by the Chernobyl accident are planted and managed for the production of timber. The export of contaminated timber, and its subsequent processing and use, could give rise to radiation doses to people who would not normally be exposed in the forest itself. Uptake of radiocaesium from forest soils into wood is rather low; aggregated TFs range from 0.0003 to $0.003 \text{ m}^2/\text{kg}$. Hence wood used for making furniture or the walls and floors of houses is unlikely to give rise to significant radiation exposure of people using these products [3.85]. However, the manufacture of consumer goods such

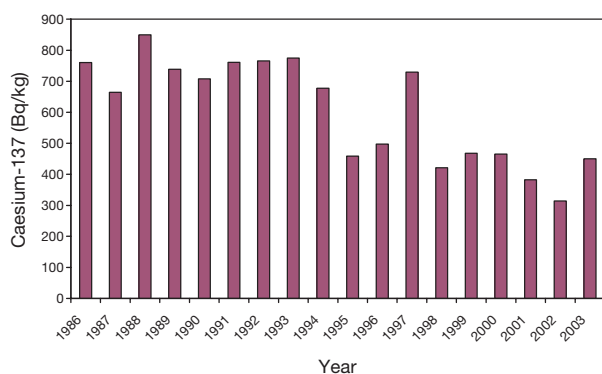


FIG. 3.41. The average concentration of ^{137}Cs in moose in one hunting area in Sweden, based on approximately 100 animals per year [3.83].

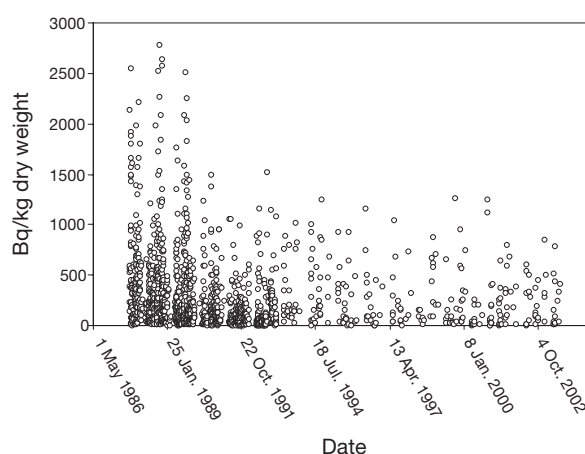


FIG. 3.42. Caesium-137 activity concentrations in the muscle of roe deer (*Capreolus capreolus*) harvested in a forest close to Bad Waldsee, southern Germany. The total deposition of ^{137}Cs at this site in 1986 was 27 kBq/m² [3.84].

as paper involves the production of both liquid and solid waste that can become significantly contaminated with radiocaesium. The handling of this waste by workers in paper pulp factories can give rise to radiation doses within the industry [3.86].

Use of other parts of trees such as needles, bark and branches for combustion may involve the problem of disposal of radioactive wood ash. This practice has increased in recent years due to the upsurge in biofuel technology in the Nordic countries, and the problem of radiocaesium in wood ash has become significant because the radiocaesium activity concentration in ash is a factor of 50–100 times higher than in the original wood. For domestic users of firewood in contaminated regions, a buildup of ash in the home and/or garden may also give rise to external exposure to gamma radiation from radiocaesium [3.85].

3.4.6. Expected future trends

Much effort has been put into developing mathematical models that make use of the large array of measurements of radiocaesium contamination in forests since 1986 [3.68]. These models are useful in helping to improve our understanding of the way the Chernobyl contamination behaves in forest ecosystems. Furthermore, they can also be used to provide forecasts of future trends of contamination, which can assist when making decisions about the future management of contaminated regions.

Predictive models of radiocaesium behaviour in forests are intended to quantify the fluxes and distributions in the ecosystem over time. Forecasts can be made for specific ecological compartments such as the wood of trees and edible products such as mushrooms. Figures 3.43 and 3.44 show examples of such forecasts obtained using a variety of models. Figure 3.43 shows predictions of the evolution of radiocaesium activity in wood for two distinct types of forest ecosystem with two age classes of trees. This illustrates the importance of both soil conditions and the stage of tree development at the time of deposition in controlling the contamination of harvestable wood. Figure 3.44 shows a summary of 50 year forecasts for a pine forest in the Zhytomyr region of Ukraine, approximately 130 km south-west of Chernobyl. The figure shows the degree of variability among the predictions made by 11 different models and also the inherent variability within data collected from a single forest site. The uncertainty in both monitoring data and among models makes the task of forecasting future trends of forest contamination rather difficult.

3.4.7. Radiation exposure pathways associated with forests and forest products

Contaminated forests can give rise to radiation exposures of workers in the forest and in associated industries, as well as of members of the general public. Forest workers receive direct radiation exposure during their working hours, due to the retention of radiocaesium in the tree canopy and the upper soil layers. Similarly, members of the public can receive external exposures from wood products, for example furniture or wooden floors, but, in addition, they may be exposed as a result of the consumption of game, wild mushrooms and berries containing radiocaesium. Forest margins may also be used to graze domestic animals such as

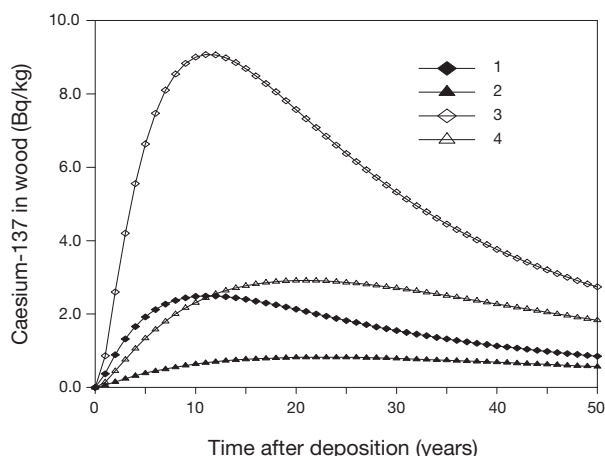


FIG. 3.43. Predicted ^{137}Cs activity concentration in wood for different types of forest soil and ages of trees calculated using a computer model, FORESTLAND, for a deposition of 1 kBq/m^2 [3.87]. 1, 2: automorphic soil, 3, 4: semi-hydromorphic soil; 1, 3: initial age 20 years; 2, 4: initial age 80 years.

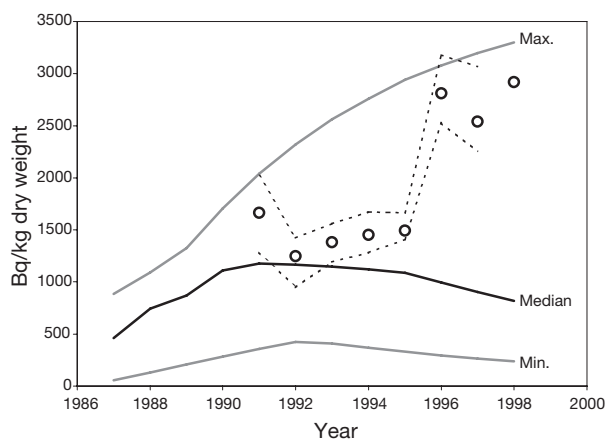


FIG. 3.44. Summary of predictions of pine wood contamination with ^{137}Cs in the Zhytomyr region of Ukraine made by use of 11 models within the IAEA's BIOMASS program. Caesium-137 soil deposition was about 555 kBq/m^2 . Max., Median and Min. indicate maximum, median and minimum values of pooled model predictions, respectively. The points show means of measured values, and the broken lines indicate the maximum and minimum values of measurements [3.88].

cattle and sheep. This can lead to the milk of these animals becoming contaminated and to human exposure as a result of the consumption of dairy products and meat. A further exposure pathway results from the collection and use of firewood for domestic purposes. This can give rise to exposures both in the home and in the garden if wood ash is used as a domestic fertilizer. Also, the industrial use of forest products for energy production can give

rise to exposure both of workers and of members of the public. Quantitative information on human radiation doses associated with forests and forest products is given in Ref. [3.85] and in Section 6 of this report.

Another set of important exposure pathways results from the harvesting, processing and use of timber and wood products from contaminated forest areas. Timber and wood products become sources of potential exposure once they are exported from the forest, often over considerable distances and sometimes across national borders. The relative importance of these exposure pathways has been evaluated and quantified [3.85].

3.5. RADIONUCLIDES IN AQUATIC SYSTEMS

3.5.1. Introduction

Radioactive material from Chernobyl affected surface water systems in many parts of Europe. The majority of the radioactive fallout, however, was deposited in the catchment of the Pripjat River, which forms an important component of the Dnieper River-reservoir system, one of the larger surface water systems in Europe [3.13]. After the accident, therefore, there was particular concern over contamination of the water supply for the area along the Dnieper cascade of reservoirs covering a distance of approximately 1000 km to the Black Sea (see Figs 3.6–3.9). Other large river systems in Europe, such as the Rhine and Danube, were also affected by fallout, although the contamination levels in those rivers were not radiologically significant [3.5, 3.6].

Initial radionuclide concentrations in river water in parts of Belarus, the Russian Federation and Ukraine were relatively high compared both with other European rivers and with the safety standards for radionuclides in drinking water. The contamination was due to direct fallout on to river surfaces and runoff of contamination from catchment areas. During the first few weeks after the accident, activity concentrations in river waters declined rapidly, because of the physical decay of short lived isotopes and absorption of radionuclides on to catchment soils and bottom sediments. In the longer term, the long lived ^{137}Cs and ^{90}Sr comprised the major component of contamination of aquatic ecosystems. Although the levels of these radionuclides in rivers were low after the initial

peak, temporary increases in activity concentrations during flooding of the Pripyat River caused serious concern in areas using water from the Dnieper cascade.

Lakes and reservoirs were contaminated by fallout on the water surface and by transfers of radionuclides from the surrounding catchment areas. Radionuclide concentrations in water declined rapidly in reservoirs and in those lakes with significant inflow and outflow of water (open lake systems). In some cases, however, activity concentrations of radiocaesium in lakes remained relatively high due to runoff from organic soils in the catchment. In addition, internal cycling of radiocaesium in closed lake systems (i.e. lakes with little inflow and outflow of water) led to much higher activity concentrations in their water and aquatic biota than were typically seen in open lakes and rivers.

Bioaccumulation of radionuclides (particularly radiocaesium) in fish resulted in activity concentrations (both in the most affected regions and in western Europe) that were in some cases significantly above the permissible levels for consumption [3.89–3.94]. In some lakes in Belarus, the Russian Federation and Ukraine these problems have continued to the present day and may continue for the foreseeable future. Freshwater fish provide an important source of food for many inhabitants of the contaminated regions. In the Dnieper cascade in Ukraine, commercial fisheries catch more than 20 000 t of fish per year. In some parts of western Europe, particularly parts of Scandinavia, radiocaesium activity concentrations in fish are still relatively high [3.95].

The marine systems closest to Chernobyl are the Black Sea and the Baltic Sea — both several hundred kilometres from the site. Radioactivity in the water and fish of these seas has been intensively studied since the Chernobyl accident. Since the average deposition to these seas was relatively low, and owing to the large dilution in marine systems, radionuclide concentrations were much lower than in freshwater systems [3.96].

3.5.2. Radionuclides in surface waters

3.5.2.1. Distribution of radionuclides between dissolved and particulate phases

Retention of radionuclide fallout by catchment soils and river and lake sediments plays an important role in determining subsequent

transport in aquatic systems. The fraction of a radionuclide that is adsorbed to suspended particles (which varies considerably in surface waters) strongly influences both its transport and its bioaccumulation. Most ^{90}Sr is present in the dissolved phase (0.05–5% in the solid phase), but in the near zone a significant proportion of strontium fallout was in the form of fuel particles. The soils of the CEZ are heavily contaminated with ^{90}Sr (see Fig. 7.7), and some of it is washed off during flood events when the low lying areas become inundated.

In the Pripyat River, during the first decade after the accident approximately 40–60% of radiocaesium was found in the particulate phase [3.97], but estimates in other systems [3.98] vary from 4% to 80%, depending on the composition and concentration of the suspended particles and on the water chemistry. Fine clay and silt particles absorb radiocaesium more effectively than larger, less reactive sand particles. Sandy river beds, even close to the reactor, were relatively uncontaminated, but fine particles transported radiocaesium over relatively large distances. The settling of fine particles in the deep parts of the Kiev reservoir led to high levels of contamination of bed sediments [3.99].

Measurements of the distribution of radionuclides between the dissolved and particulate phases in Pripyat River water showed that the strength of adsorption to suspended particles increases in the following order: ^{90}Sr , ^{137}Cs , transuranic elements ($^{239,240}\text{Pu}$, ^{241}Am) [3.100]. There is a possibility that natural organic colloids may determine the stability of transuranic elements in surface water and in their transport from contaminated soil; such colloids have less effect on ^{90}Sr and ^{137}Cs [3.101].

Generally in marine systems, lower particle sorption capacities and higher concentrations of competing ions (i.e. higher salinity) tend to make particle sorption of radionuclides less significant than in freshwaters. In the Baltic Sea after the Chernobyl accident less than 10% of ^{137}Cs was bound to particles and the average particulate sorbed fraction was approximately 1% [3.102, 3.103]. In the Black Sea the particulate bound fraction of ^{137}Cs was less than 3% [3.96].

3.5.2.2. Radioactivity in rivers

Initial radioactivity concentrations in rivers close to Chernobyl (the Pripyat, Teterev, Irpen and Dnieper Rivers) were largely due to direct deposition of radioactivity on to the river surface.

TABLE 3.7. MAXIMUM RADIONUCLIDE ACTIVITY CONCENTRATIONS (DISSOLVED PHASE) MEASURED IN THE PRIPYAT RIVER AT CHERNOBYL [3.91, 3.104, 3.105]

	Maximum concentration (Bq/L)
Caesium-137	1591
Caesium-134	827
Iodine-131	4440
Strontium-90	30
Barium-140	1400
Molybdenum-99	670
Ruthenium-103	814
Ruthenium-106	271
Cerium-144	380
Cerium-141	400
Zirconium-95	1554
Niobium-95	420
Plutonium-241	33
Plutonium-239, 240	0.4

The highest concentrations of radionuclides were observed in the Pripyat River at Chernobyl, where the ^{131}I activity concentration was up to 4440 Bq/L (Table 3.7). In all water bodies the radioactivity levels declined rapidly during the first few weeks, due to decay of short lived isotopes and absorption of nuclides to catchment soils and river bed sediments.

Over longer time periods after the fallout occurred, relatively long lived ^{90}Sr and ^{137}Cs retained in catchment soils are slowly transferred to river water by erosion of soil particles and by desorption from soils. The rates of transfer are influenced by the extent of soil erosion, the strength of radionuclide binding to catchment soils and migration down the soil profile. An example time series of ^{90}Sr and ^{137}Cs activity concentrations in the water of the Pripyat River near Chernobyl is shown in Fig. 3.45.

After the Chernobyl accident, water monitoring stations were established within the exclusion zone and along the major rivers to determine the concentrations of radionuclides and their total fluxes. Measurements from these stations allow estimates to be made of radionuclide fluxes of ^{90}Sr and ^{137}Cs into and out of the CEZ. The migration of ^{137}Cs has decreased markedly with time and shows relatively little change from upstream to downstream of the CEZ (see Fig. 3.46(a)).

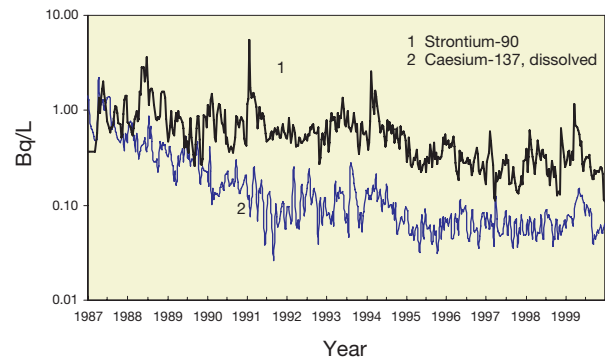


FIG. 3.45. Monthly averaged ^{90}Sr and ^{137}Cs activity concentrations in the Pripyat River near Chernobyl [3.106].

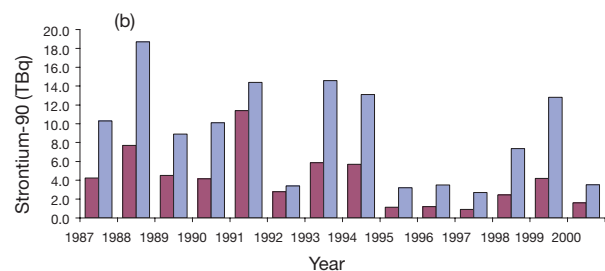
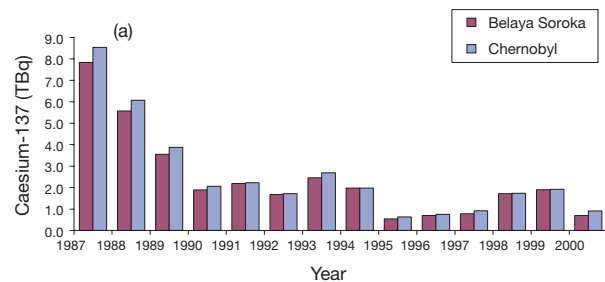


FIG. 3.46. Annual fluxes of ^{137}Cs (a) and ^{90}Sr (b) in the Pripyat River at Belaya Soroka, near the Belarus–Ukraine border (inlet to the CEZ), and downstream of Chernobyl (outlet of the CEZ) [3.107].

In contrast, the transboundary migration of ^{90}Sr has fluctuated yearly depending on the extent of annual flooding along the banks of the Pripyat River (Fig. 3.46(b)). There is also a significant flux from the CEZ — fluxes downstream of the zone are much higher than those upstream. Note, however, that the extent of washout of radionuclides by the river system is only a very small percentage of the total inventory contained in the catchment area.

The decline in ^{90}Sr and ^{137}Cs activity concentrations occurred at a similar rate for different rivers in the vicinity of Chernobyl and in rivers in western Europe [3.108]. Measurements of ^{137}Cs activity concentration in different European rivers (Fig. 3.47) show a range of approximately a factor of

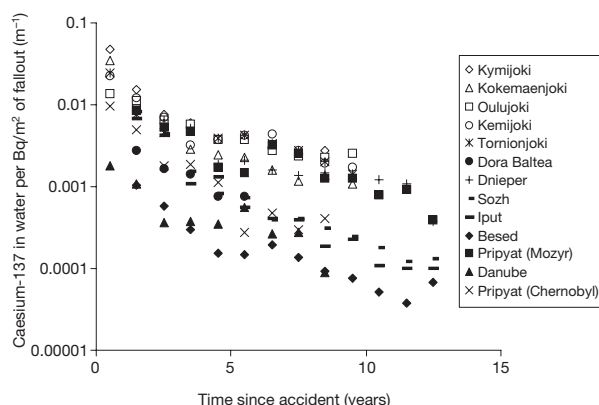


FIG. 3.47. Caesium-137 activity concentration in different rivers per unit of deposition [3.109–3.111].

30, even when differences in fallout have been accounted for. In small catchments [3.67, 3.112, 3.113], highly organic soils (particularly saturated peat soils) released up to an order of magnitude more radiocaesium to surface waters than some mineral soils. Thus rivers in Finland with large areas of wet organic soils in the catchment have higher radiocaesium concentrations (per unit of radioactive fallout) than rivers with predominantly mineral catchments [3.109, 3.111].

3.5.2.3. Radioactivity in lakes and reservoirs

In the affected areas of Belarus, the Russian Federation and Ukraine many lakes were significantly contaminated by radionuclides. In most lakes radionuclides were well mixed throughout the lake water during the first days to weeks after the fallout occurred. In deep lakes such as Lake Zurich (mean depth 143 m), however, it took several months for full vertical mixing to take place [3.114]. In some areas of northern Europe lakes were covered with ice at the time of the accident and maximum activity concentrations in lake waters were only observed after the ice melted.

Radionuclides deposited to a lake or reservoir are removed through water outflow and by transfer to bed sediments. As in rivers, radiocaesium activity concentrations in lakes declined relatively rapidly during the first weeks to months after the fallout. This was followed by a slower decline over a period of years as radiocaesium became more strongly absorbed to catchment soils and lake sediments and migrated to deeper layers in the soil and sediments. Figure 3.48 illustrates the temporal change in ^{137}Cs activity concentration in lakes using measurements

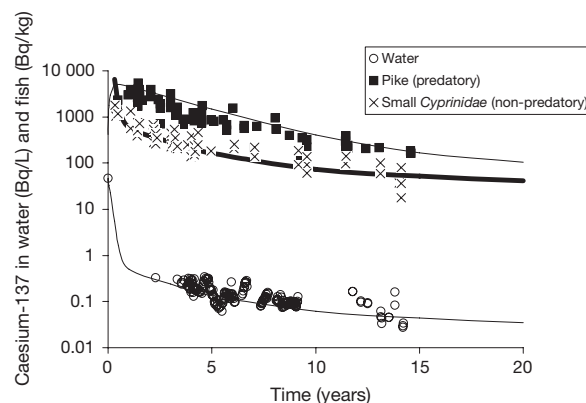


FIG. 3.48. Time series of ^{137}Cs in Lake Vorse, Germany [3.93].

from Lake Vorse, a small shallow lake in Germany.

Inputs to lakes also result from transport of radionuclides from contaminated catchment soils. In the longer term (secondary phase), ^{137}Cs activity concentrations in Lake Vorse remained much higher than in most other lakes due to inputs of ^{137}Cs from organic soils in the catchment and remobilization from bed sediments (Fig. 3.48 [3.93]). In Devoke Water (UK), radiocaesium flowing from organic catchment soils maintained activity concentrations in the water that were approximately an order of magnitude higher than in nearby lakes with mineral catchments [3.112]. In some cases, lakes in western Europe with organic catchments had activity concentrations in water and fish similar to those in the more highly contaminated areas of Belarus and Ukraine.

Long term contamination can also be caused by remobilization of radionuclides from bed sediments [3.115]. In some shallow lakes where there is no significant surface inflow and outflow of water, the bed sediments play a major role in controlling radionuclide activity concentration in the water. Such lakes have been termed 'closed' lakes [3.105, 3.116]. The more highly contaminated water bodies in the Chernobyl affected areas are the closed lakes of the Pripjat floodplain within the CEZ. During 1991 ^{137}Cs activity concentrations in these lakes were up to 74 Bq/L (Lake Glubokoye) and ^{90}Sr activity concentrations were between 100 and 370 Bq/L in six of the 17 water bodies studied [3.105]. Seventeen years after the accident there were still relatively high activity concentrations in the closed lakes in the CEZ [3.117] and at quite large distances from the reactor; for example, during 1996 Lakes Kozhanovskoe and Svyatoye in

the Bryansk region of the Russian Federation (approximately 200 km from Chernobyl) contained 0.6–1.5 Bq/L of ^{90}Sr and 10–20 Bq/L of ^{137}Cs (Fig. 3.49). Activity concentrations in water were higher than in many lakes close to Chernobyl, because of remobilization from sediments in these closed lakes [3.116]. The Russian intervention level for drinking water of 11 Bq/L for ^{137}Cs [3.119] is shown for comparison.

(a) Chernobyl cooling pond

The Chernobyl cooling pond covers an area of approximately 23 km² and contains approximately 149×10^6 m³ of water. It is located between the former Chernobyl nuclear power plant and the Pripjat River. The total inventory of radionuclides

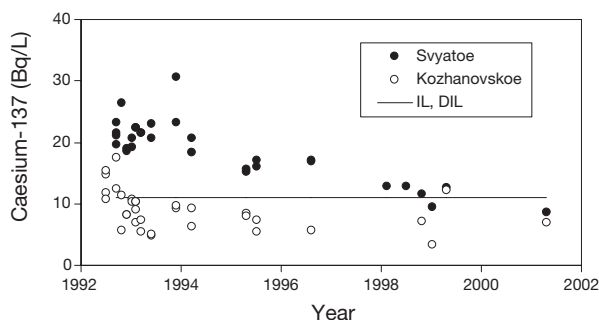


FIG. 3.49. Dynamics of ^{137}Cs activity concentration in the water of Lakes Svyatoye and Kozhanovskoye (Russian Federation), approximately 200 km from Chernobyl [3.118].

in the pond is in excess of 200 TBq (about 80% is ^{137}Cs , 10% ^{90}Sr , 10% ^{241}Pu and less than 0.5% each is of ^{238}Pu , ^{239}Pu , ^{240}Pu and ^{241}Am), with the deep sediments containing most of the radioactivity. The ^{90}Sr annual flux to the Pripjat River from the cooling pond via groundwater was estimated in a recent study to be 0.37 TBq [3.120]. This is a factor of 10–30 less than the total annual ^{90}Sr fluxes in the Pripjat River in recent years. Thus the cooling pond is not a significant source of ^{90}Sr contamination of the Pripjat River. Radionuclide activity concentrations in the cooling pond water (Fig. 3.50) are currently low, at 1–2 Bq/L. Seasonal variations of ^{137}Cs concentration are caused by changes in algae and phytoplankton biomass [3.121].

(b) Reservoirs of the Dnieper cascade

The Dnieper cascade reservoirs were significantly affected, due to both atmospheric fallout and riverine inputs from the contaminated zones (see Fig. 3.6). The different affinities of ^{137}Cs and ^{90}Sr for suspended matter influenced their transport through the Dnieper system. Caesium-137 tends to become fixed on to clay sediments, which are deposited in the deeper sections of the reservoirs, particularly in the Kiev reservoir (Fig. 3.51). Owing to this process, very little ^{137}Cs flows through the cascade of reservoirs, and consequently the present concentration entering the Black Sea is indistinguishable from the background level.

However, although the ^{90}Sr activity concentration decreases with distance from the source

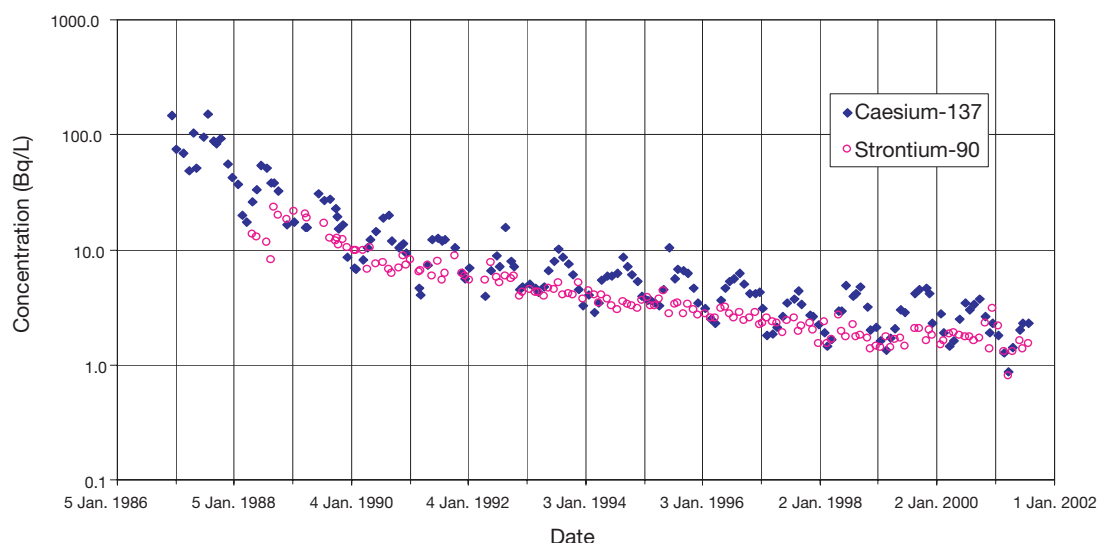


FIG. 3.50. Monthly averaged ^{137}Cs and ^{90}Sr activity concentrations in the water of the Chernobyl cooling pond [3.121].

(mainly due to dilution), about 40–60% passes through the cascade and reaches the Black Sea. Figure 3.52 shows the trend in average annual ^{90}Sr activity concentration in the Dnieper reservoirs since the accident. As ^{137}Cs is trapped by sediments in the reservoir system, activity concentrations in the lower part (Novaya Kakhovka) of the system are orders of magnitude lower than in the Kiev reservoir (Vishgorod). In contrast, ^{90}Sr is not strongly bound by sediments, so activity concentrations in the lower part of the river–reservoir system are similar to those measured in the Kiev reservoir.

The peaks in ^{90}Sr activity concentration in the reservoirs of the Dnieper cascade (Fig. 3.52) were caused by flooding of the most contaminated floodplains in the CEZ; for example, flooding of the Pripyat River, caused by blockages of the river by ice in the winter of 1990–1991, led to temporary significant increases in ^{90}Sr in this system, but did not significantly affect ^{137}Cs levels. Activity concentrations of ^{90}Sr in the river water increased from about 1 to 8 Bq/L for a five to ten day period [3.105]. Similar events took place during the winter flood of 1994, during summer rainfall in July 1993 and during the high spring flood in 1999 [3.122].

(c) Radionuclide runoff from catchment soils

Small amounts of radionuclides are eroded from soils and transferred to rivers, lakes and eventually the marine system. Such transfers can take place through erosion of surface soil particles and by runoff in the dissolved phase. Studies of

nuclear weapon tests and of Chernobyl ^{90}Sr in rivers [3.109, 3.110, 3.123, 3.124] suggest long term loss rates of about 1–2%/a or less from the terrestrial environment to rivers. Thus, in the long term, runoff of radionuclides does not significantly reduce the amount of radioactivity in the terrestrial system, although it does result in continuing (low level) contamination of river and lake systems.

3.5.2.4. Radionuclides in freshwater sediments

Bed sediments are an important long term sink for radionuclides. Radionuclides can become attached to suspended particles in lakes, which then fall and settle on bed sediments. Radionuclides in lake water can also diffuse into bed sediments. These processes of radionuclide removal from lake water have been termed ‘self-cleaning’ of the lake or reservoir [3.114].

In the Chernobyl cooling pond approximately one month after the accident, most of the radioactivity was found in bed sediments [3.91, 3.97]. In the long term, approximately 99% of the radiocaesium in a lake is typically found in the bed sediment. In measurements in Lake Svyatoye (Kostiukovichy region, Belarus) during 1997, approximately 3×10^9 Bq of ^{137}Cs was in the water and 2.5×10^{11} Bq was in sediments [3.125]. In Lake Kozhanovskoye in the Russian Federation, approximately 90% of the radiostrontium was found in the bed sediments during 1993–1994 [3.126].

In the rapidly accumulating sediments of the Kiev reservoir, the layer of maximum radiocaesium

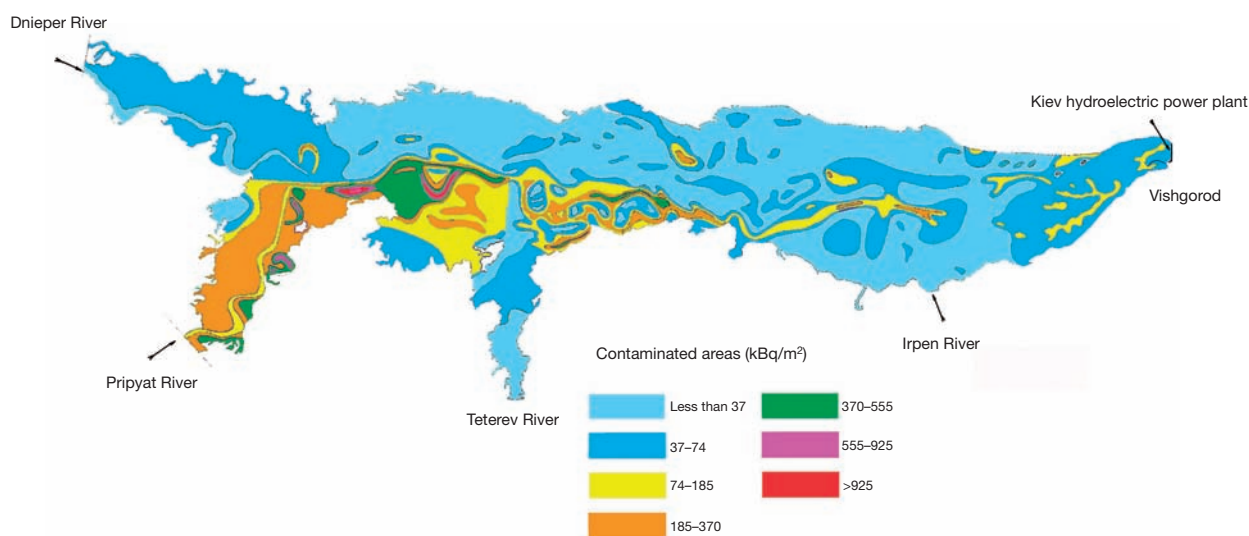


FIG. 3.51. Caesium-137 in the bottom sediments of the Kiev reservoir [3.97].

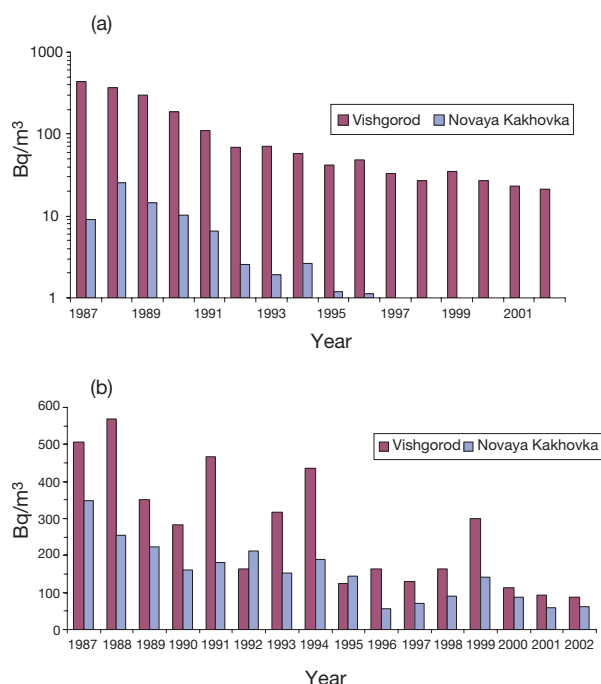


FIG. 3.52. Annually averaged ^{137}Cs (a) and ^{90}Sr (b) activity concentrations in the water of the Kiev reservoir (Vishgorod) near the dam and in the Kakhovka reservoir of the Dnieper cascade [3.107].

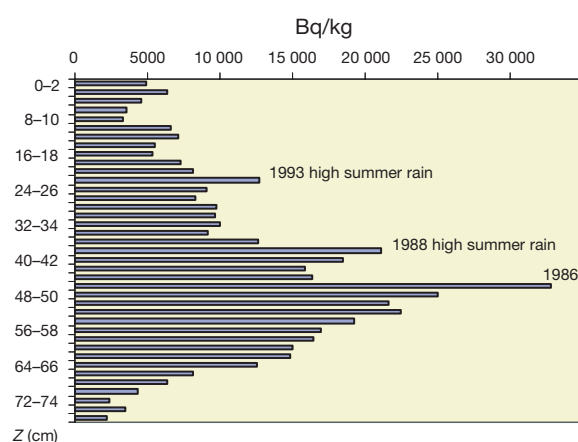


FIG. 3.53. Activity concentrations of ^{137}Cs in the deep silt deposits in the upper part of the Kiev reservoir, 1998 [3.106].

concentration is now buried several tens of centimetres below the sediment surface (Fig. 3.53). In more slowly accumulating sediments, however, the peak in radiocaesium activity concentration remains near the sediment surface. Peaks in the sediment layer contamination in 1988 and 1993 reflect the consequences of high summer rainfall floods and soil erosion events.

Close to Chernobyl, a high proportion of the deposited radioactive material was in the form of

fuel particles (see Section 3.1). Radionuclides deposited as fuel particles are generally less mobile than those deposited in a dissolved form. In the sediments of Lake Glubokoye in 1993, most fuel particles remained in the surface 5 cm of sediment [3.126]. Fuel particle breakdown was at a much lower rate in lake sediments than in soils. Studies in the cooling pond have shown that the half-life of fuel particles in sediments is approximately 30 years, so by 2056 (70 years after the Chernobyl accident) one quarter of the radioactive material deposited as fuel particles in the cooling pond will still remain in fuel particle form [3.39].

3.5.3. Uptake of radionuclides to freshwater fish

Consumption of freshwater fish is an important part of the aquatic pathway for the transfer of radionuclides to humans. Although the transfer of radionuclides to fish has been studied in many countries, most attention here is focused on Belarus, the Russian Federation and Ukraine, because of the higher contamination of water bodies in these areas.

3.5.3.1. Iodine-131 in freshwater fish

There are limited data on ^{131}I in fish. Iodine-131 was rapidly absorbed by fish in the Kiev reservoir, with maximum concentrations in fish being observed in early May 1986 [3.91]. Activity concentrations in fish muscle declined from around 6000 Bq/kg fresh weight on 1 May 1986 to 50 Bq/kg fresh weight on 20 June 1986. This represents a rate of decline similar to that of the physical decay of ^{131}I . Owing to the rapid physical decay, ^{131}I activity concentrations in fish became insignificant a few months after the accident.

3.5.3.2. Caesium-137 in freshwater fish and other aquatic biota

During the years following the Chernobyl accident there have been many studies of the levels of radiocaesium contamination of freshwater fish. As a result of high radiocaesium bioaccumulation factors, fish have remained contaminated in some areas, despite low radiocaesium levels in water. Uptake of radiocaesium into small fish was relatively rapid, the maximum concentration being observed during the first weeks after the accident [3.93, 3.95]. Due to the slow uptake rates of radiocaesium in large predatory fish (pike, eel),

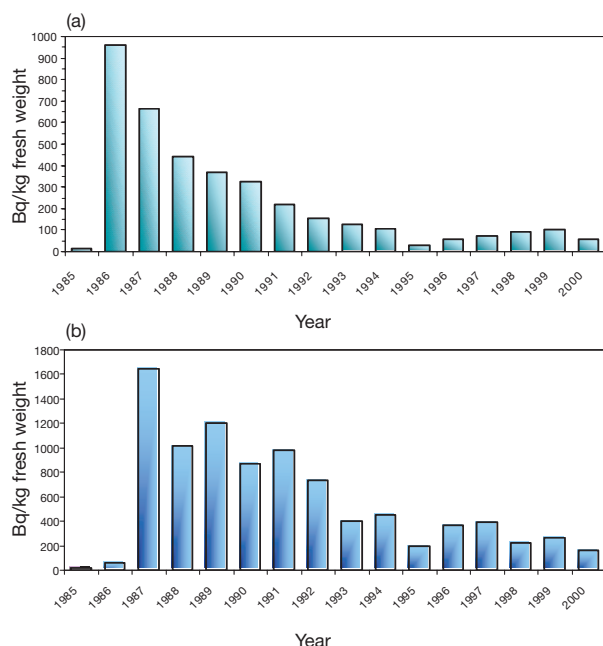


FIG. 3.54. Averaged ^{137}Cs activity concentrations in non-predatory (bream (a)) and predatory (pike (b)) fish; the fish are from the Kiev reservoir [3.106].

maximum activity concentrations were not observed until six to 12 months after the fallout event [3.93, 3.127] (Fig. 3.48).

In the Chernobyl cooling pond, ^{137}Cs activity concentrations in carp, silver bream, perch and pike were about 100 kBq/kg fresh weight in 1986, declining to a few tens of kBq/kg in 1990 [3.89, 3.91] and 2–6 kBq/kg in 2001. In some closed lakes in the vicinity of the Chernobyl nuclear power plant [3.121] the ^{137}Cs activity concentration in predatory fish 15 years after the accident was 10–27 kBq/kg fresh weight. Typical changes with time in ^{137}Cs in two fish species over 16 years after the accident are illustrated in Fig. 3.54.

In the Kiev reservoir, ^{137}Cs activity concentrations in fish were 0.6–1.6 kBq/kg fresh weight (in 1987) and 0.2–0.8 kBq/kg fresh weight (for 1990–1995), and declined to 0.2 kBq/kg or less for adult non-predatory fish in 2002. Values for predatory fish species were 1–7 kBq/kg during 1987 and 0.2–1.2 kBq/kg from 1990 to 1995 [3.106].

In the lakes of the Bryansk region of the Russian Federation, approximately 200 km from Chernobyl, ^{137}Cs activity concentrations in a number of fish species varied within the range of 0.2–19 kBq/kg fresh weight during the period 1990–1992 [3.126, 3.150]. In shallow closed lakes such as Lake Kozhanovskoe (Bryansk region of the Russian Federation) and Lake Svyatoye (Kostiukovichy

region in Belarus), ^{137}Cs activity concentrations in fish have declined slowly in comparison with fish in rivers and open lake systems, due to the slow decline in ^{137}Cs activity concentrations in the water of the lakes [3.92, 3.116].

In western Europe, lakes in some parts of Finland, Norway and Sweden were particularly heavily contaminated. About 14 000 lakes in Sweden had fish with ^{137}Cs activity concentrations above 1500 Bq/kg fresh weight (the Swedish guideline value) in 1987 [3.90]. In some alpine lakes in Germany, ^{137}Cs activity concentrations in pike were up to 5000 Bq/kg fresh weight shortly after the Chernobyl accident [3.93]. In Devoke Water in the UK Lake District, perch and brown trout contained around 1000 Bq/kg fresh weight in 1988, declining slowly to a few hundreds of Bq/kg in 1993 [3.129].

Bioaccumulation of radiocaesium in fish is dependent on a number of factors. The presence of potassium in a lake or river influences the rate of accumulation of radiocaesium in fish because of its chemical similarity to caesium [3.130]. Strong inverse relationships were observed between the lake water potassium concentration and the ^{137}Cs activity concentration in fish following nuclear weapon testing [3.128, 3.130] and the Chernobyl accident [3.94]. In the long term, activity concentrations in predatory fish were significantly higher than in non-predatory fish, and large fish tended to have higher activity concentrations than small fish. The higher activity concentration in large fish is termed the 'size effect' [3.127, 3.131] and is due to metabolic and dietary differences. In addition, older, larger fish were exposed to higher levels of ^{137}Cs in the water than younger, smaller fish.

The differences in the bioaccumulation of radiocaesium in different fish species can be significant; for example, in Lake Svyatoye in Belarus, the levels in large pike and perch (predatory fish) were five to ten times higher than in non-predatory fish such as roach. Similarly, bioaccumulation factors in lakes with a low potassium concentration can be one order of magnitude higher than in lakes with a high potassium concentration. Thus it was observed [3.94] that fish from lakes in the agricultural areas of Belarus (where runoff of potassium fertilizer is significant) had lower bioaccumulation factors than fish from lakes in seminatural areas.

3.5.3.3. Strontium-90 in freshwater fish

Strontium behaves, chemically and biologically, in a similar way to calcium. Strontium is most

TABLE 3.8. RADIONUCLIDES IN VARIOUS SAMPLES TAKEN FROM THE BLACK SEA COAST DURING 1998–2001 [3.96]

Environmental sample	Caesium-137	Strontium-90	Plutonium-239, 240
Sea water (Bq/m ³)	14–29	12–28	$(2.4–28) \times 10^{-3}$
Beach sand and shells (Bq/kg)	0.9–8.0	0.5–60 (shell)	$(80–140) \times 10^{-3}$
Seaweeds, <i>Cystoseira barbata</i> (Bq/kg fresh weight)	0.2–2.3	0.4–0.9	$(9.0–14) \times 10^{-3}$
Mussels, <i>Mytilus galloprovincialis</i> (tissue, Bq/kg fresh weight)	0.3–1.7	0.02–3.2	$(1.5–2.5) \times 10^{-3}$
Fish, <i>Sprattus sprattus</i> , <i>Trachurus</i> (Bq/kg fresh weight)	0.2–6.0	0.02–0.7	$(0.3–0.5) \times 10^{-3}$

strongly bioaccumulated in low calcium ('soft') waters. The relatively low fish–water bioaccumulation factors for ⁹⁰Sr (of the order of 10² L/kg) and the lower fallout of this isotope meant that ⁹⁰Sr activity concentrations in fish were typically much lower than those of ¹³⁷Cs. In the Chernobyl cooling pond, ⁹⁰Sr activity concentrations were around 2 kBq/kg (whole fish) in fish during 1986, compared with around 100 kBq/kg for ¹³⁷Cs in 1993 [3.91]. In 2000, for the most contaminated lakes around Chernobyl, the maximum level of ⁹⁰Sr concentration in the muscles of predatory and non-predatory fish varied between 2 and 15 Bq/kg fresh weight. In 2002–2003, ⁹⁰Sr in fish in reservoirs of the Dnieper cascade was only 1–2 Bq/kg, which is close to the pre-Chernobyl level. Freshwater molluscs showed significantly higher bioaccumulation of ⁹⁰Sr than fish. In the Dnieper River, molluscs had approximately ten times more ⁹⁰Sr in their tissues than in fish muscle [3.132]. Similarly, the bioaccumulation of ⁹⁰Sr in the bones and skin of fish is approximately a factor of ten times higher than in muscle [3.130].

3.5.4. Radioactivity in marine ecosystems

Marine ecosystems were not seriously affected by fallout from Chernobyl, the nearest seas to the reactor being the Black Sea (around 520 km) and the Baltic Sea (about 750 km). The primary route of contamination of these seas was atmospheric fallout, with smaller inputs from riverine transport occurring over the years following the accident. Surface deposition of ¹³⁷Cs was approximately 2.8 PBq over the Black Sea [3.96, 3.133] and 3.0 PBq over the Baltic Sea [3.105].

3.5.4.1. Distribution of radionuclides in the sea

Radioactive fallout on to the surface of the Black Sea was not uniform and mainly occurred

during 1 and 3 May 1986 [3.105, 3.133]. In the Black Sea surface water concentrations of ¹³⁷Cs ranged from 15 to 500 Bq/m³ in June–July 1986, although by 1989 horizontal mixing of surface waters had resulted in relatively uniform concentrations in the range of 41–78 Bq/m³ [3.105], which by 2000 had declined to between 20 and 35 Bq/m³ [3.96].

In addition to the caesium isotopes, short lived radionuclides such as ¹⁴⁴Ce and ¹⁰⁶Ru were observed. The inventory of ¹³⁷Cs in the water of the Black Sea due to the Chernobyl deposition doubled the existing inventory of ¹³⁷Cs from global fallout from atmospheric nuclear weapon testing to approximately 3100 TBq. The amount of ⁹⁰Sr increased by 19% in comparison with the pre-Chernobyl period and was estimated to be about 1760 TBq [3.96, 3.105]. Vertical mixing of surface deposited radioactivity also reduced the maximum concentrations observed in water over the months to years after the fallout. Removal of radioactivity to deeper waters steadily reduced ¹³⁷Cs activity concentrations in the surface (0–50 m) layer of the Black Sea. The present situation with regard to the Black Sea marine environment is shown in Table 3.8 [3.96].

A significant proportion of the ¹³⁷Cs, ⁹⁰Sr and ^{239,240}Pu in the Black Sea originated from nuclear weapon testing rather than from the Chernobyl accident. The riverine radionuclide input to the Black Sea was much less significant than direct atmospheric fallout to the sea surface. Over the period 1986–2000, riverine input of ¹³⁷Cs was only 4–5% of the atmospheric deposition, although ⁹⁰Sr riverine inputs were more significant, being approximately 25% of the total inputs from atmospheric deposition [3.96, 3.134]. For the Baltic Sea, riverine inputs were at a similar level as for the Black Sea, being approximately 4% and 35% of atmospheric fallout for ¹³⁷Cs and ⁹⁰Sr, respectively [3.135]. The greater relative riverine input of ⁹⁰Sr is due to its weaker adsorption to catchment soils and lake and

river sediments and to lower ^{90}Sr atmospheric fallout (compared with ^{137}Cs) at large distances from the Chernobyl reactor site. Sedimentation processes in the marine environment, as in the freshwater environment, are an important factor in the 'self-purification' of the aquatic ecosystem. However, the sedimentation rate for the Black Sea is relatively low [3.96].

Data presented in Fig. 3.55 demonstrate that, in the central deep basin of the Black Sea, the Chernobyl deposition is covered by a layer of less than 1 cm of sediment formed since the accident [3.96].

Due to dilution and sedimentation, the concentration of ^{137}Cs quickly declined, reducing the seawater contamination at the end of 1987 to two to four times lower than that observed in the summer of 1986. The average ^{137}Cs activity concentration in the Baltic Sea estimated in Ref. [3.136] for the initial period after deposition was approximately 50 Bq/m^3 , with maximum values two to four times greater being observed in some areas of the sea.

3.5.4.2. Transfers of radionuclides to marine biota

Bioaccumulation of radiocaesium and radiostrontium in marine systems is generally lower than in freshwater, because of the much higher content of competing ions in saline water. The lower bioaccumulation of ^{137}Cs and ^{90}Sr in marine systems, and the large dilution in these systems, meant that activity concentrations in marine biota after the Chernobyl accident were relatively low. Table 3.8 gives examples of ^{137}Cs , ^{90}Sr and $^{239,240}\text{Pu}$ in water and marine biota of the Black Sea during the period 1998–2001 [3.96]. Detailed data on Baltic Sea fish contamination during the post-Chernobyl decades are available in Ref. [3.136], which shows that most species of fish had a relatively low level of radio-caesium contamination, in most cases in the range of 30–100 Bq/kg or less during the period up to 1995.

3.5.5. Radionuclides in groundwater

3.5.5.1. Radionuclides in groundwater: Chernobyl exclusion zone

Sampling of groundwater in the affected areas showed that radionuclides can be transferred from surface soil to groundwater. However, the level of the groundwater contamination in most areas

(excluding locations of radioactive waste storage and the Chernobyl shelter industrial site) is low. Furthermore, the rates of migration from the soil surface to groundwater are also very low. Some areas in the CEZ with relatively fast radionuclide migration to the aquifers were found in areas with morphological depressions [3.137]. Horizontal fluxes of radionuclides in groundwaters are also very low because of the slow flow velocity of groundwaters and high retardation of radionuclides [3.138].

Short lived radionuclides are not expected to affect groundwater supplies, because groundwater residence times are much longer than the physical decay time of short lived nuclides. The only significant transfer of radionuclides to groundwater has occurred within the CEZ. In some wells during the past ten years the ^{137}Cs activity concentration has declined, while that of ^{90}Sr has continued to increase in shallow groundwaters (Fig. 3.56). Transfer of radionuclides to groundwater has occurred from radioactive waste disposal sites in the

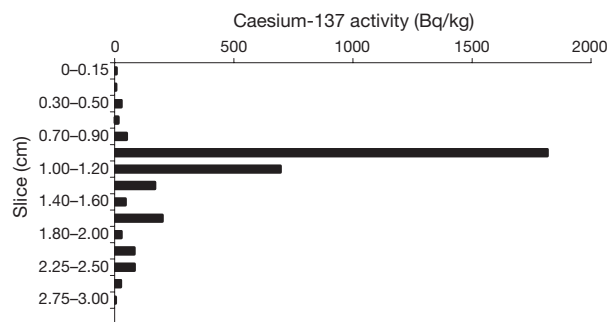


FIG. 3.55. Caesium-137 profile in the bottom sediment of the Black Sea (core BS-23/2000), taken during the IAEA Black Sea expedition in 2000 [3.96].

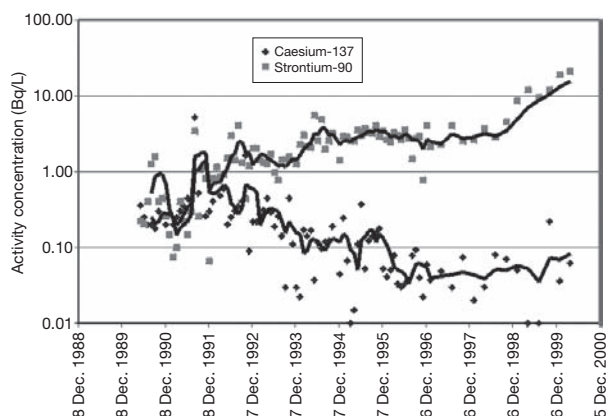


FIG. 3.56. Caesium-137 and ^{90}Sr in shallow groundwater in the Red Forest area near the Chernobyl industrial site [3.139].

CEZ. After the accident, FCM and radioactive debris were temporarily stored at industrial sites at the power station and in areas near the floodplain of the Pripyat River. In addition, trees from the Red Forest were buried in shallow unlined trenches. At these waste disposal sites, ^{90}Sr activity concentrations in groundwaters are, in some cases, of the order of 1000 Bq/L [3.140]. The health risks from groundwater consumption by hypothetical residents returning to these areas, however, were low in comparison with external radiation and radiation doses from the intake of foodstuffs [3.138].

Although there is a potential for off-site transfer of radionuclides from the disposal sites, Bugai et al. [3.138] concluded that this will not be significant in comparison with washout of surface deposited radioactivity. Studies have shown that groundwater fluxes of radionuclides are in the direction of the Pripyat River, but the rate of radionuclide migration is very low and does not present a significant risk to the Dnieper reservoir system. Off-site transport of groundwater contamination around the shelter is also expected to be insignificant, because radioactivity in the shelter is separated from groundwaters by an unsaturated zone of 5–6 m thickness, and groundwater velocities are low [3.138]. It is predicted that the maximum subsurface ^{90}Sr transport rate from waste disposal sites to surface water bodies will occur from 33 to 145 years after the accident. The maximum cumulative transport from all the sources described above is estimated to be 130 GBq over approximately 100 years, or 0.02%/a of the total inventory within the contaminated catchments. Integrated radionuclide transport for a 300 year period is estimated by Bugai et al. [3.138] to be 15 TBq, or 3% of the total initial inventory of radioactive material within the catchments (Fig. 3.57).

The water level of the Chernobyl cooling pond significantly influences groundwater flows around the Chernobyl site. Currently, the water level of the cooling pond is kept artificially high, at 6–7 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 the pumping of water into the pond is terminated. As the pond dries out, the sediments will be partly exposed and subject to dispersal. Recent studies suggest that the best strategy for remediation of the cooling pond is to allow the water level to decline naturally, with some limited action to prevent secondary wind resuspension using phytoremediation techniques [3.141].

When the water level in the cooling pond declines to that of the river water surface level, this will lead to reduction of groundwater fluxes from the Chernobyl industrial site towards the river. This will also reduce radionuclide fluxes from the main radioactive waste disposal sites and the shelter to the Dnieper cascade. The groundwater fluxes of ^{90}Sr from the Chernobyl shelter to the Pripyat River have been modelled within the framework of environmental impact assessment studies for the NSC to be erected above the shelter [3.142] (see Fig. 3.58). It has been predicted that it would take approximately 800 years for ^{90}Sr to reach the Pripyat River. With its half-life of 29.1 years, the activity of ^{90}Sr would reduce to an insignificant level during this time. Thus infiltration of ^{90}Sr from the shelter will not cause harmful impacts on the Pripyat River. Caesium-137 moves much more slowly than ^{90}Sr , and even after 2000 years its plume is predicted to be only 200 m from the shelter.

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

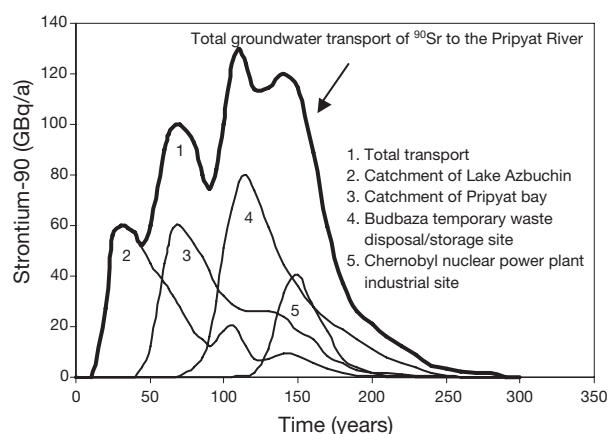


FIG. 3.57. Prediction of ^{90}Sr transport via the groundwater pathway to the Pripyat River in the Chernobyl nuclear power plant near zone [3.138].

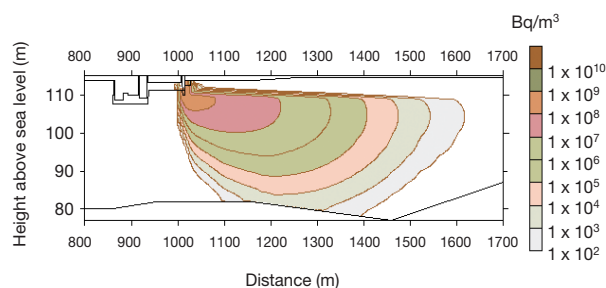


FIG. 3.58. Predicted ^{90}Sr groundwater concentration (Bq/m^3) in the vicinity of the Chernobyl shelter without the NSC after 100 years [3.142].

years). The maximum groundwater ^{239}Pu influx from the shelter into the Pripyat River is predicted to be 2 Bq/s. When this influx is fully mixed with the average Pripyat River discharge of 400 m³/s, the resulting ^{239}Pu concentration in the river would be only 0.005 Bq/m³, as compared with the current ^{239}Pu level of 0.25 Bq/m³ [3.142]. In Ukraine the regulatory limit for ^{239}Pu in water is 1 Bq/m³. Thus infiltration of ^{239}Pu from the shelter, even without the NSC, will not cause any significant impact on the Pripyat River.

3.5.5.2. Radionuclides in groundwater: outside the Chernobyl exclusion zone

The most detailed current studies of groundwater contamination in the far zone (beyond the CEZ) [3.137, 3.143] have concluded that ten years after the initial surface ground pollution, the levels of ^{137}Cs and ^{90}Sr in groundwater of the upper horizons of the aquifer were 40–50 mBq/L around Kiev and 20–50 mBq/L in the Bryansk region of the Russian Federation and the majority of the contaminated areas in Belarus. In these areas, far from the Chernobyl reactor (in Belarus and the Russian Federation), the ^{137}Cs activity concentration of water in the saturated zone of soils had a significant correlation with the ^{137}Cs soil deposition. In most of the studied area the activity concentration in groundwater (per unit of ^{137}Cs soil deposition) was significantly lower than in most river and lake systems. All studies reported that the radionuclide concentration in the contaminated area outside the CEZ never exceeded the safety level for consumption of water and was usually several orders of magnitude below it.

After fallout from nuclear weapon testing, it was observed that ^{90}Sr in Danish groundwater was

approximately ten times lower than in surface streams [3.144]. Reference [3.144] also shows that after the Chernobyl accident, although there were measurable quantities of ^{137}Cs in streams, activity concentrations in groundwater were below detection limits.

3.5.5.3. Irrigation water

In the Dnieper River basin there is more than 1.8×10^6 ha of irrigated agricultural land. Almost 72% of this territory is irrigated with water from the Kakhovka reservoir and other Dnieper reservoirs. Accumulation of radionuclides in plants on irrigated fields can take place via root uptake of radionuclides introduced with irrigation water and due to direct incorporation of radionuclides through leaves due to sprinkling. However, in the case of the irrigated lands of southern Ukraine, radionuclides in irrigation water did not add significant radioactivity to crops in comparison with that which had been initially deposited in atmospheric fallout and subsequently taken up in situ from the soil [3.145].

3.5.6. Future trends

3.5.6.1. Freshwater ecosystems

For the rivers and reservoirs of the Dnieper system, the intensity of runoff of radionuclides will gradually reduce. In the worst case scenario, hydrological runoff during the next 50 years [3.146] would cause average concentrations of ^{137}Cs and ^{90}Sr approaching pre-accident levels. Contamination levels of the water and the main consumer fish species in the reservoirs of the middle and lower Dnieper River will approach background levels (Fig. 3.59). At the same time, in the isolated (closed)

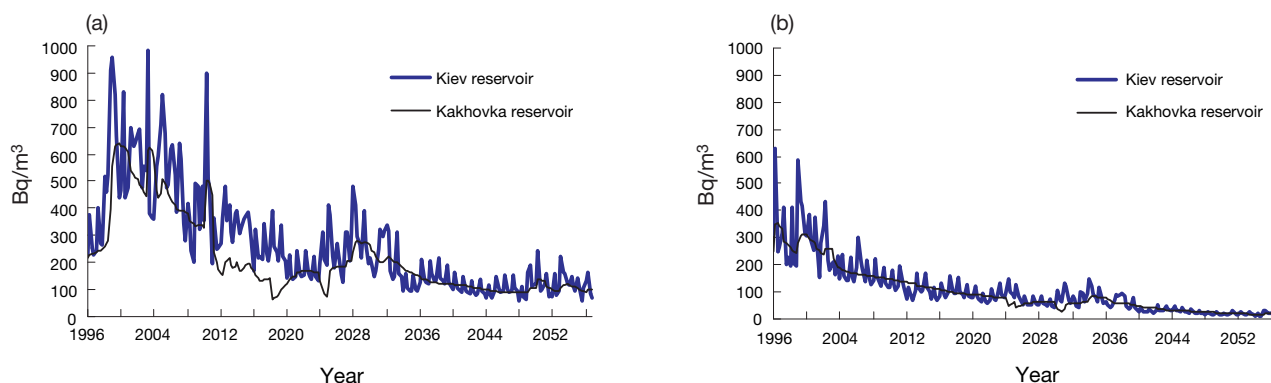


FIG. 3.59. Predicted concentrations of ^{90}Sr in water of the upper and downstream reservoirs for the worst (a) and best (b) probabilistic hydrological scenarios expected for the Pripyat River basin [3.146].

water bodies of the contaminated territories, increased contents of ^{137}Cs , both in water and aquatic biota, will be maintained for several decades.

Recent data [3.95, 3.147] show that, at present, ^{137}Cs activity concentrations in surface water and fish are declining quite slowly. The effective ecological half-life in water and young fish has increased from one to four years during the first five years after the accident to six to 30 years in recent years. Future contamination levels can be estimated with the use of an estimated long term decline of radiocaesium activity concentrations in water and fish with an effective ecological half-life (T_{eff}) of

approximately 20 years, although there is wide variation in the rates of decline [3.125].

Activity concentrations of radiocaesium in water are, at present, relatively low (1 Bq/L at most), except in the shallow closed lakes in the CEZ and in other highly contaminated areas. Activity concentrations are expected to continue to decline slowly during the coming decades. In some lakes, however, ^{137}Cs activity concentrations in both water and fish are expected to remain relatively high for some decades, as illustrated in Tables 3.9 and 3.10. Activity concentrations of ^{90}Sr in water were also estimated using a predicted T_{eff} of 20 years. This may, again, be slightly conservative, as long term

TABLE 3.9. CAESIUM-137 ACTIVITY CONCENTRATIONS IN WATER IN VARIOUS CHERNOBYL AFFECTED LAKES AROUND EUROPE AND PREDICTIONS FOR 30, 50 AND 70 YEARS AFTER THE ACCIDENT [3.125]

	Measured ^{137}Cs (Bq/L) (year of measurement)	Predicted ^{137}Cs (Bq/L)		
		2016	2036	2056
Lake Kozhanovskoe, Russian Federation	7.0 (2001)	4.2	2.1	1.0
Kiev reservoir, Ukraine	0.028 (1998)	0.015	0.007	0.004
Chernobyl cooling pond	2.5 (2001)	1.5	0.8	0.4
Lake Svyatoye, Belarus ^a	4.7 (1997)	2.4	1.2	0.6
Lake Vorsee, Germany	0.055 (2000)	0.032	0.016	0.008
Devoke Water, UK	0.012 (1998)	0.006	0.003	0.002

^a This lake had a countermeasure applied in 1998. The prediction is for levels in the absence of countermeasures.

TABLE 3.10. CAESIUM-137 ACTIVITY CONCENTRATIONS (PER UNIT FRESH WEIGHT) IN FISH IN VARIOUS CHERNOBYL AFFECTED LAKES AROUND EUROPE AND PREDICTIONS FOR 30, 50 AND 70 YEARS AFTER THE ACCIDENT [3.125]

	Fish species	Measured ^{137}Cs (Bq/kg) (year of measurement)	Predicted ^{137}Cs (Bq/kg fresh weight)		
			2016	2036	2056
Lake Kozhanovskoe, Russian Federation	Goldfish	10 000 (1997)	5 200	2 600	1 300
Kiev reservoir, Ukraine	Perch	300 (1997)	160	80	40
Chernobyl cooling pond	Perch	18 000 (2001)	11 000	5 400	2 700
Lake Svyatoye, Belarus ^a	Perch	104 000 (1997)	54 000	27 000	14 000
Lake Vorsee, Germany	Pike	174 (2000)	100	50	25
Lake Høysjøen, Norway	Trout	390 (1998)	210	100	50
Devoke Water, UK	Trout	370 (1996–1998)	200	100	50

^a This lake had a countermeasure applied in 1998. The prediction is for levels in the absence of countermeasures.

rates of decline of ^{90}Sr from weapons testing had a T_{eff} of about ten years [3.148]. Similar to ^{137}Cs , activity concentrations of ^{90}Sr in water are expected to decline from their current low levels during the coming decades (Table 3.11).

Fuel particle breakdown took place at a much slower rate in lake sediments than in soils [3.149]. The half-life of fuel particles in sediments in the cooling pond is approximately 30 years [3.39], and hence radionuclides in fuel particles will remain in their original form for many years.

3.5.6.2. Marine ecosystems

At present, radionuclides (mainly radio-caesium) in marine systems are at much lower concentrations than those observed in freshwater systems. Activity concentrations in sea water and marine biota in the Black Sea are expected to continue to decline (see Table 3.8). This is mainly due to physical decay, but continued transfers to seabed sediments and further dilution will also contribute to the decline.

3.6. CONCLUSIONS

The highest radionuclide deposition occurred in Belarus, the Russian Federation and Ukraine, but high depositions also occurred in a number of other European countries.

Most of the strontium and plutonium radionuclides were deposited close to the reactor and were associated with fuel particles. The environmental mobility of these radionuclides was lower than that of the fallout associated with condensed particles, which predominated in other areas, although the

bioavailability of ^{90}Sr has increased with time as the fuel particles have partially dissolved.

Most of the originally released radionuclides have disappeared, due to radioactive decay; ^{137}Cs is currently of most concern. In the long term future (more than 100 years) only plutonium isotopes and ^{241}Am will remain.

The deposition in urban areas in the nearest city of Pripjat and surrounding settlements could have initially given rise to a substantial external dose to the inhabitants, which was averted by the evacuation measures. The deposition of radioactive material in other urban areas has provided substantial contributions to the dose to humans during the years after the accident and up to the present.

During the first weeks to months after the accident, the transfer of short lived radioiodine isotopes to milk was rapid and high, leading to substantial doses to humans in the former USSR. Due to the emergency situation and the short half-life of ^{131}I , there are few reliable data on the spatial distribution of deposited radioiodine. Current measurements of ^{129}I may assist in estimating ^{131}I deposition better and thereby improve thyroid dose reconstruction.

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

Due to radioactive decay, rain and wind, human activities, and countermeasures, surface contamination in urban areas by radioactive material has been substantially reduced. External doses in urban areas, compared with open areas, are reduced by shielding effects.

TABLE 3.11. STRONTIUM-90 ACTIVITY CONCENTRATIONS IN WATER IN VARIOUS CHERNOBYL AFFECTED LAKES AND RIVERS AND PREDICTIONS FOR 30, 50 AND 70 YEARS AFTER THE ACCIDENT [3.125]

	Measured ^{90}Sr (Bq/L) (year of measurement)	Predicted ^{90}Sr (Bq/L)		
		2016	2036	2056
Pripjat River	0.28 (1998)	0.15	0.08	0.04
Kiev reservoir	0.16 (1998)	0.09	0.04	0.02
Chernobyl cooling pond	2.0 (2001)	1.2	0.6	0.3
Lake Glubokoye, CEZ	120 (2004)	80–90	40–60	20–30

At present, in most of the settlements subjected to radioactive contamination, the radiation dose rate above solid surfaces has returned to the pre-accident background level. Elevated dose rates remain mainly in areas of undisturbed soil.

From the summer of 1986 onwards, ^{137}Cs was the dominant radionuclide of concern in agricultural products (milk and meat). During the first few years, substantial amounts of food were discarded from human consumption. The highest activity concentrations of ^{137}Cs have been found in food products from forest areas, especially in mushrooms, berries, game and reindeer. High ^{137}Cs activity concentrations in fish occur in lakes with slow or no turnover of water, particularly if the lake is also shallow and mineral nutrient poor.

The importance of ^{90}Sr in food products is lower than that of ^{137}Cs because of its lower deposition and because milk is the only major animal food product to which it is transferred. Strontium accumulation in the bones of agricultural animals and fish occurs but does not typically lead to radiation doses to humans.

There have been large long term variations in ^{137}Cs activity concentrations in food products, due not only to deposition levels but also to differences in soil types and management practices. In many areas there are still food products, particularly from extensive agricultural production systems and forests, with ^{137}Cs activity concentrations exceeding the intervention limits. Large land areas in the former USSR are still excluded from agricultural production for radiological reasons.

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

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

There has been a particularly slow decrease since deposition in ^{137}Cs activity concentrations in some products from forests, and some species of mushrooms are expected to have high ^{137}Cs activity

concentrations for decades to come. Under certain weather and ecological conditions, the biomass of mushrooms in autumn can be much higher than normal, leading to relatively high seasonal increases in ^{137}Cs activity concentrations in game. Thus it must not always be assumed that ^{137}Cs activity concentrations in animals will remain as they are now or decline each year.

Radiocaesium in timber is of minor importance, although doses in the timber industry have to be considered. Wood ash can contain higher amounts of ^{137}Cs . Forest fires have increased the air activity concentrations in local areas, but not to a high extent.

Due to dilution, there were never high concentrations of ^{137}Cs in marine fish in the Black Sea or the Baltic Sea.

3.7. FURTHER MONITORING AND RESEARCH NEEDED

Updated mapping of ^{137}Cs deposition in Albania, Bulgaria and Georgia should be performed in order to complete the study of post-Chernobyl contamination of Europe.

Improved mapping of ^{131}I deposition, based both on historical environmental measurements carried out in 1986 and on recent measurements of ^{129}I in soil samples in areas where elevated thyroid cancer incidence has been detected after the Chernobyl accident, would reduce the uncertainty of the thyroid dose reconstruction needed for determination of radiation risks.

Long term monitoring of ^{137}Cs and ^{90}Sr activity concentrations in agricultural vegetable and animal products produced in areas with various soil and climate conditions and different agricultural practices should be performed for decades to come within focused research programmes at selected sites.

The study of the distribution of ^{137}Cs and plutonium radionuclides in the urban environment (Pripyat, Chernobyl and some other contaminated towns) in the future would improve the modelling of human external exposure and inhalation of radionuclides for possible application to any future nuclear or radiological accident or malicious action.

The continued long term monitoring of specific forest products such as mushrooms and game needs to be carried out in those areas in which forests were significantly contaminated. The results from such monitoring are being used by the relevant

authorities in affected countries to provide advice to the general public on the continued use of forests for recreation and the gathering of wild foods.

In addition to the general monitoring of forest products, required for radiation protection, more detailed, scientifically based, long term monitoring of specific forest sites is required to provide an ongoing and improved understanding of the long term dynamics and persistence of radiocaesium contamination and its variability. Such monitoring is also necessary to improve the existing predictive models. Monitoring programmes are being carried out in several of the more severely affected countries, such as Belarus and the Russian Federation, and it is important that these continue for the foreseeable future if current uncertainties in long term forecasts are to be reduced.

Aquatic systems have been intensively studied and monitored during the years after the Chernobyl accident, and transfers and bioaccumulation of the most important long term contaminants, ^{90}Sr and ^{137}Cs , are now well understood. There is therefore little urgent need for major new research programmes on radionuclides in aquatic systems. There is, however, a requirement for continued (but perhaps more limited) monitoring of the aquatic environment and for further research in some specific areas, as detailed below.

Predictions of the future contamination of aquatic systems with ^{90}Sr and ^{137}Cs would be improved by continued monitoring of radioactivity in key systems (the Pripyat–Dnieper system, the seas, and selected rivers and lakes in the more affected areas and western Europe). This would continue the time series measurements of activity concentrations in water, sediments and fish and enable the refinement of predictive models for these radionuclides.

Although they are currently of minor radiological importance in comparison with ^{90}Sr and ^{137}Cs , further studies of transuranic elements in the Chernobyl accident area would improve predictions of environmental contamination in the very long term (hundreds to thousands of years). Further empirical studies of transuranic elements and ^{99}Tc are unlikely to have direct implications for radiological protection in the Chernobyl affected areas, but would further add to our knowledge of the environmental behaviour of these very long lived radionuclides.

Future plans to reduce the water level of the Chernobyl cooling pond will have significant implications for its ecology and the behaviour of radionu-

clides/fuel particles in newly exposed sediments. Specific studies on the cooling pond should therefore continue. In particular, further study of fuel particle dissolution rates in aquatic systems such as the cooling pond would improve knowledge of these processes.

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4. ENVIRONMENTAL COUNTERMEASURES AND REMEDIATION

The need for the application of urgent protective actions became evident very soon after the Chernobyl accident occurred. A wide range of countermeasures was applied for protecting the public from radiation, from urgent evacuation in 1986 of the inhabitants from the area of highest radioactive contamination to long term monitoring of radionuclides in foodstuffs in many European countries. The whole spectrum of the applied countermeasures and their effectiveness have been considered in a number of international reports [4.1–4.7].

The main subject of this section is the countermeasures that have been applied to the environment in order to reduce the radiological impact on humans. At the time of the Chernobyl accident the philosophy of radiation protection of non-human species had not been sufficiently developed to be practically applied for the purposes of justifying appropriate countermeasures. Such policies are currently still under development [4.8].

This section does not consider specifically the emergency and mitigatory actions applied to the damaged reactor aimed at reducing radioactive releases to the environment; these aspects have been covered elsewhere [4.2].

Environmental countermeasures have been applied since 1986 to urban, agricultural, forest and aquatic ecosystems. Most of these countermeasures were driven by relevant international and national radiological criteria.

4.1. RADIOLOGICAL CRITERIA

Countermeasures, termed protective actions at the emergency stage and remedial actions at the post-emergency stage, are actions taken to reduce the level of exposure as much as is reasonably achievable. A fundamental aspect of radiation protection philosophy is to optimize the dose averted against the costs of applying the countermeasure. However, the costs and benefits of countermeasures are not always quantifiable in purely monetary terms. The advantages of countermeasures often include reassurance and a decrease in anxiety in the affected population. However,

countermeasures may also have negative consequences, either directly to ecosystems (e.g. disruption of nutrient cycles) or to sectors of the population either economically or due to disruption of normal life.

4.1.1. International radiological criteria and standards

At the time of the Chernobyl accident in 1986, the relevant international radiation protection standards for protection of the public and workers were contained in International Commission on Radiological Protection (ICRP) Publication 26 [4.9]. Specific recommendations on the protection of the public in the event of a major radiation accident were given in ICRP Publication 40 [4.10]. The corresponding IAEA Basic Safety Standards, based on ICRP recommendations, were issued in 1982 [4.11]. The basic principles of modern radiation protection — justification, optimization and dose limitation — and the clear distinction between protection in normal and intervention situations were contained in these documents. At that time, the annual limit for occupational exposure was equal to 50 mSv and that for public exposure was 5 mSv. The latter value was perceived as a safe level of human exposure.

Special limits for public radiation protection in the event of nuclear or radiological emergencies were not specifically established in these documents, and instead it was recommended:

- (a) By almost all means to reduce human accidental exposure below doses that may result in deterministic health effects (acute radiation syndrome, radiation damage to particular organs or tissues);
- (b) To intervene (i.e. to apply and subsequently withdraw countermeasures aimed at reducing stochastic health effects (cancer, genetic anomalies)) based on an optimization assessment taking into account both the collective dose reduction achieved by the application of the countermeasures and the associated economic and social intervention costs.

The most relevant ICRP guidance [4.10] recommended some generic two level criteria for intervention in the early accident phase — for sheltering, 5–50 mSv of whole body dose or 50–500 mSv to particular organs; for administration of stable iodine aimed at thyroid protection against intake of radioiodines, 50–500 mSv to the thyroid; for evacuation, 50–500 mSv of whole body dose or 500–5000 mSv to particular organs. For the intermediate accident phase, the generic criteria of 5–50 mSv of whole body dose or 50–500 mSv to particular organs were recommended for control of foodstuff contamination with radionuclides, and 50–500 mSv of whole body dose for relocation.

Afterwards, in connection with public concerns over the radiological consequences of the Chernobyl accident, new additional international regulations were developed. Thus in 1989 the Codex Alimentarius Commission approved guidance levels for radionuclides in food moving in international trade for the first year after a major nuclear accident (see Table 4.1) [4.12].

New international basic radiation protection standards for the protection of the public and workers were developed by the ICRP in 1990 after research data had shown that radiation risk coefficients for stochastic human health effects were substantially higher than previously thought. The annual limits of exposure were substantially (by a factor of 2.5–5) reduced and established equal to 20 mSv for workers and 1 mSv for members of the general public [4.13]. The latter value is currently perceived as a safe level of human exposure.

Special limits for public protection in the event of nuclear or radiological emergencies were not established in these documents. Appropriate specific recommendations were developed later on

intervention for the protection of the public in a radiological emergency [4.14]. In this guidance the optimization concept was confirmed as the basic one applicable in the event of an emergency and further elaborated with regard to dose averted as the consequence of intervention (see Fig. 4.1). The ICRP discarded the previous two level intervention criteria and recommended instead some intervention levels (in terms of averted effective dose) — 50 mSv for sheltering, 500 mSv (thyroid dose) for administration of stable iodine, 500 mSv for evacuation, 1000 mSv (lifetime dose) for relocation and 10 mSv/a for the control of foodstuffs.

A more recent ICRP publication (Publication 82) [4.15] considered public radiation protection in conditions of prolonged radiation exposure, such as in areas contaminated due to the Chernobyl accident. In this document, the ICRP generally recommends retaining the optimization principle, but also suggests generic radiological criteria for making decisions on countermeasure application. In particular, it proposes the value of the ‘existing annual dose’, including external and internal doses from natural and human-made radionuclides, of 10 mSv as the generic dose below which intervention is not usually expedient. This does not exclude intervention at lower doses if site specific optimization analysis proves it to be expedient. Inter alia, the ICRP recommended a generic intervention exemption level for radionuclides in commodities dominating human exposure equal to 1 mSv/a. This criterion could be applied for justification of the reference levels for radionuclides in food.

TABLE 4.1. GUIDELINE LEVELS FOR RADIONUCLIDES IN FOOD FOLLOWING ACCIDENTAL NUCLEAR CONTAMINATION, FOR USE IN INTERNATIONAL TRADE [4.12]

	Food for general consumption (Bq/g)	Milk and infant food (Bq/g)
Caesium-134, 137	1	1
Iodine-131	1	0.1
Strontium-90	0.1	0.1
Plutonium-239, americium-241	0.01	0.001

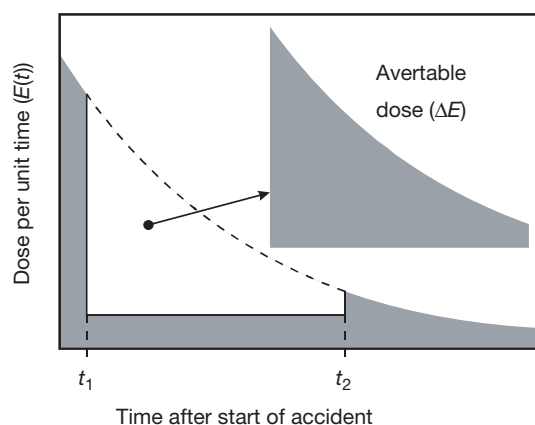


FIG. 4.1. Avertable dose and effective dose accumulated per unit time as a function of time when the protective measure is introduced at time t_1 and lifted again at time t_2 .

4.1.2. National radiological criteria and standards

Limitations on human exposure caused by the Chernobyl accident, including standards for radionuclides in food, drinking water, timber, etc., were introduced soon after the accident, first by the USSR but also by many other European countries (i.e. Nordic countries, EU countries and eastern European countries [4.1]).

In accordance with the Standards of Radiation Safety [4.16] in force in 1986, the USSR Ministry of Health introduced a temporary limit of average equivalent whole body dose of 100 mSv for the first

year after the Chernobyl accident (from 26 April 1986 until 26 April 1987), then 30 mSv for the second year and 25 mSv in each of 1988 and 1989 [4.3]. In all, until 1 January 1990, a dose to the general public not exceeding 173 mSv was allowed from the radioactive fallout of the Chernobyl accident.

In order to limit the internal exposure of members of the population, temporary permissible levels (TPLs) of radionuclide content in food products and drinking water were introduced in the USSR. Table 4.2 presents the TPLs for the main food products [4.3, 4.17]. The first TPL set approved

TABLE 4.2. TEMPORARY PERMISSIBLE LEVELS (Bq/kg) OF RADIONUCLIDE CONTENT IN FOOD PRODUCTS AND DRINKING WATER ESTABLISHED IN THE USSR (1986–1991) AFTER THE CHERNOBYL ACCIDENT [4.3, 4.17]

	TPL				
	4104–88	129–252	TPL-88	TPL-91	
	6 May 1986	30 May 1986	15 December 1987	22 January 1991	
Radionuclide	Iodine-131	Beta emitters	Caesium-134 and caesium-137	Caesium-134 and caesium-137	Strontium-90
Drinking water	3700	370	18.5	18.5	3.7
Milk	370–3700	370–3700	370	370	37
Dairy products	18 500–74 000	3700–18 500	370–1850	370–1850	37–185
Meat and meat products	—	3700	1850–3000	740	—
Fish	37 000	3700	1850	740	—
Eggs	—	37 000	1850	740	—
Vegetables, fruit, potato, root crops	—	3700	740	600	37
Bread, flour, cereals	—	370	370	370	37

TABLE 4.3. ACTION LEVELS (Bq/kg) FOR CAESIUM RADIONUCLIDES IN FOOD PRODUCTS ESTABLISHED AFTER THE CHERNOBYL ACCIDENT [4.3, 4.5]

	Action level				
	Codex Alimentarius Commission	EU	Belarus	Russian Federation	Ukraine
	1989	1986	1999	2001	1997
Milk	1000	370	100	100	100
Infant food	1000	370	37	40–60	40
Dairy products	1000	600	50–200	100–500	100
Meat and meat products	1000	600	180–500	160	200
Fish	1000	600	150	130	150
Eggs	1000	600	—	80	6 Bq/egg
Vegetables, fruit, potato, root crops	1000	600	40–100	40–120	40–70
Bread, flour, cereals	1000	600	40	40–60	20

by the USSR Ministry of Health on 6 May 1986 concerned ^{131}I activity concentrations in foodstuffs and was aimed at limiting the thyroid dose to children to 300 mGy. The next TPL set, adopted on 30 May 1986, concerned the content of all beta emitters in food products caused by surface contamination, with particular attention given to ecologically mobile and long lived caesium radionuclides. Later, TPLs introduced in 1988 (TPL-88) and 1991 (TPL-91) concerned the sum of ^{134}Cs and ^{137}Cs activities. The TPL-91 for caesium radionuclides was supplemented by TPLs for ^{90}Sr .

Annual consumption by rural inhabitants of the usual food ration, if all components contained caesium radionuclides at the level of TPL-86, would cause an internal dose of less than 50 mSv (at TPL-88 it would be less than 8 mSv and at TPL-91 it would be less than 5 mSv).

Action levels for ^{131}I in food established in some European countries in May 1986 varied within the range of 500–5000 Bq/kg. Later, the authorities of the EU established two values for caesium radionuclides in imported food, one for milk and infant food and another for all other food products (see Table 4.3) [4.3, 4.5]. Similar values were introduced in Nordic countries, with an exception for wild foods (reindeer meat, game, freshwater fish, forest berries, fungi and nuts), which are important products for some local populations and especially for indigenous people. Thus in the first month Sweden imposed action levels of 5 kBq/kg for ^{131}I and 10 kBq/kg for ^{137}Cs in imported food; for domestic foods the respective values were 2 and 1 kBq/kg. In the middle of May, action levels of 300 Bq/kg for ^{137}Cs in all food and 2 kBq/kg for ^{131}I in milk and dairy products were introduced. For wild foods produced or consumed in the Nordic countries, the action levels varied between 1500 and 6000 Bq/kg in different countries and time periods.

Along with the standards for food products, standards were introduced by the USSR for agricultural raw material, wood (see Section 4.3) and herbs, and for beta contamination of different surfaces [4.3].

The general policy of the USSR, and later of the authorities in the separate republics, was to reduce both the radiological criteria and the TPLs along with the natural improvement of radiological conditions due to radionuclide decay and penetration/fixation in soil. Gradual TPL reduction has been used as an instrument to force producers to apply technologies that decrease radionuclide content in products in order to limit associated

human exposure. The TPLs were established by experts balancing the desire to reduce internal dose in populations with the need to maintain profitable agricultural production and forestry in the controlled areas. Different reference levels for numerous groups of food products were established with the aim of not restricting consumption of any foods unless the dose criterion might be exceeded.

By the end of 1991 the USSR had split into separate countries, among them Belarus, the Russian Federation and Ukraine, which had been strongly affected by the Chernobyl accident. Afterwards each country implemented its own policy of radiation protection of the public. Owing to the acceptance by the ICRP in 1990 of the annual effective dose limit for the public in regulated situations (practices) equal to 1 mSv, this level was considered by the authorities of the three countries as safe also in post-emergency conditions. Therefore it is still used in national legislations as an intervention level of annual dose caused by Chernobyl fallout for the introduction of countermeasures, including long term remediation measures.

Current national TPLs for food products, drinking water and wood in the three countries are comparable with each other (see Table 4.3), and all of them are substantially lower than both the EU maximum permissible levels for import [4.5] and the Codex Alimentarius Commission's guidance levels for radionuclides in food moving in international trade [4.12].

The State authorities in the three countries have struggled to meet the established TPLs for products and the dose criteria by implementation of environmental countermeasures as described below and by inspection of foods throughout each country.

4.2. URBAN DECONTAMINATION

Decontamination of settlements was one of the main countermeasures applied to reduce external exposure of the public and cleanup workers during the initial stage of response to the Chernobyl accident. The immediate purpose of settlement decontamination was the removal of radiation sources distributed in urban environments inhabited by humans.

Analysis of the sources of external exposure in different population groups living in contaminated areas revealed that a significant fraction of dose is received by people from sources located in soil, on coated surfaces such as asphalt and concrete and to

a small extent on building walls and roofs. This is why most effective decontamination technologies involved removal of the upper soil layer.

The decontamination efficiency can be characterized by means of the following parameters: the dose rate reduction factor (DRRF), which is the relative reduction of dose rate above a surface following decontamination, and the dose reduction factor (DRF), which is the reduction of the effective external dose to an individual from gamma emitting radionuclides deposited in the environment.

4.2.1. Decontamination research

In order to ensure high decontamination effectiveness and to keep the associated costs low, several research projects have been implemented aimed at determining the values of the DRRF and DRF for particular decontamination technologies applied to different surfaces and artefacts in the human environment [4.18–4.20]. Reports from these experimental and theoretical studies contain validated models of urban decontamination and sets of model parameters and practical recommendations for cleanup in different time periods after urban radioactive contamination. A preliminary remediation assessment based on well developed cost–benefit techniques is recommended in order to justify decontamination and to optimize its implementation.

According to these and other studies, the contributions of different urban surfaces to the human external dose and the associated opportunities for dose reduction are determined by settlement and house design, construction material, the habits of the populations, the mode of radionuclide deposition (dry or wet), the radionuclide and physicochemical composition of the fallout, and time (see Section 3.2).

Following dry deposition, street cleaning, removal of trees and shrubs and ploughing of gardens are efficient and inexpensive means of achieving very significant reductions in dose and would rate highly in a list of short term remediation priorities. Roofs are important contributors to dose, but the cost of cleaning roofs is high and this countermeasure would not rank highly in a list of priorities. Walls contribute little to dose, are expensive and difficult to decontaminate and would therefore carry a very low rating.

In the case of wet deposition, gardens and lawns, both in the short term and the long term,

would be given first priority, because a considerable reduction in dose (~60%) can be achieved at relatively low cost. Street cleaning would also be of benefit.

While planning decontamination for the long term, it is important to take into account the contribution of external dose to the total (external and internal) dose. In areas dominated by clay soils, transfer of caesium radionuclides in the food chain and the associated internal doses are low. In these areas the relative decrease in the total dose is close to the DRF value. In contrast, in sandy and peaty soil areas, where long term internal exposure dominates, the relative decrease in the total dose due to village decontamination is expected to be less significant.

4.2.2. Chernobyl experience

Large scale decontamination was performed between 1986 and 1989 in the cities and villages of the USSR most contaminated after the Chernobyl accident. This activity was performed usually by military personnel and included washing of buildings with water or special solutions, cleaning of residential areas, removal of contaminated soil, cleaning and washing of roads, and decontamination of open water supplies. Special attention was paid to kindergartens, schools, hospitals and other buildings frequently visited by large numbers of persons. In total, about one thousand settlements were treated; this included cleaning tens of thousands of residences and public buildings and more than a thousand agricultural farms [4.18, 4.21, 4.22].

In the early period following the accident, inhalation of resuspended radioactive particles of soil and nuclear fuel could contribute significantly to internal dose. To suppress dust formation, dispersion of organic solutions over contaminated plots was used in order to create an invisible polymer film after drying. This method was implemented at the Chernobyl nuclear power plant and in the CEZ during the spring and summer of 1986. Streets in cities were watered to prevent dust formation and to remove radionuclides to the sewerage system. The effectiveness of early decontamination efforts in 1986 still remains to be quantified. However, according to Los and Likhtarev [4.23] daily washing of streets in Kiev decreased the collective external dose to its three million inhabitants by 3000 man Sv, and decontamination of schools and school areas saved another 600 man Sv.

Depending on the decontamination technologies used, the dose rate over different measured plots was reduced by a factor of 1.5–15. However, the high cost of these activities hindered their comprehensive application on contaminated areas. Due to these limitations, the actual effectiveness of the decrease in annual external dose was 10–20% for the average population and ranged from about 30% for children visiting kindergartens and schools to less than 10% for outdoor workers (herders, foresters, etc.). These data were confirmed by individual external dose measurements conducted before and after large scale decontamination campaigns in 1989 in the Bryansk region of the Russian Federation [4.18].

Regular monitoring of decontaminated plots in settlements over five years showed that after 1986 there was no significant recontamination and that the exposure rate was decreasing over the long term, as described in Section 5.1 of this report. The averted collective external dose to 90 000 inhabitants of the 93 most contaminated settlements of the Bryansk region was estimated to be about 1000 man Sv [4.18].

Since 1990 large scale decontamination in the countries of the former USSR has been stopped, but particular contaminated plots and buildings with measured high contamination levels have been specifically cleaned. Some decontamination activities still continue in Belarus, aimed mostly at public buildings and areas: hospitals, schools, recreation areas, etc. However, in some contaminated Belarusian villages, cleanup of dwellings and farms has also been performed [4.22].

Another area of continuing decontamination activity is the cleanup of industrial equipment and premises contaminated as a result of ventilation systems being operated during the release/deposition period in 1986 and immediately afterwards. Some 20 to 30 industrial buildings and ventilation systems have been decontaminated annually in Belarus [4.22].

4.2.3. Recommended decontamination technologies

In accordance with present radiation protection methodology, a decision on intervention (decontamination) and selection of optimal decontamination technologies should be made giving consideration to the costs of all actions and to social factors. The calculated cost should address the various decontamination technologies for which an

assessment of the averted dose has been made. The benefit (averted collective effective dose) and detriment (expenses, collective dose to decontamination workers) are to be compared for each decontamination technology by means of a cost–benefit analysis [4.9] or multiattribute analysis [4.24], which may include qualitative social factors.

The priorities that different procedures would be given in a decontamination strategy should be environment specific. Nevertheless, based on accumulated experience and research, the following generic set of the major simple decontamination procedures can be recommended for the long term:

- (a) Removal of the upper 5–10 cm layer (depending on the activity–depth distribution) of soil in courtyards in front of residential buildings, around public buildings, schools and kindergartens, and from roadsides inside a settlement. The removed, most contaminated, layer of soil should be placed into holes specially dug on the territory of a private homestead or on the territory of a settlement. The clean soil from the holes should be used to cover the decontaminated areas. Such a technology excludes the formation of special burial sites for radioactive waste.
- (b) Private fruit gardens should be treated by deep ploughing or removal of the upper 5–10 cm layer of soil. By now, vegetable gardens have been ploughed many times, and the activity distribution in soil will be uniform in a layer 20–30 cm deep.
- (c) Covering the decontaminated parts of courtyards, etc., with a layer of clean sand, or, where possible, with a layer of gravel to attenuate residual radiation (see item (a)).
- (d) Cleaning or replacement of roofs.

These procedures can be applied both for decontaminating single private gardens and houses and for decontaminating settlements as a whole. It is evident that, in the latter case, the influence of the decontamination on further reduction in external radiation dose will be greater. Achievable decontamination factors for various urban surfaces are presented in Table 4.4. Detailed data on the efficiency, technology, necessary equipment, cost and time expenses, quantity of radioactive waste, and other parameters of decontamination procedures are contained in Ref. [4.25].

Radioactive waste generated from urban decontamination should be disposed of in

accordance with established regulatory requirements. In the event of large scale decontamination, temporary storage should be arranged in special isolated areas from which future activity release into the environment will be negligible. The site should be marked by the international symbol of radiation hazard.

4.3. AGRICULTURAL COUNTERMEASURES

The implementation of agricultural countermeasures after the Chernobyl accident has been extensive, both in the most severely affected countries of the former USSR and in western Europe. The main aim of agricultural countermeasures was the production of food products with radionuclide activity concentrations below action levels². The application of countermeasures in intensive agricultural production systems was largely confined to Belarus, the Russian Federation and Ukraine, although some food bans were initially applied in western Europe. Many countermeasures were used extensively in the first few years after the accident, and their application continues today. In addition, in these three countries countermeasures have been applied to private food production from unimproved meadows, where high ¹³⁷Cs activity concentrations have persisted for many years [4.3, 4.4, 4.7].

High and persistent transfer of ¹³⁷Cs has also occurred in many contaminated areas of western Europe. In these countries countermeasures have

largely been focused on animal food products, for example for grazing animals on unimproved pastures.

4.3.1. Early phase

From 2–5 May 1986 about 50 000 cattle, 13 000 pigs, 3300 sheep and 700 horses were evacuated from the CEZ together with the people [4.26]. In the CEZ more than 20 000 agricultural and domestic animals, including cats and dogs, remaining after the evacuation were killed and buried. Due to a lack of forage for the evacuated animals and difficulties in managing the large number of animals in the territories to which they had been moved, many of the evacuated animals were also slaughtered [4.27, 4.28]. In the acute period after the accident it was not possible to differentiate between the different levels of contamination of animals, and in the period May–July 1986 the total number of slaughtered animals reached 95 500 cattle and 23 000 pigs.

Many carcasses were buried and some were stored in refrigerators, but this produced great hygiene, practical and economic difficulties. Condemnation of meat was an immediately available and effective countermeasure to reduce ingested dose from animal products and was widely used in the USSR and elsewhere. However, this was very expensive and resulted in large quantities of contaminated waste.

In the first weeks after the accident, the main aim of countermeasure application in the USSR was to lower ¹³¹I activity concentrations in milk or to prevent contaminated milk from entering the food chain. The following were recommendations [4.29] on how to achieve this:

TABLE 4.4. ACHIEVABLE DECONTAMINATION FACTORS (DIMENSIONLESS) FOR VARIOUS URBAN SURFACES [4.25]

	Technique	DRRF
Windows	Washing	10
Walls	Sandblasting	10–100
Roofs	Hosing and/or sandblasting	1–100
Gardens	Digging	6
Gardens	Removal of surface	4–10
Trees and shrubs	Cutting back or removal	~10
Streets	Sweeping and vacuum cleaning	1–50
Streets (asphalt)	Lining	>100

² Referred to in the countries of the former USSR as temporary permissible levels (TPLs).

- (a) Exclusion of contaminated pasture grasses from the animals' diet by changing from pasture to indoor feeding of uncontaminated feed;
- (b) Radiation monitoring at processing plants and subsequent rejection of milk in which ^{131}I activity concentrations were above the action level (3700 Bq/L at that time);
- (c) Processing rejected milk (mainly converting milk to storable products such as condensed or dried milk, cheese or butter).

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

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

As early as the beginning of June 1986 maps were constructed of the density of radioactive deposition in the contaminated regions. This allowed estimates to be made of the extent of the contamination of pasture and identification of where contaminated milk would be found.

During the growing period of 1986, when there was still substantial surface contamination of plants, the major countermeasures in agriculture were of a restrictive nature. In the first few months severely contaminated land was taken out of use and recommendations were developed on suitable countermeasures that would allow continued production on less heavily contaminated land. In the more heavily affected regions, a ban was imposed on keeping dairy cattle. To reduce contamination levels in crops, an effective method was to delay harvesting of forage and food crops. Radiation control of products was introduced at each stage of food production, storage and processing [4.3, 4.30].

Based on a radiological survey performed from May to July 1986, approximately 130 000,

17 300 and 57 000 ha of agricultural land were initially excluded from economic use in Belarus, the Russian Federation and Ukraine, respectively [4.31].

From June 1986 other countermeasures aimed at reducing ^{137}Cs uptake into farm products were implemented as follows:

- (i) Banning cattle slaughter in regions where ^{137}Cs contamination levels exceeded 555 kBq/m² (animals had to be fed clean food for 1.5 months before slaughter);
- (ii) Minimizing external exposure and formation of contaminated dust by omitting some procedures normally used in crop production;
- (iii) Limiting the use of contaminated manure for fertilization;
- (iv) Preparation of silage from maize instead of hay;
- (v) Restricting the consumption of milk produced in the private sector;
- (vi) Obligatory radiological monitoring of agricultural products;
- (vii) Obligatory milk processing.

Decontamination by removal of the top soil layer was not found to be appropriate for agricultural lands because of its high cost, destruction of soil fertility and severe ecological problems related to burial of the contaminated soil.

As early as August–September 1986 each collective farm received maps of contamination levels of their agricultural land and guidance on potential contamination of products, including instructions on the farming of private plots [4.3, 4.30].

In western Europe advice was initially given on avoiding the consumption of drinking water from local supplies in some countries.

Sweden received some of the highest levels of deposition outside of the countries of the former USSR. Initially, Sweden imposed action levels on ^{131}I and ^{137}Cs activities in imported and domestic foods (see Section 4.1.2). A range of other responses were applied: (a) cattle were not put on to pasture if the ground deposition exceeded 10 kBq/m² of ^{131}I and 3 kBq/m² of radiocaesium; (b) advice was given not to consume fresh leafy vegetables and to wash other fresh vegetables; (c) restrictions were placed on the use of sewage sludge as fertilizer for soil; (d) deep ploughing was recommended; and (e) a higher cutting level for harvesting of grass was advised.

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

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

In the UK advice was issued for the regulation of the consumption of red grouse, and restrictions were imposed on the movement and slaughter of upland sheep from a number of the more contaminated areas of the UK.

In Austria there was advice not to feed fresh grass to cows for a short period in May 1986 [4.32].

4.3.2. Late phase

Radiological surveys of agricultural products showed that by the end of 1986 four regions of the Russian Federation (Bryansk, Tula, Kaluga and Orel), five regions of Ukraine (Kiev, Zhytomyr, Rovno, Volyn and Chernigov) and three regions of Belarus (Gomel, Mogilev and Brest) had food products that exceeded the action levels for radiocaesium. In the more contaminated areas of the Gomel, Mogilev, Bryansk, Kiev and Zhytomyr regions in the first year after the accident, the proportion of grain and milk exceeding the action levels was about 80% [4.3, 4.7, 4.26].

Additionally, in the early 1990s in Ukraine, 101 285 ha of agricultural land was withdrawn from agricultural use (about 30% of this area had a ^{137}Cs contamination level above 555 kBq/m²). Privately owned cattle were moved with the people from some settlements. Provision of 'clean' foodstuffs produced in the collective sector or imported from 'clean' regions was organized for those residents not resettled.

In the Russian Federation in 1987–1988 further evacuations of agricultural animals were carried out, but on a more elective basis than in Ukraine. All sheep in the areas contaminated at over 555 kBq/m² were removed, because of the high transfer of radiocaesium to these ruminants. Of cattle in the regions above 555 kBq/m², 6880 animals were removed, but many families retained their animals.

In Belarus in 1989, 52 settlements were relocated after decontamination and counter-

measure use were found to be inadequate to lower doses to an acceptable level. Additionally, in 1991 under two new laws, some people were allowed to resettle away from contaminated areas, and some settlements were moved. In total, 470 settlements were moved. In all these resettlements, the agricultural animals accompanied their owners to the new locations where possible.

Application of countermeasures in contaminated areas had two major radiation protection aims. The first was to guarantee foodstuff production corresponding to the action levels and to ensure an annual effective dose to local inhabitants of less than 1 mSv. The second was to minimize the total flux of radionuclides in agricultural production. Generally, the earlier agricultural countermeasures were applied, the more cost effective they were [4.33].

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

The most difficult issue remaining was the production of milk in compliance with the standards. However, large scale application of a range of countermeasures (described below) made it possible to achieve a sharp decrease in the amount of animal products with radiocaesium activity concentrations above the action levels in all three countries. Changes with time of milk and meat exceeding the action levels can be seen in Fig. 4.2. It should be noted that the values of the action levels have been reduced with time in each of the three countries, so the data are not directly comparable. Changes in the action levels in each country are shown in Fig. 4.3.

The differences in the time trend shown in Fig. 4.2 among the countries mainly relate to changes in the action levels but also to the scale of countermeasure application. This is particularly clear for Russian milk, where radiocaesium activity concentrations rose after 1997 due to a reduction in countermeasure use. The recent

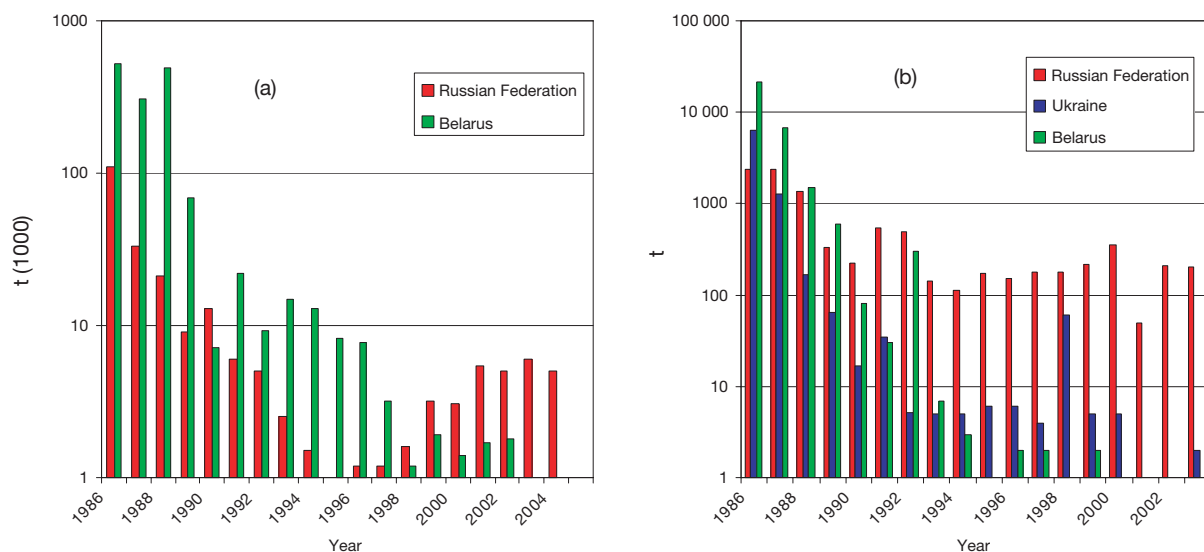


FIG. 4.2. Amounts of milk (a) and meat (b) exceeding the action levels in the Russian Federation (collective and private), Ukraine and Belarus (only milk and meat entering processing plants) after the Chernobyl accident [4.26].

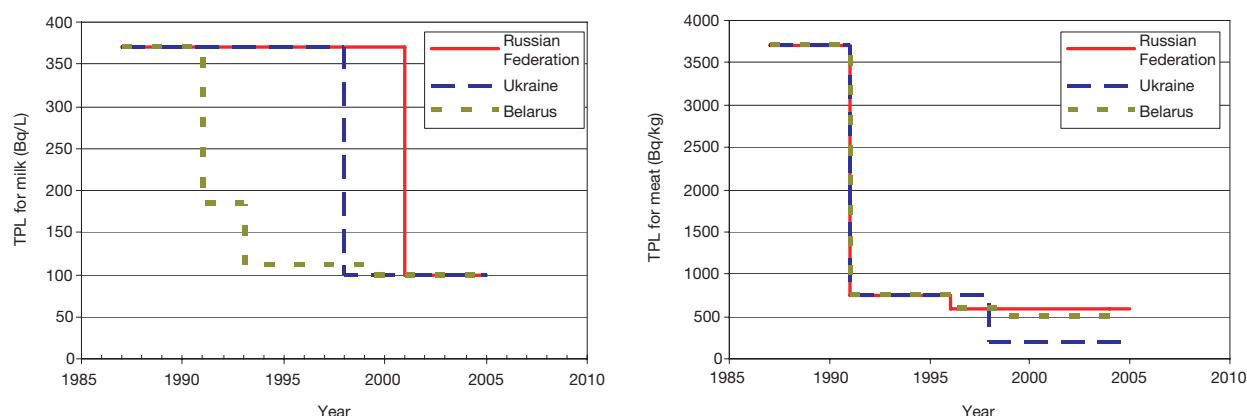


FIG. 4.3. Changes with time in the action levels (TPL) in the USSR and later in the three independent countries [4.34].

reduction in the amounts of meat above the action levels in Ukraine and Belarus is because animals are monitored before slaughter to ensure that the meat is below the required level. In the Russian Federation, where animals are also monitored before slaughter, the concentration data are higher, because they refer to both privately and collectively produced meat.

The maximum effect from countermeasure application was achieved in 1986–1992. Thereafter, because of financial constraints in the mid-1990s, the use of agricultural countermeasures was drastically reduced. However, by optimizing available resources, ^{137}Cs countermeasure effectiveness remained at a level sufficient to

maintain an acceptable ^{137}Cs content in most animal products (Fig. 4.2).

4.3.3. Countermeasures in intensive agricultural production

The main countermeasures used in the USSR, and later in the three independent countries, are briefly described below. The priority was on chemical amendments to improve soil fertility and to reduce the uptake of radiocaesium by crops and plants used for fodder. The extent to which each measure was used varied among the three countries. The recommendations on countermeasures have been repeatedly revised and updated [4.35–4.37].

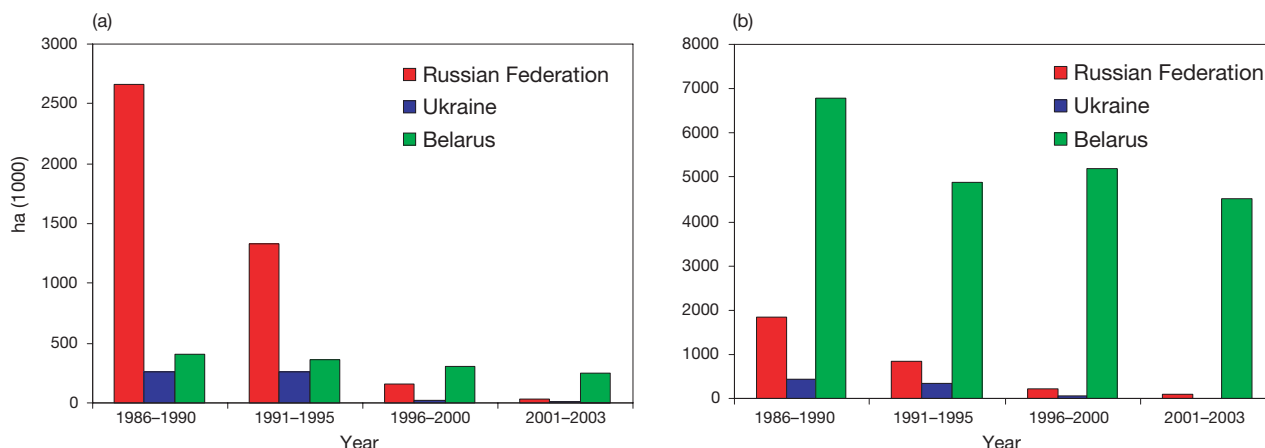


FIG. 4.4. Changes in the extent of agricultural areas treated with liming (a) and mineral fertilizers (b) in the countries most affected by the Chernobyl accident [4.34].

4.3.3.1. Soil treatment

Soil treatment reduces uptake of radio-caesium (and radiostrontium). The procedure can involve ploughing, reseeding and/or the application of nitrogen, phosphorus, potassium (NPK) fertilizers and lime. Ploughing dilutes the radioactive contamination originally in the upper soil layers, where most plant roots absorb their nutrients. Both deep and shallow ploughing were used extensively, and skim and burial ploughing were also used. The use of fertilizers increases plant production, thereby diluting the radioactivity in the plant. In addition, the use of fertilizers reduces root uptake into plants by decreasing the Cs:K ratio in the soil solution [4.30].

When soil treatment includes all the above measures it is commonly called radical improvement; this has been found to be the most efficient and practical countermeasure for meadows contaminated by Chernobyl fallout. In the first few years after the accident the focus was on radical improvement, including greatly increased fertilization rates. Commonly, high value legumes and cereal grasses were grown on the treated land. The nature of the treatment and the efficiency of the radical improvement of hay meadows and pastures strongly depend on the type of meadow and the soil properties. Traditional surface improvement, involving soil discing, fertilization and surface liming, was less effective. Some marshy plots were drained, deep ploughed, improved and used as grassland. In the 1990s there was a greater focus on site specific characteristics to ensure that the soil treatment used was the most appropriate and

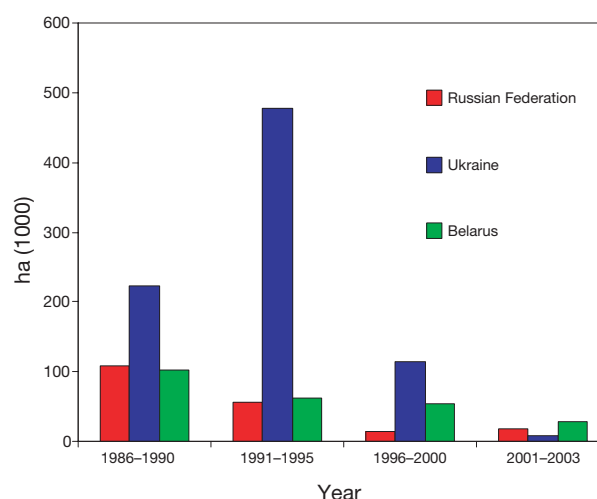


FIG. 4.5. Areas of radical improvement in the countries most affected by the Chernobyl accident [4.34].

effective for the prevailing conditions. With time, repeated fertilization of already treated soils was necessary, but the appropriate application rates were carefully assessed. However, actual rates of application were sometimes constrained by availability of funds [4.30, 4.38].

Areas that received additional fertilizers in each of the three most affected countries are shown in Fig. 4.4; areas receiving radical improvement are shown in Fig. 4.5. The average amount of additional potassium fertilizers added was about 60 kg/ha of K_2O annually between 1986 and 1994. In the mid-1990s the productivity of arable land fell because a worsening economic condition prevented the implementation of countermeasures at the previous rates; this resulted in an increasing proportion of contaminated products. In some areas of the Russian

Federation this halted the previous decrease in the amounts of milk and meat exceeding the radiation safety standards (see Fig. 4.2); for example, in the more contaminated areas, such as Novozybkov (Bryansk region), because of insufficient use of potassium fertilizers, ^{137}Cs activity concentrations in agricultural products in 1995–1996 increased by more than 50% compared with the period of optimal countermeasure application (1991–1992).

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

Even though the radiological problems associated with ^{90}Sr are less acute than those of ^{137}Cs , some countermeasures have been developed and a reduction of two to four in the soil–plant transfer of radiostrontium following disking, ploughing and reseedling has been achieved.

Despite these countermeasures, in the more highly contaminated areas of the Bryansk region the radiocaesium contamination of 20% of the pasture and hay on farms still exceeded the action levels in 1997–2000. Concentrations of ^{137}Cs in hay varied between 650 and 66 000 Bq/kg dry weight.

4.3.3.2. *Change in fodder crops grown on contaminated land*

Some plant species take up less radiocaesium than others, as can be seen from experimental data collated in Belarus from 1997 until 2002 (Fig. 4.6). The extent of the difference is considerable, and fodder crops such as lupin, peas, buckwheat and clover, which accumulate high amounts of radiocaesium, were completely or partly excluded from cultivation.

In Belarus rapeseed is grown on contaminated areas with the aim of producing two products: edible oil and protein cake for animal fodder. Varieties of rapeseed are grown that have a twofold to threefold lower ^{137}Cs and ^{90}Sr uptake rate than other varieties. When the rapeseed is grown, additional fertilizers (liming with 6 t/ha and fertili-

zation with $\text{N}_{90}\text{P}_{90}\text{K}_{180}$) are used to reduce radiocaesium and radiostrontium uptake into the plant by a factor of about two. This reduces contamination of the seed that is used for the protein cake. During processing of the rapeseed, both radiocaesium and radiostrontium are effectively removed, and negligible amounts remain. The production of rapeseed oil in this way has proved to be an effective, economically viable way to use contaminated land and is profitable for both the farmer and the processing industry. During the past decade the area under rapeseed cultivation has increased fourfold to 22 000 ha [4.40].

4.3.3.3. *Clean feeding*

The provision of uncontaminated feed or pasture to previously contaminated animals for an appropriate period before slaughter or milking ('clean' feeding) effectively reduces radionuclide contamination, respectively, in meat and milk at a rate that depends on the animal's biological half-life for each radionuclide. Radiocaesium activity concentration in milk responds rapidly to changes in diet, as the biological half-life is a few days. For meat the response time is longer, due to the longer biological half-life in muscle [4.28].

Clean feeding reduces uptake of the contaminating radionuclides; it has been one of the most important and frequently used countermeasures after the Chernobyl accident for meat from agricultural animals in both the countries of the former USSR and western Europe. Official estimates of the number of cattle treated are between 5000 and 20 000 annually in the Russian Federation and 20 000 in Ukraine (supported by the government up

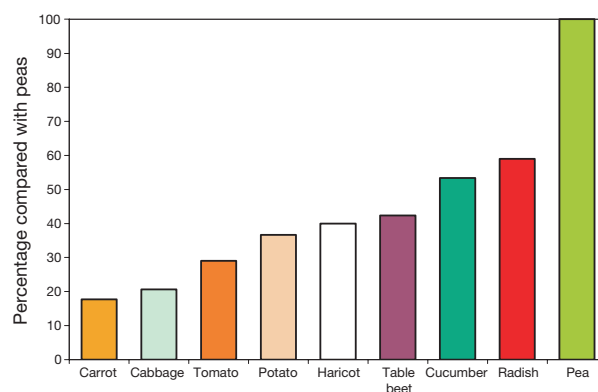


FIG. 4.6. Comparison of ^{137}Cs uptake in different crops, normalized to that of peas [4.39].

to 1996) [4.3]. Clean feeding is routinely used in all three countries for meat production and is combined with live monitoring of animals, so that if animal flesh is above the action levels the animals can be returned to the farm for further clean feeding.

4.3.3.4. Administration of caesium binders

Hexacyanoferrate compounds (commonly referred to as Prussian blue) are highly effective radiocaesium binders. They may be added to the diet of dairy cows, sheep and goats, as well as to meat producing animals, to reduce radiocaesium transfer to milk and meat by reducing absorption in the gut. They have a low toxicity and are therefore safe to use. Many different formulations of hexacyanoferrates have been developed in different countries, partly to identify the most effective compound and partly to produce a cheaper, locally available product. Hexacyanoferrate compounds can achieve reduction factors in animal products of up to ten [4.41].

Prussian blue can be added to the diet of animals as a powder, incorporated into pelleted feed during manufacturing or mixed with sawdust. A locally manufactured hexacyanoferrate called ferrocyn (a mixture of 5% $\text{KFe}[\text{Fe}(\text{CN})_6]$ and 95% $\text{Fe}_4[\text{Fe}(\text{CN})_6]_3$) has been developed in the Russian Federation. It has been administered as 98% pure powder, salt licks (10% ferrocyn) and in sawdust with 10% adsorbed ferrocyn (called bifege) [4.42].

The number of cattle treated annually with Prussian blue in each of the three countries is shown in Fig. 4.7. In addition, slow release boli containing hexacyanoferrate have been developed that are introduced into the animals' rumen and gradually release the caesium binder over a few months. The boli, originally developed in Norway, consist of a

compressed mixture of 15% hexacyanoferrate, 10% beeswax and 75% barite [4.43].

Prussian blue has been used to reduce the ^{137}Cs contamination of animal products since the beginning of the 1990s. Prussian blue application has been especially useful and effective in settlements where there is a lack of meadows suitable for radical improvement. In initial trials, Prussian blue reduced ^{137}Cs transfer from fodder to milk and meat by a factor of 1.5–6.0 [4.44]. In Belarus a special concentrate with Prussian blue is distributed at a rate of 0.5 kg of concentrate per cow daily, and an average value of three for the reduction factor for milk has been achieved.

Prussian blue has not been used as extensively in Ukraine as in the Russian Federation and Belarus, and its use was confined to the early 1990s. This is because in Ukraine no local source of Prussian blue is available and the cost of purchasing it from western Europe was considered to be too high. Therefore, instead, locally available clay mineral binders have been used on a small scale. These were cheaper but somewhat less effective than Prussian blue.

4.3.4. Summary of countermeasure effectiveness in intensive production

The effectiveness of the different agricultural countermeasures in use on farms is summarized in Table 4.5. The reduction factors (ratio of radiocaesium activity concentration in the product before and after countermeasure application) achieved by each measure are given.

4.3.5. Countermeasures in extensive production

Extensive production in the three countries of the former USSR is largely confined to the grazing of privately owned cattle on poor, unimproved meadows. Owing to the poor productivity of these areas, radiocaesium uptake is relatively high compared with land used by collective farms. Radical improvement of meadows used by privately owned cattle has been applied in all three countries since the early 1990s. Clean feeding is not generally used by private farmers, although, on occasions, collective farms may supply private farmers with uncontaminated feed or pastures. Prussian blue is used by private farmers in both the Russian Federation and Belarus. In the Russian Federation all three Prussian blue delivery systems are used, according to availability and preference [4.46].

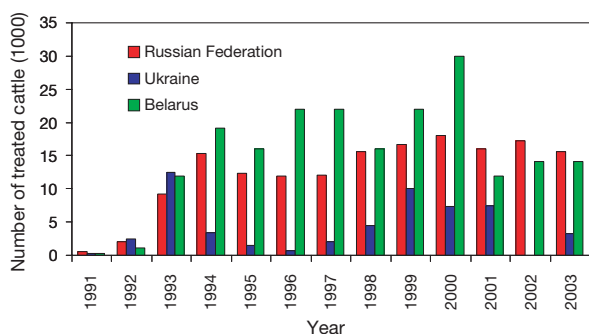


FIG. 4.7. Changes with time in the use of Prussian blue in the three countries of the former USSR (provided by Forum participants from official national sources).

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

AFCF is a highly effective hexacyanoferrate compound achieving up to a fivefold reduction in radiocaesium in lamb and reindeer meat and up to a threefold reduction in cow's milk and a fivefold reduction in goat's milk. The use of AFCF has been temporarily authorized in the EU and in some other countries. AFCF as a caesium binder is effective in extensive production systems, in contrast to many other countermeasures whose applicability is limited. Boli are particularly favourable for infrequently handled free grazing animals, as the boli can be administered when animals are gathered for routine handling operations. For use in extensive systems, the boli can be given a protective surface coating of wax to delay the onset of AFCF release,

so that effectiveness is increased at the time when animals are collected for slaughter [4.47]. It has been estimated that the use of boli as a countermeasure for sheep was 2.5 times as cost effective as feeding with uncontaminated feed [4.48]. Salt licks containing AFCF have also been used, but are less effective [4.49].

Management regimes have been modified for some animals in contaminated areas; for example, slaughter times are modified to ensure that the ^{137}Cs activity concentrations are relatively low. In the UK the movement and slaughter of upland sheep are restricted in some areas. The animals are monitored to ensure that their ^{137}Cs activity concentrations are below the action level before they are slaughtered.

Live monitoring of animal derived products (monitoring of live animals and/or of milk and tissues after slaughter) has been used to ensure that countermeasures have been effective. The use of monitoring is also important in maintaining public confidence in the products from affected areas.

An example of the long term consequences of the accident can be seen in Fig. 4.8, which shows the number of reindeer in Sweden that had radio-caesium activity concentrations above the action level and the number of slaughtered animals. The

TABLE 4.5. SUMMARY OF THE REDUCTION FACTORS ACHIEVED WITH THE DIFFERENT COUNTERMEASURES USED IN THE THREE COUNTRIES OF THE FORMER USSR [4.30, 4.34, 4.40, 4.45]

	Caesium-137	Strontium-90
Normal ploughing (first year)	2.5–4.0	—
Skim and burial ploughing	8–16	—
Liming	1.5–3.0	1.5–2.6
Application of mineral fertilizers	1.5–3.0	0.8–2.0
Application of organic fertilizers	1.5–2.0	1.2–1.5
Radical improvement:		
First application	1.5–9.0 ^a	1.5–3.5
Further applications	2.0–3.0	1.5–2.0
Surface improvement:		
First application	2.0–3.0 ^a	2.0–2.5
Further applications	1.5–2.0	1.5–2.0
Change in fodder crops	3–9	—
Clean feeding	2–5 (time dependent)	2–5
Administration of caesium binders	2–5	—
Processing milk to butter	4–6	5–10
Processing rapeseed to oil	250	600

^a For wet peat, up to 15 with drainage.

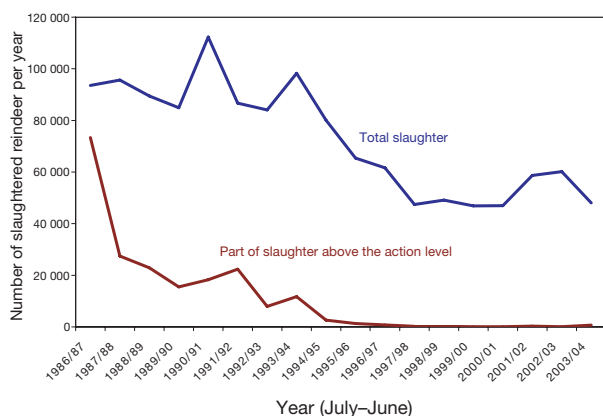


FIG. 4.8. Change with time in the number of reindeer in Sweden with radiocaesium activity concentrations above the action level and in the number of slaughtered animals [4.50].

high number of slaughtered animals in the first year was in part due to the low action level of 300 Bq/kg fresh weight, which was subsequently increased to 1500 Bq/kg from 1987. The decline has been achieved partly by extensive use of countermeasures, including clean feeding and change of slaughter time.

4.3.6. Current status of agricultural countermeasures

Currently in all three countries of the former USSR clean feeding remains an important countermeasure to ensure that meat from intensive farms can be marketed.

In Belarus, fertilization with phosphorus–potassium is used on collective farms, and milk above the action level from the farms is processed into butter. Radical improvement is used on private farms together with Prussian blue for milk. Rapeseed production is currently limited by processing capacity, although this may be increased in the future.

In Ukraine the only remaining countermeasure used on intensive systems is clean feeding of meat producing animals prior to slaughter. Any milk above the action level is used within the settlements, partially to feed pigs. All other countermeasures are directed at private farmers. These countermeasures currently comprise the radical improvement of meadows and the use of clay mineral caesium binders for privately produced milk.

In the Russian Federation, fertilizers (largely potassium) are supplied to intensive farms. For

private farms, Prussian blue is provided for privately produced milk and, on request, for privately produced meat intended for market.

In all contaminated settlements a service for the monitoring of local produce exists, although the capacity and availability of the service varies.

In western Europe countermeasures for animals in extensive systems are still used in Norway and Sweden, and the movement and slaughter of upland sheep are still restricted in certain areas of the UK.

4.3.7. A wider perspective on remediation, including socioeconomic issues

Experience after the Chernobyl accident has shown that account has to be taken, in developing restoration strategies, of a wide range of different issues to ensure the long term sustainability of large and varied types of contaminated areas [4.51]. The selection of robust and practicable restoration strategies should take into account not only radiological criteria but also: (a) practicability, including effectiveness, technical feasibility and the acceptability of the countermeasure; (b) cost–benefit; (c) ethical and environmental considerations; (d) requirements for effective public communication; (e) the spatial variation in many of these factors; and (f) the contrasting needs of people in urban, rural and industrial environments [4.52]. When not only radiological factors but also social and economic factors are taken into account, better acceptability of countermeasures by the public can be achieved.

A number of European Commission (EC) and United Nations projects have applied some of the above considerations in trying to provide appropriate information to, and interaction with, people in contaminated territories and in involving them in making decisions about responding to enhanced radiation doses and about ways of living sustainably in contaminated areas. In particular, this introduces the possibility of self-help and the opportunity for people to decide for themselves whether they wish to modify their behaviour to reduce their doses. The EC ETHOS project [4.53, 4.54] identified the dissemination of a practical radiological culture within all segments of the population as a prerequisite, especially for professionals in charge of public health. The EC Tacis Programme ENVREG project [4.55] in Belarus and Ukraine sought to minimize the environmental and secondary medical effects resulting from the

Chernobyl accident by improving the public perception and awareness of these effects.

Most recently, the EC CORE project [4.56] was initiated to address long term rehabilitation and sustainable development in the Bragin, Chechersk, Slavgorod and Stolin areas of Belarus. CORE community projects include health care, radiological safety, information and education. In addition, critical socioeconomic constraints are being addressed, specifically using a crediting system for small businesses and farmers, the cost effective production of 'clean' products, the creation of a rural entrepreneurs' centre and the promotion of community economic initiatives.

The Chernobyl debate is increasingly about socioeconomic issues and the communication of technical information in an understandable way. The ETHOS, ENVREG and CORE projects all have a strong community focus and target Chernobyl affected communities and other local stakeholders. Feedback from the communities should indicate which approaches are proving successful and to what extent. The holistic philosophy of these projects of considering both environmental and social problems is in line with the recent United Nations initiative known as Strategy for Recovery [4.57].

4.3.8. Current status and future of abandoned land

In this section the extent of recovery of abandoned land is summarized for each of the three countries of the former USSR. In 2004, 16 100, 11 000 and 6095 ha of previously abandoned land in Belarus, the Russian Federation and Ukraine, respectively, were returned to economic use [4.26]. In general, there is currently little effort being devoted to any further rehabilitation of abandoned areas.

4.3.8.1. Exclusion and resettlement zones in Belarus

The CEZ covers a total of 215 000 ha in Belarus. The people who used to reside there were evacuated in 1986. Since May 1986, lands in the CEZ have been taken out of agricultural and other production. The Polessye State Radioecological Reserve (PSRR) was set up by a government decree in 1988 and comprises mainly the CEZ but also includes some other areas with high levels of transuranium radionuclide contamination. Access to the PSRR is forbidden and very few, mostly old, people

are currently present, without permission, in the area. Pursuant to the law on the legal regime of territories contaminated as a result of the Chernobyl nuclear power plant accident [4.58], most of the land in the CEZ cannot be brought back into economic production within a millennium, because of contamination with long lived transuranium radionuclides. In the CEZ only activities related to ensuring radiation safety, fighting forest fires, preventing the transfer of radioactive substances, protecting the environment and scientific research and experimental work are permitted.

While the CEZ (i.e. the Bragin, Khoyniki and Narovlya areas of the Gomel region) is the most contaminated area adjacent to the Chernobyl nuclear power plant, a further resettlement zone was identified in the early 1990s from which more people were evacuated; this zone covers a total area of 450 000 ha.

A total area of agricultural land of 265 000 ha received a deposition of ^{137}Cs at levels in excess of 1480 kBq/m^2 and/or of ^{90}Sr in excess of 111 kBq/m^2 and/or of plutonium isotopes in excess of 3.7 kBq/m^2 . All this land is excluded from agricultural use.

The remaining abandoned agricultural land in the resettlement zone could be used for agriculture in the future. The present state of the ecosystems and the economic infrastructure of the resettlement zone are characterized by a general deterioration in the former agricultural lands, drainage systems and roads. Due to lack of drainage, there has also been a gradual elevation in the water table. Normal ecological succession has led to an increase in the number of perennial weeds and shrubs. Unlike in the CEZ, in the resettlement zone limited access for certain maintenance activities, such as the activities needed to maintain roads, electricity transmission lines, etc., is permitted.

In Belarus it is considered to be important to bring lands back to agricultural use, if possible. At the request of collective and State farms, if supported by local authorities, surveys of former agricultural lands were conducted to determine whether it is possible to rehabilitate the land for agricultural use. This was based on radiological considerations only.

By 2001 a total of 14 600 ha of previously withdrawn land had been returned to use [4.34], and recently this has been increased to about 16 000 ha. This land is closely adjacent to populated settlements. In these rehabilitated sites the soil

fertility has been restored and a variety of countermeasures has been used to minimize radiocaesium and radiostrontium uptake based on official guidelines [4.37].

Most of the agricultural and other land of the resettlement zone was transferred to the authority of the Ministry of Forestry. This is because much of the resettlement zone is considered suitable for forest production.

According to an assessment by Bogdevitch et al. [4.59], a total of about 35 000 ha of the more fertile agricultural land may be suitable for further rehabilitation. However, economic support for recovery and use of countermeasures has declined significantly over recent years. Use of countermeasures is now confined to radical improvement of meadows, feeding of Prussian blue to cattle, liming and fertilization.

Methodologies for the rehabilitation of abandoned land are being developed and improved, in particular with respect to economic evaluation. The main obstacles to the renewed agricultural use of abandoned land are the destroyed infrastructure, the high production cost and the low market demand for the agricultural goods. A large scale rehabilitation of excluded land will only be possible if there is a general improvement in the economic situation of the country.

4.3.8.2. Rehabilitation of contaminated lands in Ukraine

The first priority was the rehabilitation of land on which people are living. Consideration has since been given to the potential rehabilitation of abandoned areas. Such areas can be rehabilitated if this procedure is expedient with respect to economic and social criteria. The main condition for human occupancy of such areas without restrictions is that the additional annual effective dose should not exceed 1 mSv.

The efficiency of countermeasures is determined by the following criteria:

- (a) Radiological: reduction of radionuclide content in local products and in the associated individual and collective dose.
- (b) Economic: increased product market value.
- (c) Social and psychological: public opinion on a given countermeasure.

In 2004, on the basis of radiological criteria alone, a significant part of the abandoned agricultural lands (more than 70%) could be returned to economic use. When economic and social criteria are assessed, the amount of land that could be rehabilitated declines (see Table 4.6). Table 4.6

TABLE 4.6. REHABILITATION OF ZONES OF OBLIGATORY RESETTLEMENT (OUTSIDE THE CHERNOBYL EXCLUSION ZONE)^a

Area	Abandoned land (ha)	Can be rehabilitated judged on radiological, economic and social criteria (ha)
<i>Kiev region</i>		
1998–2000 (done)	—	3475
2001–2005	—	4720
Total	29 342	8205
<i>Zhytomyr region</i>		
1998–2000 (done)	—	2620
2001–2005	—	4960
Total	71 943	7580

^a Provided by Forum participants from official national sources.

shows a scheme for rehabilitation based on technical criteria over a seven year period. The first phase, from 1998 until 2000, was implemented, but that for the second phase was not, due to changing economic and social conditions.

In the CEZ, the limiting radionuclide is now ^{90}Sr rather than ^{137}Cs . On the basis of radiological considerations, the south-west part of the zone can be used without restrictions. However, in reality, legal restrictions, the lack of a suitable infrastructure and consideration of economic and social-psychological factors prevent its rehabilitation.

The same restrictions apply to the other abandoned areas, where legal restrictions are also in force that, together with deteriorating economic conditions, currently prevent the application of countermeasures in the remaining identified abandoned areas. The pressure to bring the abandoned land back into production is also reduced by the current abundance of agriculturally productive land in Ukraine and the presence in southern Ukraine of land that is much more productive.

Some people have returned to abandoned areas to live, and others live outside them but use the land for agricultural activities such as hay production. Countermeasures are not being applied in the abandoned areas, but there is sanitary and regulatory control of these activities.

4.3.8.3. *Abandoned zones in the Russian Federation*

Areas in the Russian Federation with high levels of radioactive soil contamination were abandoned in stages from 1986 until 1989, and in total 17 000 ha of agricultural land was excluded from economic use. The abandoned areas belonged to 17 rural settlements with about 3000 inhabitants (at the time of the accident) and 12 collective farms.

In 1987–1989 considerable efforts were made to keep the highly contaminated areas in economic use, and hence most of the abandoned areas were subjected to intensive countermeasure application. However, these efforts were only partially successful, and the land was gradually abandoned; in the 1990s, the intensity of countermeasure application was reduced. Overall, about 11 000 ha was returned to agricultural use by 1995. These decisions to return land to agricultural use were made individually for each contaminated field. Special attention was paid to highly contaminated fields surrounded by fields with relatively low levels

of contamination, because there was a natural inclination to use these fields. The assessments were based on Russian radiation safety standards, including standards governing the quality of agricultural products (TPL-93) [4.60].

Between 1995 and 2004 there was no further rehabilitation of the abandoned areas. Officially they are abandoned but, unofficially, some local people are living in these areas and using them for agricultural production, but without the benefit of countermeasures.

Recently, a technical project of gradual rehabilitation of the remaining abandoned areas, in which the mean ^{137}Cs soil deposition varies from 1540 to 3500 kBq/m², has been proposed by the Russian Institute of Agricultural Radiology and Agroecology. The criteria for agricultural production include ensuring that ^{137}Cs activity concentrations would be less than the TPL, as well as a requirement that application of countermeasures for each contaminated field would be optimized. During the first planned stage, up to 2015, it is proposed to produce grain and potatoes using agricultural workers who live elsewhere but would come into the contaminated area as necessary. Soil based countermeasures (liming, potassium fertilization) should allow the production of plant products with sufficiently low levels of ^{137}Cs on most of the abandoned area. From 2015 the implementation of animal breeding is planned, and from 2025 the re-establishment of populated settlements could commence. Thus by 2045 all abandoned land could be used once more, although application of different countermeasures would be needed up to 2055 to ensure that annual doses to the local inhabitants were less than 1 mSv.

4.4. FOREST COUNTERMEASURES

Countermeasures for forested areas contaminated with radionuclides are only likely to be implemented if they can be accepted by foresters or landowners on a practical basis (i.e. actions are likely to fit in with normal forest management practices). For countermeasures to be successful they must also be accepted by the general public. As forest countermeasures are labour consuming and expensive, they cannot be implemented quickly and must be planned carefully. They are likely to be long term activities and their beneficial effects take time to be realized.

4.4.1. Studies on forest countermeasures

Generally, prior to the Chernobyl accident countermeasures to offset doses due to large scale contamination of forests had not been given very much attention. Several international projects in the 1990s gave rise to a number of publications in which suggestions and recommendations were made for possible countermeasures to be applied in forests [4.61–4.64]. However, in the three countries of the former USSR, actions had already been taken to restrict activities in the more contaminated zones, which included significant areas of forestry [4.65]. These actions were, in general, rather simple and involved restrictions on basic activities such as accessing forests and gathering wild foods and firewood. A major question remains as to whether any more complex or technologically based countermeasures can be applied in practice, and whether the ideas developed by researchers will remain as theoretical possibilities rather than as methods that can be applied in real forests on a realistic scale. The following section describes some of the more feasible countermeasures that have been devised for forests contaminated with radio-caesium. This is illustrated in Section 4.4.3 by studies in which countermeasures have actually been put into practice.

4.4.2. Countermeasures for forests contaminated with radiocaesium

There are several categories of countermeasure that are, in principle, applicable to forest ecosystems [4.66, 4.67]. A selection of these is shown in Table 4.7. These can be broadly categorized into (a) management based and (b) technology based countermeasures.

4.4.2.1. Management based countermeasures

Under the broad heading of management based countermeasures, the principal remedial methods applied after the Chernobyl accident involved restrictions on various activities normally carried out in forests. Restriction of access to contaminated forests and restriction of the use of forest products were the main countermeasures applied in the USSR and later in the three independent countries [4.65]. These restrictions can be categorized as follows:

- (a) Restricted access, including restrictions on public and forestworker access. This has been assisted by the provision of information from local monitoring programmes and education on issues such as food preparation [4.65].
- (b) Restricted harvesting of food products by the public. The most commonly obtained food products include game, berries and mushrooms. The relative importance of these varies from country to country. In the three countries of the former USSR, mushrooms are particularly important and can often be severely contaminated.
- (c) Restricted collection of firewood by the public. This not only exposes people to in situ gamma radiation while collecting firewood but can also lead to further exposures in the home and garden when the wood is burned and the ash is disposed of, sometimes being used as a fertilizer.
- (d) Alteration of hunting practices. The consumption of fungi by animals such as roe deer leads to strong seasonal trends in their body content of radiocaesium (see Section 3.3). Thus excessive exposures can be avoided by eating the meat only in seasons in which fungi are not available as a food source for the animals.
- (e) Fire prevention is a fundamentally important part of forest management under any circumstances, but it is also important after a large scale deposition to avoid secondary contamination of the environment, which could result from burning of trees and especially forest litter, which is one of the major repositories of radiocaesium in the forest system (see Section 3.3). One of the ways in which forest fires can be avoided is by minimizing human presence in the forest, so this countermeasure is strongly linked to restricting access, as described above.

4.4.2.2. Technology based countermeasures

This category of countermeasures includes the use of machinery and/or chemical treatments to alter the distribution or transfer of radiocaesium in forests. Many mechanical operations are carried out as part of normal forestry practice; examples of these have been described by Hubbard et al. [4.69] with reference to their use as countermeasures. Similarly, applications of fertilizers and pesticides may be made at different times in the forest

TABLE 4.7. SELECTED COUNTERMEASURES THAT HAVE BEEN CONSIDERED FOR APPLICATION IN CONTAMINATED FORESTS [4.68]

Countermeasure	Category	Caveat	Benefit	Cost
Normal operation	Management	—	No loss of productivity or amenity	No dose reduction and negative social costs
Minimum management: forest fire protection, disease protection and necessary hunting	Management	—	Creation of nature reserve and reduced worker dose	Worker dose, loss of productivity, negative social costs and costs for hunting
Delayed cutting of mature trees	Management/agrotechnical	Marginal feasibility	Reduced contamination of wood due to: — Radioactive decay — Fixation of caesium in soil — Loss from soil and wood	Delay in revenue
Early clear cutting and replanting or self-regeneration	Management/agrotechnical	Must consider tree age at time of contamination; possibly in combination with soil mixing	Reduced tree contamination: — Lower soil–tree transfer — Delayed harvest time — Alternative tree crop	Higher dose to workers during replanting and operational costs
Soil improvement: harrowing after thinning or clear cutting	Agrotechnical	Cost effectiveness is dependent on the area to be treated; possibly in combination with fertilizer application	Improved tree growth, therefore growth dilution; dilutes radionuclide activity concentrations in the soil surface layer and decreases them in mushrooms, berries and understorey game	Operational costs, worker doses and environmental or ecological costs (e.g. nitrate and other nutrients lost)
Application of phosphorus–potassium fertilizer and/or liming	Agrotechnical	Phosphorus–potassium: may only be effective for caesium, especially effective for younger stands Lime: particularly useful for ⁹⁰ Sr	Reduction of uptake to trees, herbs, etc., maybe better growth and dilution effect and higher fixation	Cost of fertilizer, worker dose and negative ecological effects
Limiting public access	Management	Note: people normally residing in forests not considered	Reduction in dose, possible increase in public confidence	Loss of amenity/social value, loss of food and negative social impacts
Salt licks	Agrotechnical	—	Reduction in caesium uptake by grazing animals	Continuing cost of providing licks
Ban on hunting	Management	—	Reduction in dose due to ingestion of game	Need to find alternative supply of meat
Ban on mushroom collection	Management	—	Reduction in internal dose	Need to find alternative mushroom supply

cropping cycle as part of normal management practice. However, the cost effectiveness of many technological countermeasures is questionable, especially when applied on a large scale [4.68]. Thus it is to be expected that such countermeasures will be restricted to small scale cases only, if they are feasible at all. Such cases might include small areas of urban woodland, such as parkland, which are likely to be visited by many more people than extensive and remote forest areas.

Technological countermeasures might include mechanical removal of leaf litter or scraping of soil layers, clear cutting and ploughing, and the application of calcium- and potassium-containing fertilizers. It is evident, however, that any of these methods can damage the ecological functioning of the forest when applied outside of the normal schedule of forestry operations. This, and the high economic costs of such operations, means that the practical use of such techniques as countermeasures remains largely speculative, and such measures have not been applied after the Chernobyl accident other than in small scale experiments. Indeed, the results of cost-benefit calculations indicate that the management options likely to result in the least overall detriment are those which limit access and consumption of forest foods. Options that involve technological intervention, application of chemicals or altering the harvesting patterns in forests are unlikely to be used in practice.

4.4.3. Examples of forest countermeasures

Case studies in which forest countermeasures, particularly technology based countermeasures, have actually been applied in practice are rare. This illustrates the difficulty of implementing practical remedial measures in forests, in contrast to agriculture, in which the application of fertilizers, in particular, has been used with some success (see Section 4.3). In practice, restrictive countermeasures were applied in the USSR, and later in the three independent countries, as well as in a limited number of other countries, such as Sweden.

In the Bryansk region of the Russian Federation, individual restrictions on forestry and on the population living near forests were recommended according to the level of ^{137}Cs deposition. For forests receiving depositions greater than 1480 kBq/m², access was only allowed for forest conservation, fire fighting and control of pests and diseases. All forestry activity was stopped, and public access, including for collection of forest

plants, was prohibited. In forests receiving depositions between 555 and 1480 kBq/m², collection of forest products was also prohibited, but limited forestry activities continued. At deposition levels between 185 and 555 kBq/m², harvesting of trees was continued on the basis of radiological surveys that were used to identify individual areas in which external doses to forestry workers and contamination of wood were acceptable. However, the collection of berries and mushrooms by the public was only permitted in forests with deposition levels less than 74 kBq/m².

One of the major effects of the restrictions that were enforced on a large scale up to 1990 was a negative impact on rural populations. At the beginning of 1990 the population began gathering mushrooms and berries again over the whole Bryansk region. However, in areas where the original ^{137}Cs deposition was between 555 and 1480 kBq/m², restrictions on gathering forest food products are still in force. This example illustrates a major difficulty in implementing countermeasures involving restrictions on public activities that inevitably lead to a disturbance of normal societal behaviour patterns. Furthermore, wood production is still under the official control of local forest authorities [4.65]; the currently applicable permissible levels for contamination of wood and forest products in the Russian Federation are shown in Table 4.8. Similar restrictions and permissible levels have been implemented in different regions of Belarus, notably the Gomel and Mogilev regions.

The use of caesium binders, particularly Prussian blue, in domestic animals has been one of the more effective techniques used to reduce doses from contaminated forests in the three countries of the former USSR. The principles underlying this method are described in Section 4.3; they are equally applicable to the problem of marginal grazing of domestic animals in forests. Typically, reductions in ^{137}Cs activity concentrations of a factor of five in milk and a factor of three in meat can be achieved at optimum dosage [4.65].

One example of intervention in normal forest related practices in countries outside the former USSR is the case of roe deer hunting in Sweden. In 1988 the average muscle content of roe deer shot in the autumn was 12 000 Bq/kg in the Gävle area. The intervention level for such foodstuffs in Sweden is 1500 Bq/kg. Such high levels of contamination of roe deer meat were due to the preferential consumption of fungi by the deer in the autumn. As a result of experiments, the Swedish authorities

recommended a change of hunting season for roe deer to the spring; this change was applied voluntarily by the hunting community in the early 1990s. As a result, the radiocaesium content in roe deer meat in Gävle was reduced by approximately six times. The recommendation to shift the hunting season to the spring has remained in place until the present day [4.71].

In addition, the management of reindeer by the Sami people in northern Sweden has been altered in a variety of ways to help reduce the radiocaesium content of animals before slaughter. This includes provision of clean fodder for sufficient time to reduce the body burden below the intervention level. A similar result can be achieved by altering the time of slaughter, sometimes in combination with feeding of clean fodder [4.72].

4.5. AQUATIC COUNTERMEASURES

There are a number of different intervention measures that can be employed following fallout of radioactive material to reduce doses to the public via the surface water pathway. These actions may be grouped into two main categories: those aimed at reducing doses from radionuclides in drinking water

and those aimed at reducing doses from the consumption of contaminated aquatic foodstuffs.

In the context of the atmospheric fallout of radionuclides to both terrestrial and aquatic systems, it has been shown [4.73–4.75] that doses from terrestrial foodstuffs are in general much more significant than doses from drinking water and aquatic foodstuffs. However, in the Dnieper River system, the river water transported radionuclides to areas that were not significantly contaminated by atmospheric fallout. This created a significant stress in the population and a demand to reduce radionuclide fluxes from the affected zone via the aquatic system. Many remediation measures were put in place but, because actions were not taken on the basis of dose reduction, most of these measures were ineffective. Moreover, radiation exposures of workers implementing these countermeasures were high.

Measures to reduce doses via drinking water may, however, be required, particularly in the short term (timescale of weeks) after fallout, when activity concentrations in surface waters are relatively high. Owing to the importance of short lived radionuclides, early intervention measures, particularly the changing of supplies, can significantly reduce radiation doses to the population. Measures to reduce doses due to freshwater foodstuffs may be required over longer timescales as a result of the bioaccumulation of radionuclides in the aquatic food chain.

Reviews of aquatic countermeasures (e.g. Refs [4.76–4.79]) have considered both direct (restrictions) and indirect intervention measures to reduce doses:

- (a) Restrictions on water use or changing to alternative supplies;
- (b) Restrictions on fish consumption;
- (c) Water flow control measures (e.g. dykes and drainage systems);
- (d) Reduction of uptake by fish and aquatic foodstuffs from contaminated water;
- (e) Preparation of fish prior to consumption.

There is no evidence that countermeasures were required, or applied, in marine systems after the Chernobyl accident.

4.5.1. Measures to reduce doses at the water supply and treatment stage

Restrictions were placed on the use of water from the Dnieper River for the first year after the

TABLE 4.8. TEMPORARY PERMISSIBLE LEVELS FOR CAESIUM-137 IN WOOD AND FOREST FOOD PRODUCTS IN THE RUSSIAN FEDERATION [4.70]

	TPL (Bq/kg)
Round wood, including bark	11 100
Unseen timber with bark removed	3 100
Sawn wood (planks)	3 100
Construction wood	370
Wood used for pulp and paper production	3 100
Wood products for household use and industrial processing	2 200
Wood products for packing and food storage	1 850
Firewood	1 400
Mushrooms and berries (fresh weight)	1 480
Mushrooms and berries (dry weight)	7 400
Medical plants and medical raw material	7 400
Seeds of trees and bushes	7 400

accident. Abstraction of drinking water for Kiev was switched to the Desna River with use of a pipeline built during the first weeks after the accident. A summary of the measures taken by the Ukrainian authorities to switch to alternative supplies from less contaminated rivers and from groundwater can be found in Refs [4.76, 4.79].

Radionuclides may be removed from drinking water supplies during the water treatment process. Suspended particles are removed during water treatment, and filtration can remove dissolved radionuclides. In the Dnieper waterworks station, activated charcoal and zeolite were added to water filtration systems. It was found that activated charcoal was effective in removing ^{131}I and ^{106}Ru , and zeolite was effective in removing ^{137}Cs , ^{134}Cs and ^{90}Sr . These sorbents were effective for the first three months, after which they became saturated and their efficiency declined [4.80, 4.81]. The average removal of these radionuclides from water (dissolved phase) was up to a factor of two.

After the accident, the upper gates of the Kiev reservoir dam were opened to release surface water. It was believed at the time that the surface water was relatively low in radionuclide content, because suspended particles had sunk to deeper waters. Therefore, the release of water would allow room in the reservoir to contain runoff water from the inflowing rivers, which was believed to be highly contaminated. In fact, because of direct atmospheric deposition to the reservoir surface, the surface waters in the reservoir were much more contaminated than the deep waters. As noted by Voitsekhovitch et al. [4.80], “a better approach to lowering the water level within the Kiev reservoir would have been to open the bottom dam gates and close the surface gates. This would have reduced the levels of radioactivity in downstream drinking water in the first weeks after the accident.” Although this countermeasure was not efficiently implemented after the Chernobyl accident, regulation of flow, given the correct information on contamination, could effectively reduce activity concentrations in drinking water, as it takes some time (days or more) for lakes and reservoirs to become fully mixed.

In a large river–reservoir system such as the Dnieper, control of water flows in the system can significantly reduce transfers of radioactive material downstream [4.82]. In the Dnieper River, the time it takes for water to travel from the Kiev reservoir to the Black Sea varies between three and ten months. Over the time that the water takes to travel downstream, radioactive pollution is reduced by

decay of short lived radionuclides and transfers to reservoir bed sediments (particularly of radio-caesium) [4.82].

4.5.2. Measures to reduce direct and secondary contamination of surface waters

Standard antisoil erosion measures can be used to reduce runoff of radionuclides attached to soil particles. Note, however, that typically less than 50% of radio-caesium and less than 10% of radio-strontium and radioiodine were in the particulate phase, and this limits the potential effectiveness of this countermeasure. It should also be noted that the dissolved, rather than particulate, form of these radionuclides is important in determining activity concentrations in drinking water and freshwater biota.

Dredging of canal bed traps to intercept suspended particles in contaminated rivers was carried out in the Pripyat River [4.79]. These canal bed traps were found to be highly inefficient for two reasons: (a) the flow rates were too high to trap the small suspended particles carrying much of the radionuclide contamination; and (b) a significant proportion of the radionuclide activity (and most of the ‘available’ activity) was in dissolved form and thus would not have been intercepted by the sediment traps.

One hundred and thirty zeolite-containing dykes were constructed on smaller rivers and streams around Chernobyl in order to intercept dissolved radionuclides. These were found to be very ineffective: only 5–10% of the ^{90}Sr and ^{137}Cs in the small rivers and streams was adsorbed by these zeolite barriers [4.80]. In addition, the rivers and streams on which they were placed were later found to contribute only a few per cent to the total radionuclide load in the Pripyat–Dnieper system.

After the Chernobyl accident, spring flooding of the highly contaminated Pripyat floodplain resulted in increases in ^{90}Sr activity concentrations in the Pripyat River from annual average activity concentrations of around 1 Bq/L to a maximum of around 8 Bq/L for a flood event covering an approximately two week period [4.83]. In 1993 a dyke was constructed around the highly contaminated floodplain on the left bank of the Pripyat. This prevented flooding of this area and proved effective in reducing ^{90}Sr wash-off to the river during flood events [4.80]. A second dyke was constructed on the right bank of the Pripyat in 1999. The annual average ^{90}Sr activity concentration in Kiev reservoir

water, however, was below 1 Bq/L in all years from 1987 onwards. The radiological significance of the ^{90}Sr activity concentrations in Kiev reservoir water, even during the short flood events, is therefore very low, although it has been argued that the averted collective dose to the large number of users of the river–reservoir system is significant.

It is potentially possible to increase the sedimentation of radionuclides from lakes and reservoirs by the introduction of a strongly sorbing material such as a zeolite or an (uncontaminated) mineral soil. This method has not been tested. Using a model for the removal of radiocaesium from lakes by settling of suspended particles, Smith et al. [4.78] identified two problems with this method: (a) large, deep lakes would require extremely large amounts of sorbent; and (b) secondary contamination of the lake by remobilization of activity from the catchment and/or bottom sediments would require repeat applications in most systems.

4.5.3. Measures to reduce uptake by fish and aquatic foodstuffs

Bans on the consumption of freshwater fish have been applied in the limited zones affected by the Chernobyl accident [4.84]. In some areas, selective bans on the more contaminated predatory fish have been applied. It is believed that such bans are often ignored by fishermen. Bans on the sale of freshwater fish were applied in some areas of Norway [4.85]. Farmed fish could be used as an alternative source of freshwater fish in areas affected by fishing bans, since farmed fish fed with uncontaminated food do not accumulate radionuclides significantly [4.86].

The addition of lime to reduce radionuclide levels in fish was tested in 18 Swedish lakes [4.87]. The results of the experiments showed that liming had no significant effect on the uptake of ^{137}Cs in fish in comparison with control lakes. Although the uptake of ^{90}Sr was not studied in these experiments, it is expected that increased calcium concentration in lakes may have an effect on the ^{90}Sr concentration in fish. Experience of lake liming, in conjunction with artificial feeding of fish in Ukraine, has been summarized by Voitsekhovitch [4.79].

It is known that the concentration factor for radiocaesium in fish is inversely related to the potassium content of the surrounding water. After

the Chernobyl accident, potassium was added to 13 lakes in Sweden, either as potash or as an additive in mixed lime [4.87]. The results of the potash treatment were somewhat inconclusive, with a small reduction in activity concentrations in perch fry observed during the two year experiment. It was found that in lakes with short water retention times it was difficult to maintain high levels of K^+ in the lake.

In an experiment on Lake Svyatoye (a closed lake) in Belarus, Kudelsky et al. [4.88, 4.89] added potassium chloride fertilizer on to the frozen lake surface. Results showed a significant (factor of three) overall reduction in ^{137}Cs concentration in fish during the first years after the experiment. However, as expected, the ^{137}Cs in the water increased by a factor of two to three after the countermeasure application. It is likely that potassium treatment is only feasible in lakes with very long water residence times, which allow increased potassium concentrations to be maintained. Also, the increased ^{137}Cs in water is unlikely to be acceptable in lakes that have water abstracted for drinking.

Manipulation of the aquatic food web by intensive fishing was carried out in four lakes in Sweden [4.87], and as a complementary measure in an additional three lakes. This resulted in a reduction of the fish population by about 5–10 kg/ha. The species reduced were mainly pike, perch and roach. No effect of intensive fishing on ^{137}Cs concentrations in fish was observed. Fertilization was carried out in two Swedish lakes using Osmocoat (5% phosphorus and 15% nitrogen). The concentrations of total phosphorus generally showed no change in the long term mean value: it appears that the fertilization treatment was not carried out sufficiently effectively. No effect was observed on ^{137}Cs activity concentrations in fish.

Different methods of food preparation may affect the quantity of radionuclides in consumed food [4.90]. Ryabov suggested bans on the consumption of smoked and dried fish, because these processes increase concentrations of radionuclides (per unit of weight consumed) [4.84]. Other preparation processes may reduce radionuclide levels in fish by approximately a factor of two. An effective measure to reduce the consumption of radiostrontium is to remove the bony parts of fish prior to cooking, since strontium is mainly concentrated in the bones and skin. Various other food preparation methods are discussed in Ref. [4.91].

4.5.4. Countermeasures for groundwater

There is no evidence that measures have ever been taken to protect groundwater supplies after an atmospheric deposition of radioactivity. Groundwater residence times are long enough that shorter lived radionuclides such as ^{131}I will have decayed long before they affect drinking water. Only very small amounts of radiostrontium and radiocaesium percolate from surface soils to groundwater after atmospheric deposition. A study [4.77] has shown that, after the Chernobyl accident, exposure to ^{90}Sr and ^{137}Cs via the groundwater pathway was insignificant in comparison with other pathways (food, external exposure, etc.).

Measures were taken to protect groundwater from seepage of radionuclides from the shelter and from radioactive waste sites in the CEZ. These measures focused mainly on the construction of engineering and geochemical barriers around the local hot spots to reduce groundwater fluxes to the river network. Actions to stop precipitation from entering the shelter, and drainage of rainwater collected in the bottom rooms of the shelter, have also to be considered as preventive measures to reduce groundwater contamination around the Chernobyl nuclear power plant industrial site.

4.5.5. Countermeasures for irrigation water

As discussed previously, irrigation did not add significantly to the radionuclide contamination of crops that had previously been affected by the atmospheric deposition of radionuclides. Thus, in practice, no countermeasures were directly applied to irrigation waters. However, the experience described in Ref. [4.79] shows that the change from sprinkling to drainage irrigation of agricultural plants (e.g. vegetables) can reduce the transfer of radionuclides from water to crops by several times. This, in combination with improved fertilization of irrigated lands, can effectively reduce radionuclide levels in crops irrigated with water from reservoirs affected by radioactive pollution.

4.6. CONCLUSIONS AND RECOMMENDATIONS

The Chernobyl accident prompted the introduction of an extensive set of short and long term environmental countermeasures by the authorities

in the most affected countries to reduce its negative consequences. Unfortunately, there was not always openness and transparency towards the public, and information was withheld. This can, in part, explain some of the problems experienced later in communication with the public, and the mistrust of the competent authorities. Similar behaviour in many other countries outside Belarus, the Russian Federation and Ukraine led to a distrust in authority that, in many countries, has prompted investigations on how to deal with such major accidents in an open and transparent way and on how the affected people can be involved in decision making processes.

The unique experience of countermeasure application after the Chernobyl accident has already been widely used both at the national and international levels in order to improve preparedness against future nuclear and radiological emergencies [4.12, 4.14, 4.41, 4.91, 4.92].

4.6.1. Conclusions

- (a) The Chernobyl accident prompted the introduction of an extensive set of short and long term environmental countermeasures by the USSR and, later, independent country authorities, aimed at reducing the accident's negative consequences. The countermeasures involved large amounts of human, economic and scientific resources.
- (b) When social and economic factors along with the radiological factors are taken into account during the planning and application of countermeasures, better acceptability of these measures by the public is achieved.
- (c) The unprecedented scale and long term consequences of the Chernobyl accident required the development of some additional national and international radiation safety standards, to take account of changes of radiation exposure conditions.
- (d) Countermeasures applied in the early phase of the Chernobyl accident were only partially effective in reducing radioiodine intake via milk, because of the lack of timely information about the accident and advice on appropriate actions, particularly for private farmers.
- (e) The most effective countermeasures in the early phase were exclusion of contaminated pasture grasses from animal diets and rejection of milk (with further processing) based on radiation monitoring data. Feeding

animals with 'clean' fodder was effectively performed in some affected countries. The slaughtering of cattle was unjustified from a radiological point of view and had great hygienic, practical and economic implications.

- (f) The greatest long term problem has been radio-caesium contamination of milk and meat. In the USSR, and later in the three independent countries, this has been addressed by the treatment of land used for fodder crops, clean feeding and application of caesium binders to animals, which enabled most farming practices to continue in affected areas.
- (g) Decontamination of settlements was widely applied in contaminated regions of the USSR during the first years after the Chernobyl accident as a means of reducing the external exposure of the public; this was cost effective with regard to external dose reduction when its planning and implementation were preceded by a remediation assessment based on cost-benefit considerations and external dosimetry data.
- (h) The decontamination of urban environments has produced a considerable amount of low level radioactive waste, which creates a problem of disposal. However, secondary contamination of cleaned up plots has not been observed.
- (i) The following forest related restrictions widely applied in the USSR and later in the three independent countries and partially in Scandinavia have reduced human exposure due to residence in radioactively contaminated forests and the use of forest products:
 - (i) Restrictions on public and forest worker access as a countermeasure against external exposure.
 - (ii) Restricted harvesting by the public of food products such as game, berries and mushrooms contributed to a reduction in internal dose. In the affected countries mushrooms are a common dietary component, and therefore this restriction has been particularly important.
 - (iii) Restricted collection of firewood by the public to prevent exposures in the home and garden when the wood is burned and the ash is disposed of or used as a fertilizer.
 - (iv) Alteration of hunting practices, aimed at avoiding consumption of meat with high seasonal levels of radiocaesium.

- (v) Fire prevention, especially in areas with large scale radionuclide deposition, in order to avoid secondary contamination of the environment.

- (j) Experience has shown that forest restrictions can result in significant negative social consequences, and advice from the authorities to the general public may be ignored as a result. This situation can be offset by the provision of suitable educational programmes targeted at the local scale to explain the purpose of the suggested changes in the use of some forest areas.
- (k) It is unlikely that any technology based forest countermeasures (i.e. the use of machinery and/or chemical treatments to alter the distribution or transfer of radiocaesium in forests) will be practicable on a large scale.
- (l) Numerous countermeasures put in place in the months and years after the accident to protect water systems from transfers of radionuclides from contaminated soils were, in general, ineffective and expensive and led to relatively high exposures of the workers implementing the countermeasures.
- (m) The most effective countermeasure for aquatic pathways was the early restriction of drinking water abstraction and the change to alternative supplies. Restrictions on the consumption of freshwater fish have proved effective in Scandinavia and Germany; however, in Belarus, the Russian Federation and Ukraine such restrictions may not always have been adhered to.
- (n) It is unlikely that any future countermeasures to protect surface waters will be justifiable in terms of economic cost per unit of dose reduction. It is expected that restrictions on the consumption of fish will be retained in a few cases (in closed lakes) for several more decades.

4.6.2. Recommendations

4.6.2.1. Countries affected by the Chernobyl accident

- (a) Long term remediation measures and countermeasures in the areas contaminated with radionuclides should be applied if they are radiologically justified and optimized.
- (b) Authorities and the general public should be particularly informed on radiation risk factors

and the technological possibilities to reduce them in the long term by means of remediation and countermeasures. Local authorities and the public should be involved in related discussions and decision making.

- (c) In the long term after the Chernobyl accident, remediation measures and regular countermeasures should be maintained where they remain efficient and justified — mainly in agricultural areas with poor (sandy and peaty) soils and resulting high radionuclide transfer from soil to plants.
- (d) Particular attention must be given to private farms in several hundred settlements and to about 50 intensive farms in Belarus, the Russian Federation and Ukraine, where radionuclide concentrations in milk still exceed the national action levels.
- (e) Emphasis should be on the most efficient long term remediation measures; these are the radical improvement of pastures and grasslands and the draining of wet peaty areas. The most efficient regular agricultural countermeasures are the pre-slaughter clean feeding of animals accompanied by in vivo monitoring, the application of Prussian blue to cattle and the enhanced application of mineral fertilizers in plant cultivation.
- (f) Restricting harvesting of wild food products such as game, berries, mushrooms and fish from closed lakes by the public still may be needed in areas where their activity concentrations exceed the national action levels.
- (g) Advice should continue to be given on individual diets, as a way of reducing consumption of highly contaminated wild food products, and on simple cooking procedures to remove radioactive caesium.
- (h) It is necessary to identify sustainable ways to make use of the most affected areas that reflect the radiation hazard, but also to revive their economic potential for the benefit of the community.

4.6.2.2. *Worldwide*

- (a) The unique experience of countermeasure application after the Chernobyl accident should be carefully documented and used for the preparation of international guidance for authorities and experts responsible for radiation protection of the public and the environment.

- (a) Practically all the long term agricultural countermeasures implemented on a large scale on contaminated lands of the three most affected countries can be recommended for use in the event of future accidents. However, the effectiveness of soil based countermeasures varies at each site. Analysis of soil properties and agricultural practices before application is therefore of great importance.
- (b) Recommendations on the decontamination of the urban environment in the event of large scale radioactive contamination should be distributed to the owners and operators of nuclear facilities that have the potential for substantial accidental radioactive release (nuclear power plants and reprocessing plants) and to authorities in adjacent regions.

4.6.2.3. *Research*

- (a) Generally, the physical and chemical processes involved in environmental countermeasures and remediation technologies, both of a mechanical nature (radionuclide removal, mixing with soil, etc.) and a chemical nature (soil liming, fertilization, etc.), are understood sufficiently to be modelled and applied in similar circumstances worldwide. Much less understood are the biological processes that could be used in environmental remediation (e.g. reprofiling of agricultural production, bioremediation, etc.). These processes require more research.
- (b) An important issue that requires more sociological research is the perception by the public of the introduction, performance and withdrawal of countermeasures in the event of an emergency, as well as the development of social measures aimed at involving the public in these processes at all stages, beginning with the decision making process.
- (c) There is still substantial diversity in the international and national radiological criteria and safety standards applicable to the remediation of areas affected by environmental contamination with radionuclides. The experience of radiological protection of the public after the Chernobyl accident has clearly shown the need for further international harmonization of appropriate radiological criteria and safety standards.

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5. HUMAN EXPOSURE LEVELS

5.1. INTRODUCTION

5.1.1. Populations and areas of concern

Following the Chernobyl accident, both workers and the general public were affected by radiation that carried a risk of adverse health effects. UNSCEAR selected the following three categories of exposed populations: (a) workers involved in the accident, either during the emergency period or during the cleanup phase; (b) the inhabitants of contaminated areas who were evacuated in 1986; and (c) the inhabitants of contaminated areas who were not evacuated [5.1].

In this section consideration is given primarily to members of the general public exposed to radionuclides deposited in the environment. The workers involved in the emergency response to the accident or in the cleanup following the accident and exposed predominantly on-site (i.e. at the Chernobyl nuclear power plant and in the CEZ) are not considered here. For information on Chernobyl worker populations, the reader is referred to the comprehensive material provided by UNSCEAR [5.1, 5.2] and by the Chernobyl Forum in its report considering the human health effects [5.3].

Information on the radiation doses received by members of the general public, both those evacuated from the accident area and those who live permanently in contaminated areas, is required for the following health related purposes:

- (a) Substantiation of countermeasures and remediation programmes;
- (b) Forecast of expected adverse health effects and justification of corresponding health protection measures;
- (c) Information for the public and the authorities;
- (d) Epidemiological and other medical studies of radiation caused adverse health effects.

In this section the methodologies and data specifically required for the estimation of mean doses to population groups living in particular settlements and selected by the factors influencing either external or internal dose or both are presented. These factors are usually age, sex, occupation, food habits, etc. Dose distributions among group members and collective doses are also

considered. Individual doses to members of the public, used mainly in analytical epidemiological studies, are presented in the Chernobyl Forum report on the health consequences of the Chernobyl accident [5.3]. On these subjects, substantial progress has been achieved since publication of the comprehensive UNSCEAR report in 2000 [5.1].

As mentioned in Section 3.1, atlases have been prepared that show the deposition of ^{137}Cs and other radionuclides throughout the former USSR and other countries of Europe [5.4, 5.5]. These indicate that the most affected countries are Belarus, the Russian Federation and Ukraine. In addition, the countries of Austria, Bulgaria, Finland, Greece, Italy, Norway, Republic of Moldova, Slovenia, Sweden and Switzerland had areas that can be considered to have been ‘contaminated’ — that is, at the level of more than 37 kBq/m^2 ($>1 \text{ Ci/km}^2$) of ^{137}Cs (see Table 3.2).

5.1.2. Exposure pathways

Following the Chernobyl accident there were several pathways by which humans were exposed to radioactive material (Fig. 5.1). The main pathways are listed below in the approximate time sequence in which the doses were received:

- (a) External dose from cloud passage;
- (b) Internal dose from inhalation during cloud passage and of resuspended material;
- (c) External dose from radionuclides deposited upon soil and other surfaces;

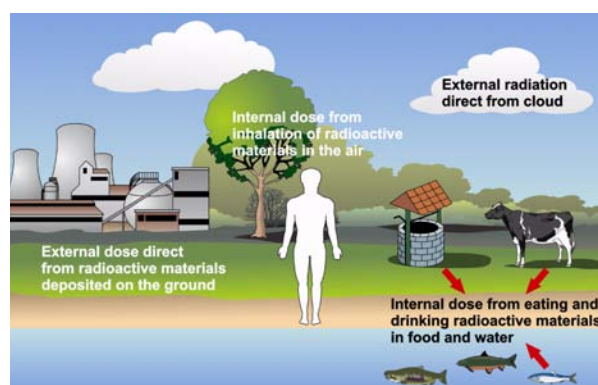


FIG. 5.1. Pathways of exposure of humans to environmental releases of radioactive material.

- (d) Internal dose from the consumption of contaminated food and water.

Under most exposure conditions for members of the general public the two most important pathways are dose from radiation from the decay of radionuclides deposited upon the soil and other surfaces and dose from the ingestion of contaminated food and water. If persons are evacuated quickly after passage of the initial cloud, then the most important pathways are the first two in the list, because the latter two pathways have been prevented.

5.1.3. Concepts of dose

Methods of calculating radiation dose have been refined over the years, and specific concepts have evolved [5.1, 5.6]. The fundamental measure of radiation dose to an organ or tissue is the absorbed dose, which is the amount of energy absorbed by that organ or tissue divided by its weight. The international unit of absorbed dose is the gray (Gy), which is equal to one joule per kilogram. Since this is a rather large amount of dose, it is common to use units of mGy (one thousandth of a gray) or μ Gy (one millionth of a gray).

Since many organs and tissues were exposed as a result of the Chernobyl accident, it has been very common to use an additional concept, effective dose, which is the sum of the products of absorbed dose to each organ multiplied by a radiation weighting factor and a tissue weighting factor. The former varies by radiation type and is related to the density of ionizations created; the latter is an approximation of the relative probability that an absorbed dose to a particular organ might lead to

the production of a cancer. The sum of all tissue weighting factors is equal to 1.0.

The concepts mentioned above are applied to individuals. Where many individuals have been exposed to an event, such as happened following the Chernobyl accident, an additional concept, the collective dose, can be used. The collective dose is the sum of the doses to all individuals within a particular group, which may be the residents of a particular country or the persons involved in some type of activity, such as cleaning up the consequences of the accident. This concept is most often applied to effective doses, and the common unit of the collective effective dose is the man-Sv.

Finally, UNSCEAR has employed the concept of dose commitment to examine the long term consequences of a practice or accident [5.1]; for example, at the very moment that the Chernobyl accident occurred, it can be considered that a dose commitment occurred at the moment of the release of the radioactive material. This is true even though it will take many years for the doses to be received by the persons alive at that time and by persons not yet born or conceived.

5.1.4. Background radiation levels

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 5.1 shows the average annual dose and typical dose range worldwide from natural sources.

In addition to natural sources, radiation exposure occurs as a result of human activities. Table 5.2 shows the annual individual effective

TABLE 5.1. RADIATION DOSES FROM NATURAL SOURCES [5.1]

	Worldwide average annual effective dose (mSv)	Typical range (mSv)
<i>External exposure</i>		
Cosmic rays	0.4	0.3–1.0
Terrestrial gamma rays	0.5	0.3–0.6
<i>Internal exposure</i>		
Inhalation (mainly radon)	1.2	0.2–10
Ingestion	0.3	0.2–0.8
Total	2.4	1–10

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 European countries and especially in areas of Belarus, the Russian Federation and Ukraine.

5.1.5. Decrease of dose rate with time

To calculate the radiation dose for particular time periods, it is necessary to predict the decrease of dose rate with time. The most obvious mechanism acting to cause such a decrease is the radioactive decay of the radionuclides. Additional DRRFs are usually called ecological half-lives; for example, external gamma exposure rates decrease with time due to the weathering of long lived radionuclides such as ^{137}Cs into the soil and subsequent migration down the soil column, which results in increased absorption of the emitted radiations within the soil. Typically, a two component exponential function describes this process [5.7, 5.8].

The availability of ^{137}Cs for ingestion also decreases with time at a rate faster than radioactive decay. This additional long term decrease is due mainly to the adsorption of ^{137}Cs to soil particles from which the caesium atoms are no longer biologically available. As with the external dose rate, the decrease of ^{137}Cs in milk or in humans living in areas contaminated by the Chernobyl accident also shows

a two component exponential decrease with time [5.9, 5.10].

5.1.6. Critical groups

In all situations that involve the exposure of large segments of the population to natural or human-made radioactive material, there is always a significant spread in the radiation dose received by various members of the population living within the same geographical area. Those individuals with the higher doses are frequently called the critical group, and these persons may have doses twice or even higher than the average dose to all members of the population considered. Usually such persons can be identified in advance, and, in some cases, special protective measures may be considered.

For external dose, members of the critical group are those who spend a considerable amount of time outdoors, either for occupational or recreational reasons; also, people living and/or working in buildings with minimal shielding might be members of the critical group. For exposure to radioiodine isotopes, the critical group is often infants drinking goat's milk. Infants have a thyroid gland weighing only two grams that concentrates roughly 30% of the radioiodine consumed; goats are more efficient than cows at secreting radioiodine into milk. For exposure to radiocaesium, critical groups have been identified as those who consume large quantities of local animal products such as milk and meat and wild products such as game meat, mushrooms, wild berries and lake fish.

TABLE 5.2. EFFECTIVE DOSES IN 2000 FROM NATURAL AND HUMAN SOURCES [5.1]

	Worldwide average annual per caput effective dose (mSv)	Range or trend in exposure
Natural background	2.4	Typical range of 1–10 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	Has decreased from a maximum of 0.15 mSv in 1963; higher in the northern hemisphere
Chernobyl accident	0.002	Has 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	Has increased with expansion of the nuclear programme but decreased with improved practice

5.2. EXTERNAL EXPOSURE

5.2.1. Formulation of the model for external exposure

In any situation of human external exposure caused by releases of radioactive substances into the environment, the following three types of data are necessary for assessment of organ or effective doses:

- Parameters that describe the external gamma radiation field;
- Parameters describing human behaviour in this field;
- Conversion factors from dose in air to organ or effective dose.

The basic model for human external exposure in the event of radioactive contamination of the environment is the model for exposure above an open plot of undisturbed soil; the absorbed dose in air $\dot{D}(t)$ at a height of 1 m above the soil surface is used as the basic parameter to describe the radiation field. The value of this basic parameter is influenced not only by the surface activity of deposited radionuclides but also by such natural factors as the initial penetration of radionuclides in soil and their radioactive decay, vertical migration of long lived radionuclides and the presence of snow cover.

Radiation exposure is influenced by altered or disturbed environments. In models this factor is taken into account by using location factors. The

location factor LF_i is defined as the ratio of the dose rate in air at point i inside a settlement to a similar value above a plot of undisturbed soil [5.11]. Human behaviour in the radiation field is described by occupancy factors OF_{ik} , which represent the fraction of time spent by individuals of the k th population group at the i th point of the settlement of interest. The third type of data necessary for assessment of the effective external dose are conversion factors CF_k , which convert measured values (the absorbed dose in air) to a parameter that can be directly related to health effects — the effective dose to the k th population group.

On this basis, a deterministic model for the assessment of the effective external dose rate E_k for representatives of the k th population group is represented in Fig. 5.2.

5.2.2. Input data for the estimation of effective external dose

Numeric values for the parameters listed above have been determined from long term dosimetric investigations in the most highly contaminated regions after the Chernobyl accident.

5.2.2.1. Dynamics of external gamma dose rate over open undisturbed soil

Immediately after the accident, external gamma exposure rates were relatively high, and contributions from many short lived radionuclides were important. Thus in the contaminated areas outside the Chernobyl nuclear power plant boundaries the initial dose rate over lawns and meadows ranged between 3 and 10 $\mu\text{Gy/h}$ in areas contaminated at about 37 kBq/m^2 (1 Ci/km^2) of ^{137}Cs and up to 10 000 $\mu\text{Gy/h}$ within the CEZ with higher deposition levels. Exposure rates decreased rapidly, due to the radioactive decay of short lived radionuclides, as shown in Fig. 5.3.

Owing to different isotopic compositions of radionuclide fallout in different geographical areas [5.8, 5.13, 5.14], the contribution of short lived radionuclides to the overall dose rate was highly variable. In the CEZ, $^{132}\text{Te} + ^{132}\text{I}$, ^{131}I and $^{140}\text{Ba} + ^{140}\text{La}$ dominated during the first month and then $^{95}\text{Zr} + ^{95}\text{Nb}$ for another half year before ^{137}Cs and ^{134}Cs became dominant (Fig. 5.4). In contrast, in the far zone only the radioiodine isotopes dominated during the first month; afterwards ^{137}Cs and ^{134}Cs dominated, with a moderate contribution from ^{103}Ru and ^{106}Ru (Fig. 5.5). Since 1987 more than

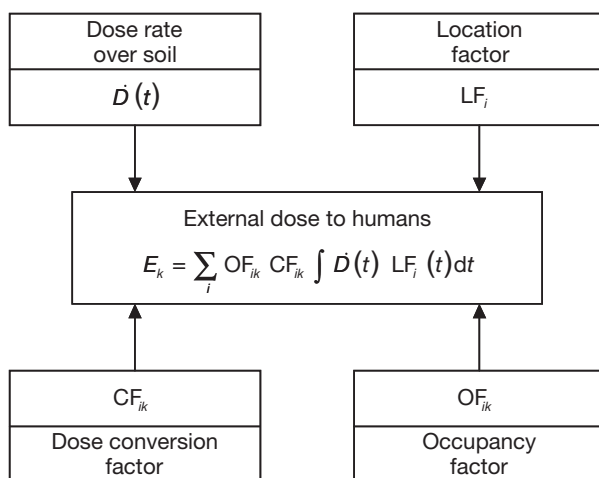


FIG. 5.2. Model of external exposure of the k th population group (i is a location index) [5.9].

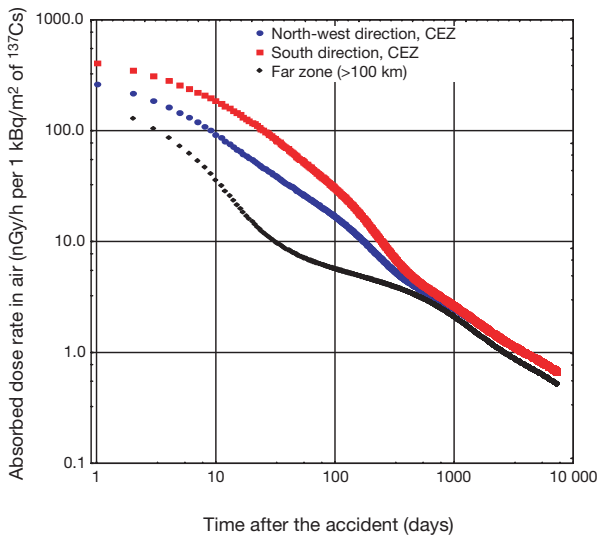


FIG. 5.3. Dynamics of standardized dose rate in air over undisturbed soil after the Chernobyl accident in different geographical areas [5.12].

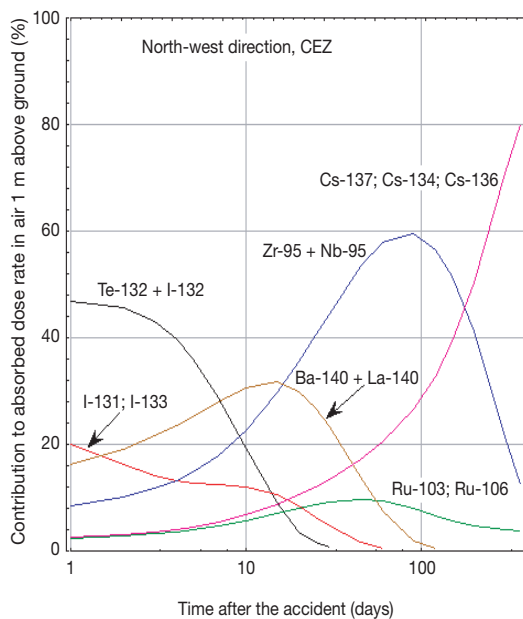


FIG. 5.4. Relative contribution of gamma radiation from individual radionuclides to the external gamma dose rate in air during the first year after the Chernobyl accident (north-west direction, CEZ) [5.12].

90% of the dose rate in air has come from the gamma radiation of long lived ¹³⁷Cs and ¹³⁴Cs. Thus the radionuclide composition of the deposited activity was a major factor in determining the external exposure of the population in the early period of time after the accident. Model estimates of the gamma dose rate in free air (90% confidence interval) based on the radionuclide composition of

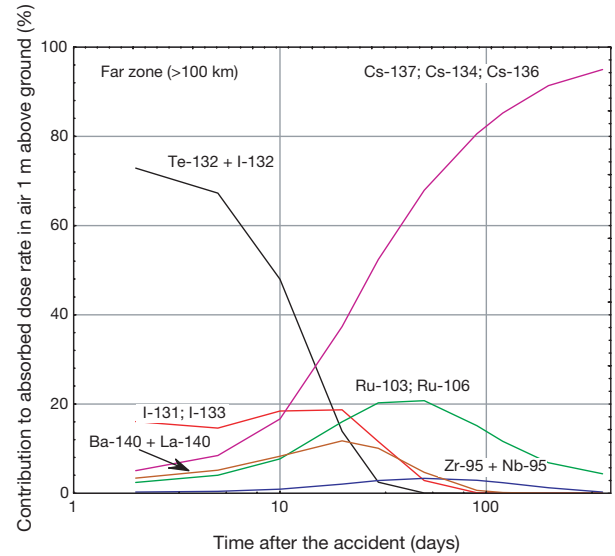


FIG. 5.5. Relative contribution of gamma radiation from individual radionuclides to the external gamma dose rate in air during the first year after the Chernobyl accident (far zone — more than 100 km from the Chernobyl nuclear power plant) [5.12].

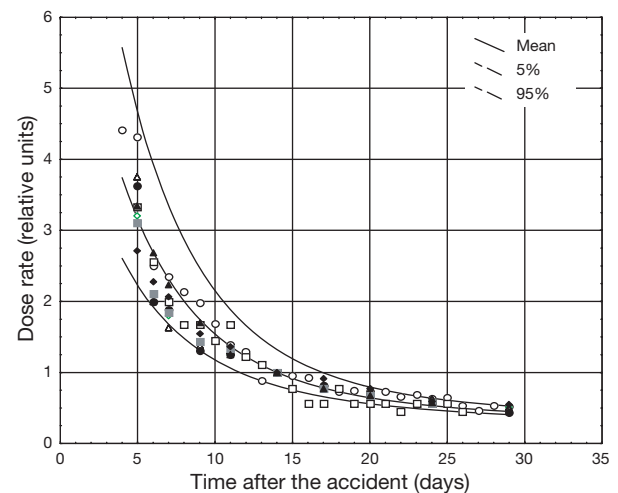


FIG. 5.6. Dose rate in air during the first days after the accident in several rural settlements in the Bryansk and Tula regions of the Russian Federation (normalized to the dose rate on 10 May 1986). Points indicate dose rate measurements and curves represent calculated values according to the isotopic composition [5.7].

the deposited activity agree well with the measured values during the first month after deposition (see Fig. 5.6).

The influence of radionuclide migration into soil on the gamma dose rate has been determined using gamma spectrometric analyses of over 400 soil samples taken during 1986–1999 in the contaminated areas of Germany (Bavaria), the Russian

Federation, Sweden and Ukraine [5.7, 5.8, 5.15]. The analysis also included data on the ^{137}Cs distribution in soil at sites in the north-east region of the USA, whose contamination was attributed to nuclear tests at the Nevada test site [5.16], and in Bavaria (Germany), where contamination was due to global fallout. The last two data sets were obtained 20 to 30 years after deposition; this allows for long term predictions to be applied to the Chernobyl depositions. The measurement sites were considered to be representative of reference sites (i.e. open, undisturbed fields).

For a few years after the accident, the dose rate over open plots of undisturbed soil decreased by a factor of 100 or more compared with the initial level (see Fig. 5.3). At that time, the dose rate was mainly determined by gamma radiation of caesium radionuclides (i.e. ^{137}Cs (half-life 30 years) and ^{134}Cs (half-life 2.1 years), and later, one decade and more after the accident, mainly the longer lived ^{137}Cs). Long term studies of external gamma exposure rates during the past 17 years have shown that the external gamma exposure rate is decreasing faster than that due to radioactive decay alone. Golikov et al. [5.7] and Likhtarev et al. [5.8] have calculated a reference function for ^{137}Cs gamma radiation dose rate that has 40–50% of the exposure rate decreasing with an ecological half-life of 1.5–2.5 years and the remaining 50–60% decreasing with an ecological half-life of 40–50 years, as indicated in Fig. 5.7. The latter value is rather uncertain. It corresponds to an effective half-life of 17–19 years that takes into account both the radioactive decay of ^{137}Cs and its gradual deepening in soil.

5.2.2.2. Dynamics of external gamma dose rate in anthropogenic areas

In settlements in urban and rural areas, the characteristics of the radiation field differ considerably from those over an open plot of undisturbed land, which is used as the reference site and starting point for calculation of external dose to people from deposited activity. These differences are attributable to varying source distributions as a result of deposition, runoff, weathering and shielding. All such effects can be summarized by the term ‘location factors’.

Location factors for typical western European buildings have been assessed [5.11, 5.17, 5.18]. Gamma spectrometric measurements performed in Germany and Sweden [5.19–5.22] allowed the

determination of location factors in urban environments and their variation with time over several years after the Chernobyl accident. The characteristic feature, and advantage, of these investigations is that they began immediately after the accident, whereas systematic investigations of location factors in the contaminated areas of Belarus, the Russian Federation and Ukraine began two to three years after the accident. The results of one such later investigation in Novozybkov (in the Bryansk region of the Russian Federation) are presented in Fig. 3.12 (Section 3).

5.2.2.3. Behaviour of people in the radiation field

The influence of the behaviour of different social population groups on the level of exposure can be taken into account if the frequency with which people of the k th population group remain at the location of the i th type is known. The times spent in various types of location (indoor, outdoors on streets or in yards, etc.) by members of different population groups have been assessed on the basis of responses to a questionnaire. Data collected included age, sex, occupation, information about dwelling, etc. An example of the results is shown in Table 5.3, where values of occupancy factors for the summer period are presented for different groups of the rural populations of Belarus, the Russian Federation and Ukraine [5.15].

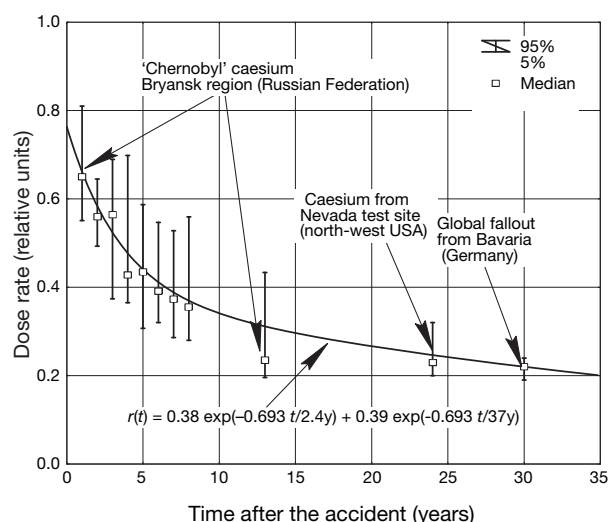


FIG. 5.7. Reduction of the ^{137}Cs gamma dose rate in air due to caesium migration in undisturbed soil relative to the dose rate caused by a plane source on the air–soil interface (from Ref. [5.7]).

5.2.2.4. Effective dose per unit gamma dose in air

Mean values of conversion factors CF_k , which convert the gamma dose rate in air to the effective dose rate in a member of population (age) group k , were obtained for the three groups of population by use of phantom experiments [5.15] and Monte Carlo calculations [5.23]. The values were 0.75 Sv/Gy for adults, 0.80 Sv/Gy for schoolchildren (7–17 years) and 0.90 Sv/Gy for pre-school children (0–7 years). For the calculation of effective doses, conversion factors CF_k were used that are independent of the location and time after the accident.

5.2.3. Results

5.2.3.1. Dynamics of external effective dose

Shortly after the deposition of the fallout the gamma radiation field was dominated by emissions from short lived radionuclides, as discussed above (see Figs 5.4 and 5.5). As the mixtures at different locations varied widely, the radionuclide composition of the deposited activity was a major factor in determining the external exposure of the population during the early period after the accident.

Another relevant parameter in the midterm period is the dependence of location factors on time, due to the relatively fast migration processes of radionuclides during this period. The dose rate over different urban surfaces caused by gamma radiation of ^{137}Cs decreased during the first years after deposition, with an exponential half-life of one to two years (see Fig. 3.12). In the five to seven years after deposition, the change in dose rate with time had stabilized — this was due to the decay of

the short lived radionuclides and the fixation of caesium radionuclides within the soil column.

According to measurements and evaluations within the first year after the accident, the external dose rate had decreased by a factor of approximately 30, mainly due to radioactive decay of short lived radionuclides (see Fig. 5.8). During the following decade the external dose rate decreased because of the radioactive decay of ^{134}Cs and ^{137}Cs and the migration of radiocaesium into the soil. Afterwards, the external dose rate was mainly due to ^{137}Cs . In the long term, radiocaesium becomes fixed within the soil matrix, and this results in a slow migration into the soil and, correspondingly, in a slow decrease of the external dose rate. On the basis of such measurements, it is predicted that, of the total external dose to be accumulated during 70 years following the accident, about 30% was accumulated during the first year and about 70% during the first 15 years (Fig. 5.8) [5.7].

5.2.3.2. Measurement of individual external dose with thermoluminescent dosimeters

In general, before the Chernobyl accident, individual external doses were measured only for occupational exposures. After the Chernobyl accident, individual external doses to members of the population were also measured. For this purpose thermoluminescent dosimeters were distributed to the inhabitants of the more contaminated areas of Belarus, the Russian Federation and Ukraine [5.24–5.28]. Inhabitants wore thermoluminescent dosimeters for about one month in the spring and summer periods. Examples of such results are presented in Figs 5.9 and 5.10 for rural and urban areas, respectively. According to these results it can be concluded that the urban

TABLE 5.3. VALUES OF OCCUPANCY FACTORS FOR THE SUMMER PERIOD FOR DIFFERENT GROUPS OF THE RURAL POPULATIONS OF THE RUSSIAN FEDERATION, BELARUS AND UKRAINE^a [5.15]

Location	Indoor workers	Outdoor workers	Pensioners	Schoolchildren	Pre-school children
Inside houses	0.65/0.77/0.56	0.50/0.40/0.46	0.56/0.44/0.54	0.57/0.44/0.75	0.64/—/0.81
Outside houses (living area)	0.32/0.19/0.40	0.27/0.25/0.29	0.40/0.42/0.41	0.39/0.45/0.21	0.36/—/0.19
Outside settlements	0.03/0.04/0.04	0.23/0.35/0.25	0.04/0.14/0.05	0.04/0.11/0.04	0/—/0

^a The first number corresponds to data for the Russian Federation, the second is for Belarus and the third is for Ukraine [5.15].

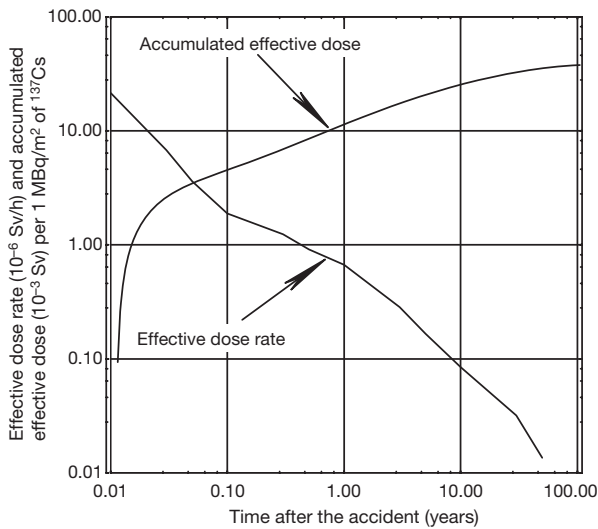


FIG. 5.8. Model prediction of the time dependence of the external effective gamma dose rate and the accumulated external effective dose to the urban population of the Bryansk region of the Russian Federation [5.7].

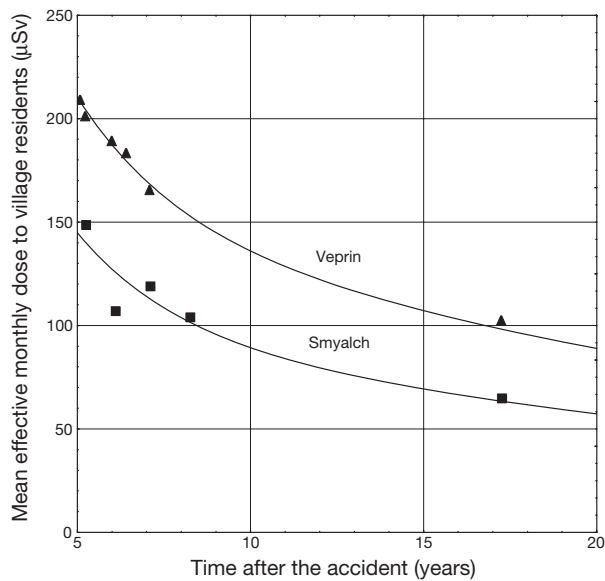


FIG. 5.9. Results of thermoluminescence measurements of mean monthly doses among inhabitants living in wooden houses in the Veprin and Smyalch villages (Bryansk region of the Russian Federation) in different time periods following deposition [5.28].

population has been exposed to a lower dose by a factor of 1.5–2 compared with 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.

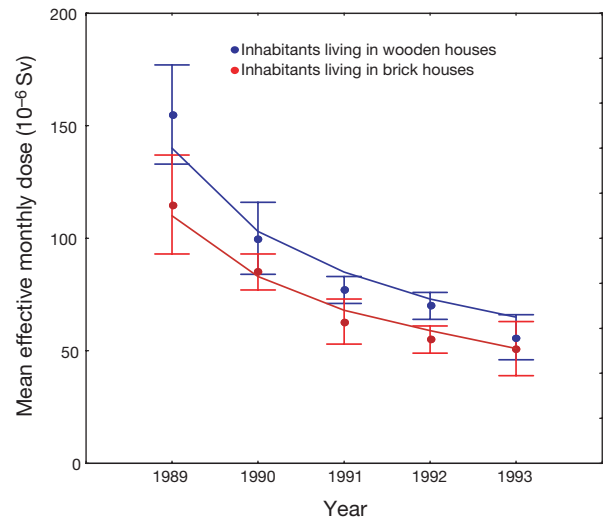


FIG. 5.10. Effective dose rates for indoor workers in Novozybkov (Russian Federation). The points with error bars represent average values and 95% confidence intervals (+/- two standard errors) of thermoluminescence measurements [5.28].

The critical group in relation to external irradiation is composed of individuals in an occupation or with habits that result in spending a significant amount of time outside in areas of undisturbed soil, in forests or meadows, and who also live in houses with the least protective properties. At present, the average external dose to any population group does not exceed the average dose in a settlement by more than a factor of two. Typical critical groups are foresters (factor 1.7), herders (factor 1.6) and field crop workers (factor 1.3) living in one-storey wooden houses [5.9, 5.15].

Analysis of the results of measurements of inhabitants of settlements showed that the distribution of individual doses can be described by a log-normal function [5.7]. Figure 5.11 presents a comparison of model calculations with individual thermoluminescence measurements performed in 1993 in four villages of the Bryansk region (565 measurements). The distributions of the ratio of individual external doses to the mean value of measured doses in each of the villages are almost identical. Thus the resulting log-normal distribution with a geometric standard deviation of about 1.5 (attributed mainly to the stochastic variability of individual doses) may be assumed to be typical for rural settlements in the zone of the Chernobyl accident.

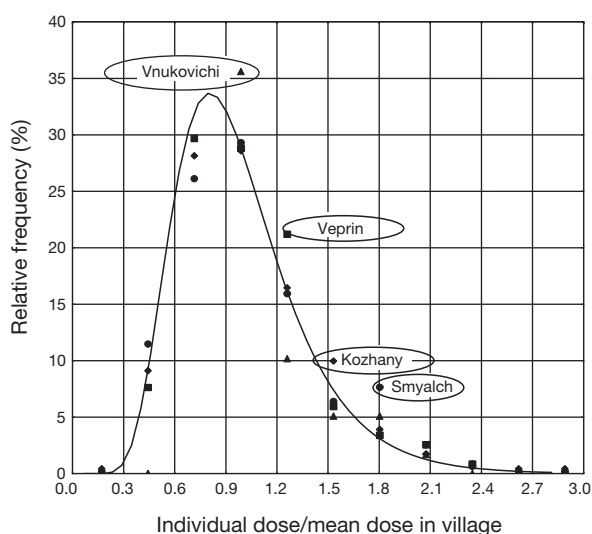


FIG. 5.11. Frequency distributions of monthly effective external doses to individual persons as measured in the summer of 1993 with thermoluminescent dosimeters in four villages of the Bryansk region of the Russian Federation (points) and calculated by the stochastic model (curve). Doses are normalized to the arithmetic mean of the individual doses determined for each of the villages (from Ref. [5.7]).

5.2.3.3. Levels of external exposure

To illustrate actual levels of external exposure and differences in the level of exposure among various population groups, Table 5.4 presents calculated values of effective external doses during different time intervals for rural and urban populations in the Russian Federation and Ukraine, and Table 5.5 presents the ratio of average effective doses in separate population groups to the mean dose in a settlement. Calculations of dose for different time intervals were performed on the basis of the model described above for the assessment of external dose in a population.

At present, the average annual external dose to residents of a rural settlement with a current ^{137}Cs soil deposition of $\sim 700 \text{ kBq/m}^2$ ($\sim 20 \text{ Ci/km}^2$) is 0.9 mSv . For the critical group, the dose value exceeds the annual dose limit of 1 mSv set for the population under normal conditions. The external dose due to Chernobyl deposition accumulated to the present time is 70–75% of the total lifetime dose (70 years) for persons born in 1986 and living all the time in contaminated areas.

TABLE 5.4. AVERAGE NORMALIZED EFFECTIVE EXTERNAL DOSE TO THE ADULT POPULATION IN THE INTERMEDIATE ($100 \text{ km} < \text{DISTANCE} < 1000 \text{ km}$) ZONE OF CHERNOBYL CONTAMINATION

		$E/\sigma_{137} (\mu\text{Sv} \cdot \text{kBq}^{-1} \cdot \text{m}^{-2} \text{ of } ^{137}\text{Cs})^a$				
		1986	1987–1995	1996–2005	2006–2056	1986–2056
Russian Federation [5.7, 5.28]	Rural	14	25	10	19	68
	Urban	9	14	5	9	37
Ukraine [5.8]	Rural	24	36	13	14	88
	Urban	17	25	9	10	61

^a σ_{137} is given as for 1986.

TABLE 5.5. RATIO OF AVERAGE EFFECTIVE EXTERNAL DOSES IN SEPARATE POPULATION GROUPS TO THE MEAN DOSE IN A SETTLEMENT [5.9]

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

5.3. INTERNAL DOSE

5.3.1. Model for internal dose

The general form of models used to calculate internal dose is shown in Fig. 5.12 [5.9]. The main pathways of radionuclide intake into the body of a person of age k are inhalation, with average inhalation rate IR_k of air with time dependent concentration $AC_r(t)$ of radionuclide r , and ingestion of the set of f food products and water with consumption rates CR_{fk} with time dependent specific activity SA_{fr} .

Data on air concentrations and food activity concentrations have been discussed in previous sections and will be summarized briefly below. Data on food consumption rates are taken from the literature [5.2, 5.10] or from special surveys of the affected populations [5.29, 5.30]. Other data needed for dosimetric calculations are taken from publications of the International Commission on Radiological Protection for age specific inhalation rates [5.31] and for age specific dose coefficients [5.32]. The latter values are for both inhalation and ingestion and give the dose per unit radionuclide inhaled or ingested. These values are calculated in terms of committed dose; that is, the dose that will be received over the next 50 years for adults or until age 70 for younger persons. For most radionuclides, but not for ^{90}Sr or ^{239}Pu , the biological residence time within the body is short, and the committed dose is only slightly larger than the dose accrued over the course of one year. Strontium and plutonium nuclides, and a few others, are

metabolized slowly, and the full committed dose is not actually received for many years.

Another method of calculating internal dose is to use direct measurements of the radionuclide of interest in the human body. This was done for ^{131}I in the human thyroid in the three most affected countries [5.33–5.35] and for ^{137}Cs (e.g. Refs [5.10, 5.36]). Especially for the thyroid, direct measurements are not sufficient to calculate doses, and such information must be supplemented by suitable intake models to determine the past and future concentration of the radionuclide in the body and its organs.

Predictions of future intakes of long lived radionuclides into the body must be made in order to predict future doses. Information on the long term transfer of the important radionuclide ^{137}Cs from the environment to the human body can be made on the basis of experience with this radionuclide in global and local fallout [5.1]. Also, enough time has now passed since the Chernobyl accident that measurements specific to Chernobyl can be used to predict the future course of concentration of ^{137}Cs in foods and the human body; for example, Likhtarev et al. [5.10] on the basis of 126 000 samples of milk collected during 1987–1997 observed a two component exponential loss curve with 90% of ^{137}Cs activity disappearing with a half-life of 2.9 ± 0.3 years and 10% with 15 ± 7.6 years. The second value is very uncertain, due to the short time of observation compared with the radiological half-life of ^{137}Cs of 30 years. These data are in general agreement with those observed in the Russian Federation [5.37, 5.38].

5.3.2. Monitoring data as input for the assessment of internal dose

A unique feature of Chernobyl related monitoring of human internal exposure was the extensive application of whole body measurements of radionuclide content in the human body and its organs (mainly thyroid); these measurements were performed along with regular measurements of radionuclides in food, drinking water and other components of the environment. This combination of various kinds of monitoring data allowed substantial improvement in the precision of the reconstruction of internal dose.

To assess internal dose from inhalation, the air concentration measurements described in a previous section have been used. The most important aspect was assessment of dose for the

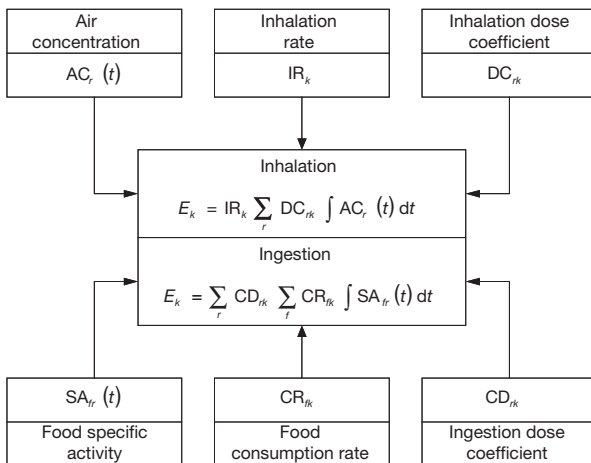


FIG. 5.12. Model for calculation of internal exposure for persons exposed to Chernobyl fallout [5.9].

first days after the accident, when the concentration of radionuclides in air was relatively high. Later, the assessment of doses via inhalation was needed in relation to the resuspension of radionuclides with low mobility in the food chain, such as plutonium.

Assessment of radionuclide intake with food and drinking water was primarily based on the numerous measurements of ^{131}I , $^{134,137}\text{Cs}$ and ^{90}Sr , which have been performed all over Europe and especially in the three most affected countries (Belarus, the Russian Federation and Ukraine). Gamma spectroscopy for ^{131}I and $^{134,137}\text{Cs}$ and radiochemical analyses for ^{90}Sr have been the main types of measurement. In some laboratories beta spectroscopy was successfully applied to determine different radionuclides in samples; when radionuclide composition was well known, total beta activity measurements were also made. In most of the measurements, ^{137}Cs in raw animal products (milk, meat, etc.) was determined; the number of these measurements performed since 1986 and available for dose estimation comprises a few million. Generic data on radionuclide measurements in food are presented in the sections pertaining to the terrestrial environment.

Activity concentrations of soluble radionuclides (mainly ^{131}I , $^{134,137}\text{Cs}$, ^{90}Sr) in drinking water were determined in 1986 both in surface and underground sources (see Section 3.5). Later, these activity concentrations declined to relatively low levels, and their contribution to internal dose was usually negligible compared with that associated with the intake of food.

In May–June 1986, ^{131}I activities were measured in the thyroids of residents of areas with substantial radionuclide deposition. In total, more than 300 000 ^{131}I measurements in the thyroid were performed in the three most affected countries, and a substantial number of measurements were also performed in other European countries. Special attention was paid to measurements of children and adolescents. After careful calibration, data on large scale measurements were used as the main basis for the reconstruction of thyroid dose.

Most of the numerous whole body measurements performed since 1986 in different European countries have been aimed at the determination of $^{134,137}\text{Cs}$. The number of measurements exceeded one million, most of which were performed in the three most affected countries. The measurement data were widely used both for model validation concerning radionuclide intake and evaluation of the effectiveness of countermeasures. In the most

contaminated regions of Belarus, the Russian Federation and Ukraine, whole body measurement data were used to obtain more precise estimates of human doses both for radiation protection purposes and as part of epidemiological studies.

Strontium-90 and plutonium radionuclides, which do not emit gamma radiation that is readily detectable by whole body counters, have been measured in excreta samples, and, since the 1990s, in samples taken at autopsy. Several hundred samples of human bone tissue have been analysed by radiochemical methods for $^{90}\text{Sr}/^{90}\text{Y}$ content. Activities of plutonium radionuclides have been successfully determined in several tens of samples of human lungs, liver and bones [5.39, 5.40].

Reduced monitoring programmes for radiation protection purposes, and specifically for the justification of remediation efforts, are continuing in the affected areas.

5.3.3. Avoidance of dose by human behaviour

In addition to the countermeasures employed to reduce levels of contamination in urban environments and in agricultural foodstuffs, changes in human habits after the accident were also effective in reducing doses to residents of the contaminated areas. The most obvious and highly effective method immediately after the accident would have been to stop the consumption of milk to reduce the intake of ^{131}I . The effectiveness of this is not well documented, and it is only in some of the more affected regions that the residents of the three countries were advised of this option in a timely manner.

The longer term option of reducing the consumption of food products known to be more highly contaminated by $^{134,137}\text{Cs}$ appears to have been more successful, at least during 1987–1993 [5.10, 5.41]. Such foods were typically locally produced milk and beef or of the ‘wild’ variety, including game meat, mushrooms and berries. Later, due to deteriorating economic conditions and the gradual reduction of the public’s caution over wild food products, such self-imposed restrictions became less widespread.

5.3.4. Results for doses to individuals

5.3.4.1. Thyroid doses due to radioiodines

One of the major impacts of the accident was exposure of the human thyroid. Doses were

accumulated rather quickly due to the rapid transfer of iodine through the food chain and the short half-life of ^{131}I of eight days; other radioiodines of interest in terms of thyroid dose also have short half-lives. The importance of thyroid doses was recognized by national authorities throughout the world, and early efforts focused on this issue. Estimates of country average individual thyroid doses to infants and adults have been provided by UNSCEAR [5.2]. Attention has been paid to thyroid dose reconstruction since the early 1990s, when an increase of thyroid cancer morbidity was discovered in children and adolescents residing in areas of Belarus, the Russian Federation and Ukraine contaminated with Chernobyl fallout [5.1, 5.3, 5.42].

In association with radioepidemiological studies, the main patterns of thyroid dose formation were clarified and published in the 1990s [5.33–5.35] and summarized in Ref. [5.1]. Nevertheless, important new work in this area has appeared recently [5.43–5.45]. The general approach to internal dose reconstruction has been elaborated in Ref. [5.46].

Methodologies of thyroid dose reconstruction for the Chernobyl affected populations developed in parallel in Belarus, the Russian Federation and Ukraine, with the participation of US and EU experts; these methodologies have a number of commonalities and some substantial distinctions that complicate their desired integration. Firstly, in all three countries there are many tens of thousands of ^{131}I thyroid measurements available, although of different quality, that are used as the basic data for thyroid dose reconstruction. In the Russian Federation, additionally, data on ^{131}I in milk were used. Owing to the use of human and environmental ^{131}I measurements, the reconstructed doses are realistic rather than conservative.

Another commonality is the use of several age groups living in one settlement or in a group of close settlements as a unit for mean thyroid dose reconstruction. When there is a substantial number of human and environmental ^{131}I measurements available in a settlement, they are used for dose reconstruction. The subsidiary quantities used for dose reconstruction in the settlements where historical ^{131}I measurements are not available are ^{137}Cs soil deposition values as indicators of radioactive contamination in the area.

However, the methodologies for thyroid dose reconstruction for settlements without environmental or human ^{131}I measurements are

substantially different in the three countries. In Ukraine, where most of the radioiodine was deposited in dry weather conditions, Likhtarev et al. [5.45] developed a model with linear dependence of thyroid dose on ^{137}Cs soil deposition. In Belarus, where both dry and wet deposition of radioiodines occurred, a semiempirical model based on non-linear dependence of thyroid dose on ^{137}Cs soil deposition was developed by Gavrilin et al. [5.35] and widely applied. In another recently published paper devoted to the same problem, a comprehensive radioecological model of radioiodine environmental transfer was developed and successfully applied for thyroid dose reconstruction [5.44]. In the Russian Federation, where wet deposition of radioiodines dominated, a linear semiempirical model of dependence of ^{131}I activity concentration in milk and of thyroid dose on ^{137}Cs soil deposition of more than 37 kBq/m^2 was developed [5.43] and applied [5.47]. Despite differences in the applied methodological approaches, the general agreement, except for areas of low contamination, is satisfactory [5.3].

The thyroid doses resulting from the Chernobyl accident comprise four contributions: (a) internal dose from intakes of ^{131}I ; (b) internal dose from intakes of short lived radioiodines (^{132}I , ^{133}I and ^{135}I) and of short lived radiotelluriums (^{131}Te and ^{132}Te); (c) external dose from the deposition of radionuclides on the ground; and (d) internal dose from intakes of long lived radionuclides such as ^{134}Cs and ^{137}Cs .

For most residents of the Chernobyl affected areas, the internal thyroid dose resulting from intakes of ^{131}I is by far the most important and has received almost all of the attention. The dose from ^{131}I was mainly due to the consumption of fresh cow's milk and, to a lesser extent, of green vegetables; children on average received a dose that was much higher than that received by adults, because of their small thyroid mass and a consumption rate of fresh cow's milk that was similar to that of adults.

An example of age and sex dependence of the mean thyroid dose to inhabitants of a settlement, based on 60 000 measurements of ^{131}I in thyroids performed in Ukraine in May 1986, is presented in Fig. 5.13 [5.48]. The mean thyroid dose to infants is larger by a factor of about seven than to young adults (19–30 years) residing in the same rural or urban settlements; this ratio decreases monotonically with age as an exponential function, with some deviation in adolescents. Differences in age

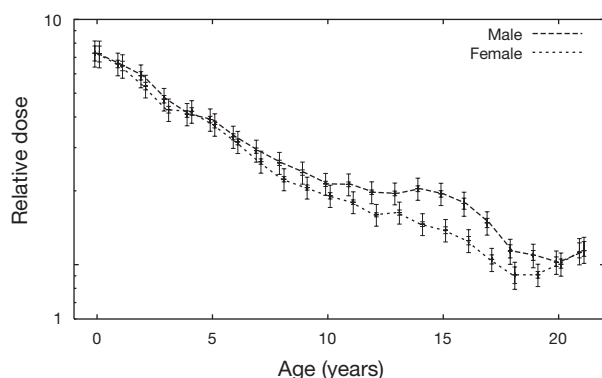


FIG. 5.13. Age–sex dependence of the mean thyroid dose to inhabitants of a settlement standardized to the mean dose to adults from the same settlement [5.48].

dependence between males and females seem to be insignificant. Similar patterns were revealed both from Belarusian and Russian measurements of ^{131}I in the thyroid [5.34, 5.35].

As the rural population living in contaminated areas depends more on local agricultural production than does an urban population, thyroid doses caused predominantly by the consumption of contaminated milk and dairy products are higher in rural than in urban populations by a factor of about two [5.1].

Although the largest contribution to thyroid dose resulted from intakes of ^{131}I , it is also important to take into consideration the internal dose from short lived radioiodines (^{132}I , ^{133}I and ^{135}I). Among members of the public, the highest relative contribution to the thyroid doses from short lived radionuclides was expected among the residents of Pripyat. This cohort was exposed to radioiodines via inhalation only and was evacuated about 1.5 days after the accident. Analysis of direct thyroid and lung spectrometric measurements performed on 65 Pripyat evacuees has shown that the contribution of short lived radionuclides to thyroid dose is about 20% for persons who did not employ stable iodine to block their thyroids and more than 50% for persons who took KI pills soon after the accident [5.49]. The total thyroid dose among the Pripyat evacuees, however, was relatively small compared with populations consuming contaminated food.

For populations permanently residing in contaminated areas, the contribution of short lived radionuclides to thyroid dose was minor, as most of the thyroid exposure resulted from the week long consumption of contaminated milk and other foodstuffs. During transport of radioiodines along

food chains, short lived radioiodines decayed, and the contribution of short lived radioiodines is estimated to have been of the order of 1% of the ^{131}I thyroid dose [5.49, 5.50].

The distribution of individual thyroid doses is illustrated in Table 5.6 for children and adolescents residing in the northern regions of Ukraine (i.e. the Kiev, Zhytomyr and Chernigov regions) most affected by radiation after the Chernobyl accident [5.45]. The dose distributions presented in Table 5.6 are based on about 100 000 human thyroid measurements. The range of thyroid dose in all groups is wide, between less than 0.2 Gy and more than 10 Gy. The latter dose group includes about 1% of younger children, less than 0.1% of children of five to nine years, and less than 0.01% of adolescents. Doses to adults are lower by a factor of about 1.5 than those to adolescents (see Fig. 5.13). In all age groups presented in Table 5.6, and especially in the younger ones, doses were high enough to cause both short term functional thyroid changes and thyroid cancer in some individuals [5.1, 5.3, 5.42].

Similar data for Belarus and the Russian Federation are available [5.35, 5.47]. Substantially more detail on the calculation of thyroid doses to individuals is provided in the dosimetry section of the Chernobyl Forum report on health effects [5.3].

Generally, it can be stated that adequate methodologies for thyroid dose reconstruction for people who resided in the spring of 1986 in the contaminated areas of Belarus, the Russian Federation and Ukraine have been developed and published. These estimates of both individual and collective doses are being widely used by research scientists and national health authorities both in forecasts of thyroid morbidity and in radioepidemiological studies.

5.3.4.2. Long term internal doses from terrestrial pathways

Inhabitants of areas contaminated with radionuclides in 1986 are still experiencing 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 [5.39], inhalation of plutonium radionuclides and ^{241}Am does not significantly contribute to human dose in this context.

Generic dose conversion parameters have been developed to reconstruct the past, assess the current and forecast future average effective internal doses. Examples for the adult rural

population of a settlement located in the intermediate ($100 \text{ km} < \text{distance} < 1000 \text{ km}$) zone of contamination based on experimental data and models developed in the Russian Federation and Ukraine are given in Table 5.7 [5.9, 5.10, 5.15]. Values for each indicated time period 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}) ($\mu\text{Sv} \cdot \text{kBq}^{-1} \cdot \text{m}^{-2}$).

In a series of experimental whole body measurements and associated annual internal dose calculations it was found that long term doses to children caused by ingestion of food containing caesium radionuclides are usually lower by a factor of about 1.1 to 1.5 than those to adults and adolescents (see, for example, Refs [5.51, 5.52]).

The mean internal doses to residents of rural settlements strongly depend on soil properties. For assessment purposes, soils are classified into three

TABLE 5.6. DISTRIBUTION OF INDIVIDUAL THYROID DOSES FOR AGE GROUPS OF CHILDREN AND ADOLESCENTS FROM THE KIEV, ZHYTOMYR AND CHERNIGOV REGIONS OF UKRAINE, BASED ON IODINE-131 IN THYROID MEASUREMENTS [5.45]

Category and age group	Number of measurements	Per cent of children with thyroid dose (Gy) in interval				
		≤0.2	>0.2–1	>1–5	>5–10	>10
<i>Settlements not evacuated</i>						
Rural areas						
1–4 years	9 119	40	43	15	1.7	0.9
5–9 years	13 460	62	31	6.5	0.44	0.07
10–18 years	26 904	73	23	3.7	0.16	<0.01
Urban areas						
1–4 years	5 147	58	33	7.5	1.0	0.7
5–9 years	11 421	82	15	2.6	0.23	0.04
10–18 years	24 442	91	7.7	1.4	0.12	<0.01
<i>Evacuated settlements</i>						
1–4 years	1 475	30	45	22	2.7	1.0
5–9 years	2 432	55	36	8.4	0.6	0.08
10–18 years	4 732	73	23	3.6	0.13	0.02

TABLE 5.7. RECONSTRUCTION AND PROGNOSIS OF THE AVERAGE EFFECTIVE INTERNAL DOSE TO THE ADULT RURAL POPULATION IN THE INTERMEDIATE ($100 \text{ km} < \text{DISTANCE} < 1000 \text{ km}$) ZONE OF CHERNOBYL CONTAMINATION

Soil type		E/σ_{137} ($\mu\text{Sv} \cdot \text{kBq}^{-1} \cdot \text{m}^{-2}$ of ^{137}Cs) ^a				
		1986	1987-1995	1996-2005	2006-2056	1986-2056
Russian Federation [5.9]	Soddy podzolic sandy	90	60	12	16	180
	Black	10	5	1	1	17
Ukraine [5.10, 5.15]	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.

major soil types: (a) black or chernozem soil; (b) podzol soil (including both podzol sandy and podzol loam soils); and (c) peat bog or peat soil. Due to the environmental behaviour of ^{137}Cs , internal exposure exceeds external dose in areas with peaty soil. Contributions due to internal and external exposure are comparable in areas with light sandy soil, and the contribution of internal exposure to the total (external and internal) dose does not exceed 10% in areas with dominantly black soil. According to numerous studies, the contribution of ^{90}Sr to the internal dose regardless of natural conditions is usually less than 5%.

The parameters obtained from independent sets of Russian and Ukrainian data significantly differ for some soil types and time periods (see Table 5.7). Some of these discrepancies can be explained by the different meteorological conditions (mainly dry deposition in Ukraine and wet deposition in the Russian Federation) that occurred in different parts of the Chernobyl affected areas and by different food consumption habits.

Multiplication of the parameters presented in Table 5.7 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) but not from radioiodines. Dose estimates are given on the assumption that countermeasures against internal exposure were not applied. In broad terms, the most important factors controlling internal dose to the rural population are the dominant soil type and the amount of ^{137}Cs deposition.

In towns and cities, internal dose is partially determined by radioactive contamination of foodstuffs produced in surrounding districts.

However, importation of foodstuffs from non-contaminated areas has significantly reduced the intake of radionuclides, and internal doses received by urban populations are typically a factor of two to three less than in rural settlements with an equal level of radioactive contamination.

The deviation in dose to critical groups compared with settlement average values varies by a factor of about three for internal exposure. The group most subjected to internal exposure from ^{137}Cs is adults consuming both locally produced agricultural animal foods (e.g. milk, dairy products, etc.) and natural foods (e.g. mushrooms, lake fish, berries, etc.) in amounts exceeding average consumption rates.

At present, inhabitants of areas of low contamination (less than 0.04 MBq/m^2 of ^{137}Cs) are receiving up to 0.004 mSv/a from ingestion of local foods 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 an additional 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.

To avoid the 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 deposition and predominant soil type; such data are given in Tables 5.8 and 5.9. The ^{137}Cs soil deposition is subdivided into two ranges: $0.04\text{--}0.6 \text{ MBq/m}^2$ ($1\text{--}15 \text{ Ci/km}^2$) and above 0.6 MBq/m^2 (i.e. $0.6\text{--}4 \text{ MBq/m}^2$ ($15\text{--}100 \text{ Ci/km}^2$)) in 1986. The level 0.04 MBq/m^2 is considered as a conventional border between ‘non-contaminated’ and ‘contaminated’ areas. In areas contaminated with ^{137}Cs above

TABLE 5.8. PAST (1986–2000) AND FUTURE (2001–2056) MEAN CHERNOBYL RELATED EFFECTIVE INTERNAL DOSES (mSv) TO ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION ABOVE 0.04 MBq/m^2 (1 Ci/km^2) IN 1986 [5.53]

Population	Caesium-137 in soil (MBq/m^2)	Soil type/time period					
		Black		Podzol		Peat	
		1986–2000	2001–2056	1986–2000	2001–2056	1986–2000	2001–2056
Rural	0.04–0.6	1–10	0.1–1	3–30	0.5–7	8–100	2–30
	0.6–4	—	—	30–100	7–50	—	—
Urban	0.04–0.6	1–8	0.1–0.6	2–20	0.3–5	6–80	1–20

0.6 MBq/m², application of active countermeasures (i.e. agricultural restrictions, decontamination measures, recommendations to restrict consumption of locally gathered natural foods (forest mushrooms and berries, lake fish, etc.)) has been mandatory.

Dosimetric models predict that by 2001 the residents had already received at least 75% of their lifetime internal dose due to ¹³⁷Cs, ¹³⁴Cs, ⁹⁰Sr and ⁸⁹Sr (see Table 5.8). In the coming years (2001–2056) they will receive the remaining 25% (i.e. less than 1 mSv for black soil, up to 7 mSv for podzol soil and up to 30 mSv for peat soil). In the more contaminated podzol soil areas, an effective dose of up to 50 mSv can still be expected.

As can be seen from Table 5.9, the more elevated internal doses in some of the settlements are above the national action level of 1 mSv/a. For some population groups in contaminated areas, wild foods (forest mushrooms, game, forest berries, fish) can make an important contribution to dose [5.9, 5.15, 5.30]. Studies of ¹³⁷Cs intake of the rural population in the Bryansk region of the Russian Federation indicated that natural foods contributed about 20% of total uptake in 1987, but up to 80% in 1994–1999 [5.29]. The relative contribution of wild foods to internal dose has risen gradually because of the substantial reduction of radionuclide content in agricultural foods derived from vegetables and animals, combined with a much slower decrease in the contamination of wild foods. In the latter period, the highest contributions to ¹³⁷Cs intake (and, by inference, internal dose) came from forest mushrooms, followed by forest berries, game and lake fish.

Similar trends were found in residents of Kozhany (Bryansk region), located on the coast of a highly contaminated lake, where natural foods contributed an average of 50–80% of ¹³⁷Cs intake [5.30]. Men were more likely to eat natural foods

than women, and there was a positive correlation between consumption of mushrooms and fish that indicated a liking by many inhabitants for ‘gifts of nature’. The average annual internal dose due to ¹³⁷Cs was estimated to be 1.2 mSv for men and 0.7 mSv for women in 1996.

5.3.4.3. Long term doses from aquatic pathways

Human exposure via the aquatic pathway occurs as a result of consumption of drinking water, fish and agricultural products grown using irrigation water from contaminated water bodies. Use of water bodies as a source of drinking water for livestock and flooding of agricultural land can also lead to human exposure via terrestrial pathways.

In the middle and lower areas of the Dnieper River catchment, which were not significantly subjected to direct radionuclide contamination in 1986, a significant proportion (10–20%) of the Chernobyl related exposures was attributed to aquatic pathways [5.53]. Although these doses were, in fact, estimated to be very low, there was an inadequate appreciation by the local population of the risks of using water from contaminated aquatic systems. This created an (unexpected) stress in the population concerning the safety of the water supply system. In areas close to Chernobyl, radiation exposures via the aquatic pathway are much higher, but are again minor in comparison with terrestrial pathways.

Three pathways of exposure due to aquatic systems need to be considered [5.53]:

- (a) Consumption of drinking water from rivers, lakes, reservoirs and wells in the contaminated areas. The most significant exposures via consumption of drinking water resulted from the use of water from the Dnieper River basin, and, in particular, the reservoirs of the

TABLE 5.9. ANNUAL (2001) MEAN CHERNOBYL RELATED EFFECTIVE INTERNAL DOSES (mSv) TO ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION ABOVE 0.04 MBq/m² (1 Ci/km²) IN 1986 [5.53]

Population	Caesium-137 in soil (MBq/m ²)	Soil type		
		Black	Podzol	Peat
Rural	0.04–0.6	0.004–0.06	0.03–0.4	0.1–2
	0.6–4	—	0.4–2	—
Urban	0.04–0.6	0.003–0.04	0.02–0.2	0.1–1

Dnieper River system. 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, water from the Dnieper and Desna Rivers is used by about 750 000 people. The remaining part of the population use water mainly derived from groundwater sources.

- (b) Consumption of fish. The Dnieper River reservoirs are used intensively for commercial fishing. The annual catch is more than 25 000 t. There was no significant decrease in fishing in most of these reservoirs during the first decade after the accident. During the first two to three years, however, restrictions were placed on the consumption of fish from the Kiev reservoir. In some smaller lakes, both in the former USSR and in parts of western Europe, fishing was prohibited during the first months and even years after the accident.
- (c) Consumption of agricultural products grown on land irrigated with water from the Dnieper reservoirs. In the Dnieper River basin there is more than 1.8×10^6 ha of irrigated agricultural land. Almost 72% of this territory is irrigated with water from the Kakhovka reservoir in the Dnieper River–reservoir system. Accumulation of radionuclides in plants in irrigated fields can take place because of root uptake of the radionuclides introduced with irrigation water and due to direct incorporation of radionuclides through leaves following sprinkler irrigation. However, recent studies have shown that, in the case of irrigated land in southern Ukraine, irrigation water did not add significant amounts of radioactive material to crops in comparison with that which had been initially deposited in atmospheric fallout and subsequently taken up from the soil.

The contribution of aquatic pathways to the dietary intake of ^{137}Cs and ^{90}Sr is usually quite small, even in areas that were seriously affected by Chernobyl fallout. For the relatively large rural population that consumes fish from local rivers and lakes, however, exposures could be significant. In addition, collective doses to the large urban and rural populations using water from the Pripjat–Dnieper River–reservoir system were relatively high. Owing to the high fallout within the catchment of the Pripjat and Dnieper Rivers, this system has

been intensively monitored, and doses via aquatic pathways have been estimated [5.53].

Contaminated rivers could potentially have led to significant doses in the first months after the accident through consumption of drinking water, mainly through contamination with short lived radionuclides. The most significant individual dose was from ^{131}I and was estimated to be up to 0.5–1.0 mSv for the citizens of Kiev during the first few weeks after the Chernobyl accident [5.53].

After the end of the first month following the accident, the main contributors to doses via aquatic pathways became ^{137}Cs and ^{90}Sr . Estimated doses due to these radionuclides in the Dnieper River–reservoir system were made on the basis of monitoring data and predictions of flood frequencies. A worst case scenario of a series of high floods during the first decade after the accident (1986–1995) was assumed. Estimates were that individual doses via aquatic pathways would not have exceeded 1–5 $\mu\text{Sv/a}$. Thus long term doses via the drinking water pathway were small in comparison with doses (mainly from short lived radionuclides) in the early phase [5.53].

The contribution of different exposure pathways to dose is shown in Fig. 5.14 for the village of Svetilovichy in the Gomel region of Belarus. In this case, consumption of freshwater fish forms an important part of the diet, and hence doses via this pathway can be significant for some individuals.

5.4. TOTAL (EXTERNAL AND INTERNAL) EXPOSURE

The generalized data for both external and internal (not including dose to the thyroid)

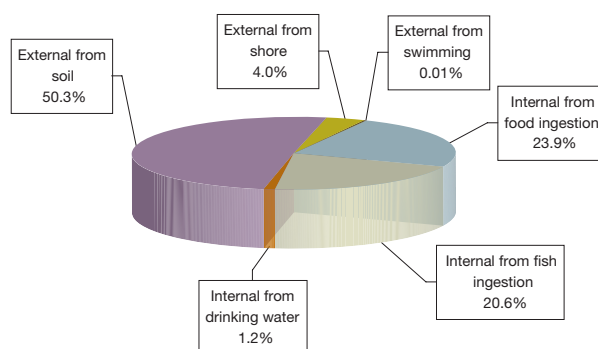


FIG. 5.14. Contributions of different pathways to the effective dose to the critical group of the population of Svetilovichy in the Gomel region of Belarus [5.53, 5.54].

exposures of the general public presented in Tables 5.4 and 5.9, respectively, have been summarized in Table 5.10 in order to estimate broadly the mean individual total (external and internal) effective doses accumulated by residents of radioactively contaminated areas during 1986–2000 and to forecast doses for 2001–2056. Table 5.11 gives estimates of the annual total dose in 2001. In both tables data are given for levels of ^{137}Cs soil deposition existing in 1986 in currently inhabited areas of Belarus, the Russian Federation and Ukraine, separately for rural and urban populations and for different soil types, with no account taken of current countermeasures. Both accumulated and current annual total doses are presented for adults, since, in the long term, children generally receive lower external and internal doses from ^{137}Cs environmental contamination (in contrast to thyroid internal doses from radioiodine intake), because of their occupancy (see Tables 5.3 and 5.5), food habits and metabolic features.

As can be seen from Table 5.10, both accumulated and predicted mean doses in

settlement residents vary over two orders of magnitude depending on the radioactive contamination of the area, soil type and settlement type. Thus in 1986–2000 the dose range was from 2 mSv in towns located in black soil areas, up to 300 mSv in villages located in areas with podzol sandy soil. According to the forecast, the doses expected in 2001–2056 are substantially lower than the doses already received (i.e. in the range of 1–100 mSv). In total, if countermeasures were not applied, the populations of some of the more contaminated villages in Belarus and the Russian Federation would receive lifetime effective doses of up to 400 mSv, not including dose to the thyroid. However, intensive application of countermeasures such as settlement decontamination and agricultural countermeasures has reduced dose levels by a factor of about two. For comparison, a worldwide average lifetime dose from natural background radiation is about 170 mSv, with a typical range of 70–700 mSv in various regions.

Based on local demographic data [5.51], ^{137}Cs soil deposition maps (see Section 3.1) and the

TABLE 5.10. PAST (1986–2000) AND FUTURE (2001–2056) MEAN CHERNOBYL RELATED TOTAL EFFECTIVE DOSES (mSv) TO ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION ABOVE 0.04 MBq/m² (1 Ci/km²) IN 1986 [5.53]

Population	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 5.11. ANNUAL (2001) MEAN CHERNOBYL RELATED TOTAL EFFECTIVE DOSES (mSv) TO ADULT RESIDENTS OF AREAS WITH CAESIUM-137 SOIL DEPOSITION ABOVE 0.04 MBq/m² (1 Ci/km²) IN 1986 [5.53]

Population	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

current level of countermeasure application (see Section 4), the vast majority of the five million people currently residing in the contaminated areas of Belarus, the Russian Federation and Ukraine (see Table 3.2) — that is, in the early 2000s — receive annual effective doses of less than 1 mSv (i.e. less than the national action levels in the three countries). For comparison, a worldwide average annual dose from natural background radiation is about 2.4 mSv, with a typical range of 1–10 mSv in various regions [5.1].

The number of residents of the contaminated areas in the three most affected countries that currently receive more than 1 mSv annually can be estimated to be about 100 000 persons. As the future reduction of both the external dose rate and radionuclide (mainly ¹³⁷Cs) activity concentrations in food will be rather slow (see Sections 5.2 and 3.3–3.5), the reduction of human exposure levels is expected to be slow (i.e. about 3–5%/a with currently applied countermeasures).

5.5. COLLECTIVE DOSES

5.5.1. Thyroid

A summary of the collective doses to the thyroid for the three most contaminated countries, based on the thyroid dose reconstruction techniques described in Section 5.3.4.1, is shown in Table 5.12. The total thyroid collective dose is 1.6×10^6 man Gy, with nearly half received by the group of persons exposed in Ukraine. The present estimate of the collective thyroid dose does not differ from that made in Ref. [5.1].

5.5.2. Total (external and internal) dose from terrestrial pathways

Estimates of collective dose accumulated in 1986–2005 via the terrestrial pathways of external irradiation and ingestion of contaminated foods are given in Table 5.13 for the three most affected countries. The total collective dose was estimated to be 43 000 man Sv in 1986–1995, including 24 000 man Sv from external exposure and 19 000 man Sv from internal exposure, according to UNSCEAR [5.1], annex J, table 34. According to the models of exposure dynamics presented above [5.7], the estimated collective effective external doses in 1986–2005 are about a factor of 1.2 higher, and collective effective internal doses are higher by a factor of 1.1–1.5 (depending on soil properties and applied countermeasures), than those obtained in 1986–1995. In total, the collective dose increased by 9000 man Sv, or by 21%, during the second decade, compared with the first decade, after the accident,

TABLE 5.12. COLLECTIVE THYROID DOSES IN THE THREE COUNTRIES MOST CONTAMINATED BY THE CHERNOBYL ACCIDENT [5.1]

	Collective thyroid dose (10 ³ man Gy)
Russian Federation	300
Belarus	550
Ukraine	740
Total	1600

TABLE 5.13. ESTIMATED COLLECTIVE EFFECTIVE DOSES IN 1986–2005 TO THE POPULATIONS OF THE CONTAMINATED AREAS OF BELARUS, THE RUSSIAN FEDERATION AND UKRAINE (CAESIUM-137 SOIL DEPOSITION IN 1986 MORE THAN 37 kBq/m²)^a

	Population (millions of people)	Collective dose (10 ³ man Sv)		
		External	Internal	Total
Belarus	1.9	11.9	6.8	18.7
Russian Federation	2.0	10.5	6.0	16.5
Ukraine	1.3	7.6	9.2	16.8
Total	5.2	30	22	52

^a Excluding thyroid dose. (Modified from Ref. [5.1], annex J, table 34, using dosimetric models presented in this report.)

and reached 52 000 man Sv. This is in good agreement with the predictions made by UNSCEAR in 1988 [5.2].

The recent estimate of collective dose based on both human and environmental measurements implicitly accounts for substantial, but not specified, amounts of collective dose saved by the institution of countermeasures that included evacuation, relocation, prohibition on the use of foodstuffs and longer term remediation of contaminated areas.

5.5.3. Internal dose from aquatic pathways

The most important aquatic system (the Dnieper River basin) occupies a large area with a population of about 32 million people who use the water for drinking, fishing and irrigation. Estimates have been 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) [5.55, 5.56]. A long term hydrological scenario has been analysed using a computer model [5.57]. 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 [5.58]. The results of the calculations are given in Table 5.14.

Dose estimates for the Dnieper River system show that if there had been no action to reduce radionuclide fluxes to the river, the collective dose commitment for the population of Ukraine (mainly due to radiocaesium and radiostrontium) could have reached 3000 man Sv. Protective measures (see Section 4) carried out during 1992–1993 on the left bank floodplain of the Pripjat River decreased exposure by approximately 700 man Sv. Other protective measures on the right bank in the CEZ (during 1999–2001) will further reduce collective doses by 200–300 man Sv [5.59].

5.6. CONCLUSIONS AND RECOMMENDATIONS

5.6.1. Conclusions

- (a) The collective effective dose (not including dose to the thyroid) received by about five million residents living in the areas of Belarus, the Russian Federation and Ukraine contaminated by the Chernobyl accident (^{137}Cs deposition on soil of $>37 \text{ kBq/m}^2$) was approximately 40 000 man Sv during the period 1986–1995. The groups of exposed

TABLE 5.14. COLLECTIVE DOSE COMMITMENT (CDC_{70}) DUE TO STRONTIUM-90 AND CAESIUM-137 FLOWING FROM THE PRIPYAT RIVER TO THE DNEPER RIVER AND DOWNSTREAM [5.56, 5.58]

Region	Population (millions of people)	Strontium-90 CDC_{70} (man-Sv)	Caesium-137 CDC_{70} (man-Sv)	Ratio $^{90}\text{Sr} \text{ CDC}_{70} / ^{137}\text{Cs} \text{ CDC}_{70}$
Chernigov	1.4	4	2	2
Kiev	4.5	290	190	1.5
Cherkassy	1.5	115	50	2.3
Kirovograd	1.2	140	40	3.5
Poltava	1.7	130	60	2.2
Dnepropetrovsk	3.8	610	75	8
Zaporozhe	2	320	35	9
Nikolaev	1.3	150	20	8
Kharkov	3.2	60	4	15
Lugansk	2.9	15	1	15
Donetsk	5.3	330	20	17
Kherson	1.2	100	20	5
Crimea	2.5	175	5	35
Total	32.5	2500	500	5

persons within each country received an approximately equal collective dose. The additional amount of collective effective dose projected to be received between 1996 and 2006 is about 9000 man Sv.

- (b) The collective dose to the thyroid was nearly 2×10^6 man Gy, with nearly half received by persons exposed in Ukraine.
- (c) The main pathways leading to human exposure were external exposure from radionuclides deposited on the ground and the ingestion of contaminated terrestrial food products. Inhalation and ingestion of drinking water, fish and products contaminated with irrigation water were generally minor pathways.
- (d) The range in thyroid dose in different settlements and in all age–gender groups is large, between less than 0.1 Gy and more than 10 Gy. In some groups, and especially in younger children, doses were high enough to cause both short term functional thyroid changes and thyroid cancer effects in some individuals.
- (e) The internal thyroid dose from the intake of ^{131}I was mainly due to the consumption of fresh cow's milk and, to a lesser extent, of green vegetables; children, on average, received a dose that was much higher than that received by adults, because of their small thyroid masses and consumption rates of fresh cow's milk that were similar to those of adults.
- (f) For populations permanently residing in contaminated areas and exposed predominantly via ingestion, the contribution of short lived radioiodines (i.e. ^{132}I , ^{133}I and ^{135}I) to thyroid dose was minor (i.e. about 1% of the ^{131}I thyroid dose), since short lived radioiodines decayed during transport of the radioiodines along the food chains. The highest relative contribution (20–50%) to the thyroid dose to the public from short lived radionuclides was received by the residents of Pripyat through inhalation; these residents were evacuated before they could consume contaminated food.
- (g) Both measurement and modelling data show that the urban population was exposed to a lower external dose by a factor of 1.5–2 compared with 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. Also, as the urban population depends less on local agricultural products and wild foods than the rural population, both effective and thyroid internal doses caused predominantly by ingestion were lower by a factor of two to three in the urban than in the rural population.

- (h) The initial high rates of exposure declined rapidly due to the decay of short lived radionuclides and to the movement of radio-caesium into the soil profile. The latter caused a decrease in the rate of external dose due to increased shielding. In addition, as caesium moves into the soil column it binds to soil particles, which reduces the availability of caesium to plants and thus to the human food chain.
- (i) The great majority of dose from the accident has already been accumulated.
- (j) Persons who received effective doses (not including dose to the thyroid) higher than the average by a factor of two to three were those who lived in rural areas in single storey homes and who ate large amounts of wild foods such as game meats, mushrooms and berries.
- (k) The long term internal doses to residents of rural settlements strongly depend on soil properties. Contributions due to internal and external exposure are comparable in areas with light sandy soil, and the contribution of internal exposure to the total (external and internal) dose does not exceed 10% in areas with predominantly black soil. The contribution of ^{90}Sr to the internal dose, regardless of natural conditions, is usually less than 5%.
- (l) The long term internal doses to children caused by ingestion of food containing caesium radionuclides are usually lower by a factor of about 1.1–1.5 than those in adults and adolescents.
- (m) Both accumulated and predicted mean doses in settlement residents vary in the range of two orders of magnitude, depending on the radioactive contamination of the area, predominant soil type and settlement type. In the period 1986–2000 the accumulated dose ranged from 2 mSv in towns located in black soil areas up to 300 mSv in villages located in areas with podzol sandy soil. The doses expected in the period 2001–2056 are substantially lower than the doses already received (i.e. in the range of 1–100 mSv).

- (n) If countermeasures had not been applied, the populations of some of the more contaminated villages could have received lifetime (70 years) effective doses of up to 400 mSv. Intensive application of countermeasures such as settlement decontamination and agricultural countermeasures has substantially reduced the doses. For comparison, a worldwide average lifetime dose from natural background radiation is about 170 mSv, with a typical range of 70–700 mSv in various regions of the world.
- (o) The vast majority of the approximately five million people residing in the contaminated areas of Belarus, the Russian Federation and Ukraine currently receive annual effective doses of less than 1 mSv (equal to the national action levels in the three countries). For comparison, a worldwide average annual dose from natural background radiation is about 2.4 mSv, with a typical range of 1–10 mSv in various regions of the world.
- (p) The number of residents of the contaminated areas in the three most affected countries that currently receive more than 1 mSv annually can be estimated to be about 100 000 persons. As the future reduction of both the external dose rate and the radionuclide (mainly ^{137}Cs) activity concentrations in food is predicted to be rather slow, the reduction in the human exposure levels is also expected to be slow (i.e. about 3–5%/a with current countermeasures).
- (q) Based upon available information, it does not appear that the doses associated with hot particles were significant.
- (r) The assessment of the Chernobyl Forum agrees with that of UNSCEAR [5.1] in terms of the dose received by the populations of the three most affected countries: Belarus, the Russian Federation and Ukraine.
- (b) Sentinel or marker individuals in more highly contaminated areas not scheduled for further remediation might be identified for continued periodic whole body counting and monitoring of external dose. The goal would be to follow the expected continued decrease in external and internal dose and to determine whether such decreases are due to radioactive decay alone or to further ecological elimination.

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5.6.2. Recommendations

- (a) Large scale monitoring of foodstuffs, whole body counting of individuals and provision of thermoluminescent dosimeters to members of the general public are no longer necessary. The critical groups in areas of high contamination and/or high transfer of radiocaesium to foods are known. Representative members of these critical groups should be monitored with dosimeters for external dose and with whole body counting for internal dose.

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6. RADIATION INDUCED EFFECTS ON PLANTS AND ANIMALS

6.1. PRIOR KNOWLEDGE OF RADIATION EFFECTS ON BIOTA

The effects of radiation on plants and animals have long been of interest to scientists; in fact, much of the information on the effects on humans has evolved from studies on plants and animals. Additional research followed the development of nuclear energy and concerns about the possible impacts of increased, but authorized, discharges of waste radionuclides into the terrestrial and aquatic environments. The magnitude of these authorized releases has always been controlled on the basis of the limitation of human exposure, but it has been recognized that animals and plants have also been exposed — frequently to a higher degree than humans. By the mid-1970s, sufficient information had been accrued on the effects of ionizing radiation on plants and animals that several authoritative reviews had been compiled to summarize the findings [6.1–6.4].

Some broad generalizations about the effects of radiation exposure can be gleaned from the research that has been conducted over the past 100 years. Foremost are the relatively large differences in doses required to cause lethality among various taxonomic groups (Fig. 6.1). Considerable variation in response occurs within a taxon due to enhanced radiosensitivity of some individuals or life stages. Wide ranges in doses are also observed within a group or taxon when progressing from minor to severe effects.

Figure 6.2 summarizes information on the doses required to be delivered over a short time period to produce damage of different degrees in various plant communities, soil invertebrates and rodents. Within the plant kingdom, trees are generally more sensitive than shrubs, which in turn are more sensitive than herbaceous species. Primitive forms such as lichens, mosses and liverworts are more resistant than vascular plants. Radiation resistant plants frequently have molecular and cellular characteristics that enhance their ability to tolerate radiation stress, and differences in plant community response can be explained, in part, by the early work of Sparrow [6.8]. He showed that characteristics such as large

chromosomes, normal (rather than diffuse) centromeres, small chromosome number, uninucleated cells, diploid or haploid cells, sexual reproduction, long intermitotic time and slow rates of meiosis are associated with high radiosensitivity in plants, but that sensitivity can be modified in time due to seasonal processes (e.g. dormancy or the onset of growth in spring; Table 6.1).

Scientific reviews (e.g. Ref. [6.3]) have indicated that mammals are the most sensitive organisms and that reproduction is a more sensitive endpoint than mortality. For acute exposures of

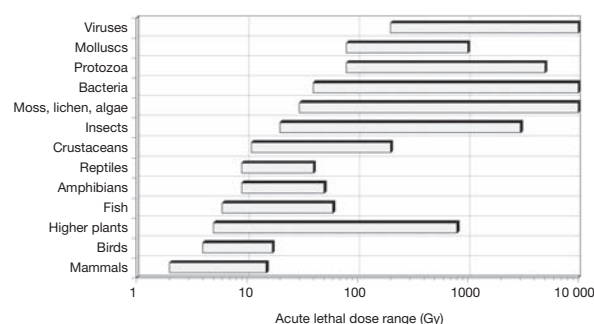


FIG. 6.1. Acute dose ranges that result in 100% mortality in various taxonomic groups. Humans are among the most sensitive mammals, and therefore among the most sensitive organisms [6.5].

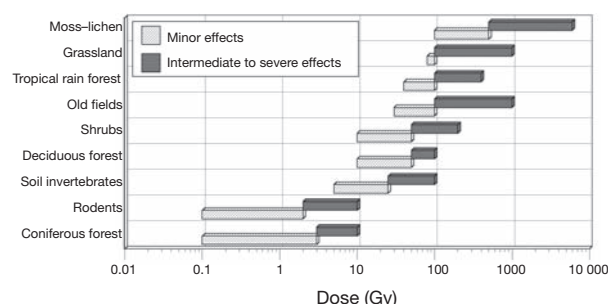


FIG. 6.2. Range of short term radiation doses (delivered over 5–60 d) that produced effects in various plant communities, rodents and soil invertebrates. Minor effects include chromosomal damage, changes in productivity, reproduction and physiology. Intermediate effects include changes in species composition and diversity through selective mortality. Severe effects (massive mortality) begin at the upper range of intermediate effects [6.6, 6.7].

mammals, mortality generally occurs at doses above 3 Gy, while reproduction is affected at doses below 0.3 Gy. Chronic exposures alter the responses, with mortality occurring at greater than 0.1 Gy/d and reproduction effected at less than 0.01 Gy/d. Among aquatic organisms, fish are the most sensitive, with gametogenesis and embryo development being the more sensitive stages. Effects on animal populations can be reduced by their mobility (in terms of moving from areas of high exposure to areas of low exposure). Comparatively stationary soil invertebrates do not have such abilities and can receive substantial doses relative to the rest of the animal kingdom, particularly because soil is a sink for most radioactive contamination.

The response of a plant or animal to radiation depends on the dose received as well as its radiosensitivity. The former is largely determined by its habitat preference in relation to the evolving distribution of radioactive contaminants as a function of time, as well as the organism's propensity to accumulate radionuclides in its organs and tissues. Owing to their particular use of the habitat, plants and animals within a contaminated area may receive radiation doses that can be substantially higher than those of humans occupying the same area (e.g. humans gain some shielding from housing and may obtain food and water from less contaminated sources [6.3]).

Although all exposures to ionizing radiation have the potential to damage biological tissue, protraction of a given total absorbed dose in time

can, depending on the dose rate, result in a reduction in response due to the intervention of cellular and tissue repair processes. This has led to the conventional, but somewhat artificial, distinction between so called acute and chronic radiation exposure regimes. In general, an acute radiation exposure is one that usually occurs at a high dose rate and in a short period of time relative to that within which obvious effects occur. Chronic exposures are taken to be continuous in time, often over a significant portion of an organism's lifespan, or throughout some particular life stage (e.g. embryonic development) and usually at a sufficiently low dose rate that the cumulative dose does not produce acute effects.

The earlier reviews noted above were consistent in concluding that it is unlikely that there will be any significant detrimental effects:

- (a) To terrestrial and aquatic plant populations, and aquatic animal populations at chronic dose rates of less than 10 mGy/d; or
- (b) To terrestrial animal populations at dose rates of less than 1 mGy/d.

It should be emphasized, however, that these dose rates were not intended for use as limits in any system to provide for the protection of the environment; they were simply the dose rates below which the available evidence, admittedly limited in the range of organisms and biological responses investigated, indicated little likelihood of any

TABLE 6.1. PRINCIPAL NUCLEAR CHARACTERISTICS AND FACTORS INFLUENCING THE SENSITIVITY OF PLANTS TO RADIATION [6.5, 6.8]

Factors increasing sensitivity	Factors decreasing sensitivity
Large nucleus (high DNA content)	Small nucleus (low DNA content)
Much heterochromatin	Little heterochromatin
Large chromosomes	Small chromosomes
Acrocentric chromosomes	Metacentric chromosomes
Normal centromere	Polycentric or diffuse centromere
Uninucleate cells	Multinucleate cells
Low chromosome number	High chromosome number
Diploid or haploid nuclei	High polyploid
Sexual reproduction	Asexual reproduction
Long intermitotic time	Short intermitotic time
Long dormant period	Short or no dormant period
Slow meiosis	Fast meiosis

significant response. The above dose rates are with reference to population level effects, not to impacts on individual organisms.

More recent reviews of the effects of radiation exposure on individual organisms carried out in the framework of two EC projects, FASSET (Framework for the Assessment of Environmental Impact) and EPIC (Environmental Protection from Ionising Contaminants in the Arctic), have produced broadly consistent conclusions [6.9–6.11]. Although minor effects may be seen at lower dose rates in sensitive cell systems or individuals of sensitive species (e.g. haematological cell counts in mammals, immune response in fish, growth in pines and chromosome aberrations in many organisms), the threshold dose rate for significant effects in most studies is about 0.1 mGy/h (2.4 mGy/d). Detrimental responses then increase progressively with increasing dose rate and usually become clear at greater than 1 mGy/h (24 mGy/d) given over a large fraction of the lifespan. The significance of the minor morbidity and cytogenetic effects on the individual, or on populations more generally, seen at dose rates of less than 2.4 mGy/d has yet to be determined [6.11].

The recently compiled EPIC database covers a very wide range of radiation dose rates (from below 10^{-5} Gy/d up to more than 1 Gy/d) to wild flora and fauna observed in northern parts of the Russian Federation and in the Chernobyl contaminated areas [6.10]. The general conclusion from the EPIC database is that the threshold for deterministic radiation effects in wildlife lies somewhere in the range of 0.5–1 mGy/d for chronic low linear energy transfer radiation.

These broad conclusions concerning the impact of radiation on plants and animals provide an appropriate context within which to consider the available information on the effects that have been observed from the increased radiation exposures following the accident at Chernobyl.

6.2. TEMPORAL DYNAMICS OF RADIATION EXPOSURE FOLLOWING THE CHERNOBYL ACCIDENT

It is critical to frame any discussion of Chernobyl environmental effects within the specific time period of interest. Effects observed now, nearly 20 years after the accident, are drastically different from those that occurred during the first 20 days. Three distinct phases of radiation exposure have

been identified in the area local to the accident [6.4]. In the first 20 days, radiation exposures were essentially acute because of the large quantities of short lived radionuclides present in the passing cloud of contamination (^{99}Mo , $^{132}\text{Te}/^{132}\text{I}$, ^{133}Xe , ^{131}I and $^{140}\text{Ba}/^{140}\text{La}$). Most of these short lived, highly radioactive nuclides were deposited on to plant and ground surfaces, resulting in the accumulation of large doses that measurably affected biota. High exposures of the thyroids of vertebrate animals also occurred during the first days and weeks following the accident from the inhalation and ingestion of radioactive iodine isotopes or their radioactive precursors.

The measured exposure rates on the day of the accident in the immediate vicinity of the damaged reactor are shown in Fig. 6.3. These exposure rates were mainly due to gamma radiation from deposited radionuclides and range up to about 20 Gy/d. However, for surface tissues and small biological targets (e.g. mature needles and growing buds of pine trees), there was a considerable additional dose rate from the beta radiation of the deposited radionuclides. Taking into account the high dose rates during the relatively short exposure period from the short lived radioisotopes, this first phase of 20–30 days can be generally characterized as an acute exposure regime that had pronounced effects on biota.

The second phase of radiation exposure extended through the summer and autumn of 1986, during which time the short lived radionuclides decayed and longer lived radionuclides were transported to different components of the environment by physical, chemical and biological

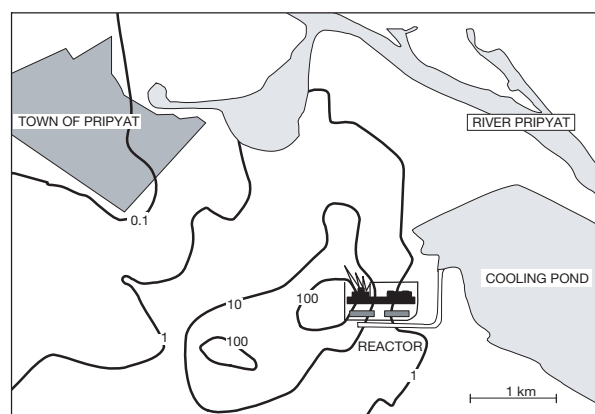


FIG. 6.3. Measured exposure rates in air on 26 April 1986 in the local area of the Chernobyl reactor. Units of isolines are R/h (1 R/h is approximately 0.2 Gy/d) [6.12].

processes. Dominant transport processes included rain induced transfer of radionuclides from plant surfaces on to soil, and bioaccumulation through plant tissues. Although the dose rates at the soil surface declined to much less than 10% of the initial values, due to radioactive decay of the short lived isotopes (see Fig. 5.3), damaging total doses were still accumulated. The modifying effect of radionuclide wash-off by rain on radiation damage of conifers is shown in Fig. 6.4.

In general, approximately 80% of the total radiation dose accumulated by plants and animals was received within three months of the accident, and over 95% of this was due to beta radiation [6.4]. This finding agrees with earlier studies on the importance of beta radiation, relative to the gamma component, to the total dose from radioactive



FIG. 6.4. A small conifer, the upper portion damaged by the initial deposition of radiation on to the crown of the plant, and the lower part of the plant damaged by the irradiation of surface deposited material subsequently washed from the plant's crown, leaving the middle section of the plant unaffected (photograph courtesy of T. Hinton, 1991).

fallout; for example, when a 10 h old mixture of fresh fission products was experimentally deposited on cereal plants at differing stages of growth, at a density of 7 GBq/m², the ratio of resulting beta and gamma dose rates, measured with thermoluminescent dosimeters, varied from 1 to 130 [6.13].

Measurements made with thermoluminescent dosimeters on the soil surface at sites within the CEZ indicated that the ratio of beta dose to gamma dose was about 26:1 (i.e. 96% of the total dose was from beta radiation). For a gamma dose rate of 0.01 mGy/h at the soil surface, 15 days after the accident, the total cumulative dose in the first month from beta and gamma radiation was estimated to be 0.5 ± 0.2 Gy, and 0.6 and 0.7 Gy at the end of the second and third months, respectively [6.14].

In the third (and continuing) phase of radiation exposure, dose rates have been chronic, less than 1% of the initial values, and derived mainly from ¹³⁷Cs contamination. With time, the decay of the short lived radionuclides and the migration of much of the remaining ¹³⁷Cs into the soil have meant that the contributions to the total radiation exposure from beta and gamma radiations have tended to become more comparable. The balance does depend, however, on the degree of bioaccumulation of ¹³⁷Cs in organisms and the behaviour of the organism in relation to the main source of external exposure (i.e. the soil). Aside from the spatial heterogeneity in the dose rate arising from the initial deposition, large variations in the radiation exposure of different organisms occurred at different times due to their habitat niche (e.g. birds in the canopy versus rodents on the ground). Immigration of animals into the CEZ and reproduction of those plants and animals that are present means that new animals and plants are constantly being introduced into the radioactively contaminated conditions that exist around Chernobyl today. The current conditions are presented in Section 6.8.

6.3. RADIATION EFFECTS ON PLANTS

Doses received by plants from the Chernobyl fallout were influenced by the physical properties of the various radionuclides (i.e. their half-lives, radiation emissions, etc.), the physiological stage of the plant species at the time of the accident and the different species dependent propensities to take up radionuclides into critical plant tissues. The

occurrence of the accident in late April heightened the damaging effects of the fallout because it coincided with the period of accelerated growth and reproduction in plants. The deposition of beta emitting contamination on critical plant tissues resulted in their receiving a significantly larger dose than animals living in the same environment [6.13, 6.15]. Large apparent inconsistencies in dose-response observations occurred when the beta radiation component was not appropriately accounted for [6.16].

Within the CEZ, deposition of total beta activity and associated doses to plants were sufficient (0.7–3.9 GBq/m²) to cause short term sterility and reduction in the productivity of some species [6.15]. By August 1986, crops that had been sown prior to the accident began to emerge. Growth and development problems were observed in plants growing in fields with contamination densities of 0.1–2.6 GBq/m² and with estimated dose rates initially received by plants reaching 300 mGy/d. Spot necroses on leaves, withered tips of leaves and inhibition of photosynthesis, transpiration and metabolite synthesis were detected, as well as an increased incidence of chromosome aberrations in meristem cells [6.17]. The frequency of various anomalies in winter wheat exceeded 40% in 1986–1987, with some abnormalities apparent for several years afterwards [6.18].

Coniferous trees were already known to be among the more radiosensitive plants, and pine forests 1.5–2 km west of the Chernobyl nuclear power plant received a sufficient dose (>80 Gy) to cause mortality [6.19] at dose rates that exceeded 20 Gy/d [6.12]. The first signs of radiation injury in pine trees in close proximity to the reactor were

yellowing and needle death, which appeared within two to three weeks. During the summer of 1986 the area of radiation damage expanded in the north-west direction up to 5 km; serious damage was observed at a distance of 7 km. The colour of the dead pine stands resulted in the forest being referred to as the Red Forest.

Tikhomirov and Shcheglov [6.19] and Arkhipov et al. [6.20] found that mortality rate, reproduction anomalies, stand viability and re-establishment of pine tree canopies were dependent on absorbed dose. Acute irradiation of *Pinus silvestris* at doses of 0.5 Gy caused detectable cytogenetic damage; at more than 1 Gy, growth rates were reduced and morphological damage occurred; and at more than 2 Gy, the reproductive abilities of trees were altered. Doses of less than 0.1 Gy did not cause any visible damage to the trees. Table 6.2 shows the variation in activity concentration and dose among pine trees within the CEZ. The radiosensitivity of spruce trees was observed to be greater than that of pines. At absorbed doses as low as 0.7–1 Gy, spruce trees had malformed needles, buds and shoot growth [6.22].

Of the absorbed dose to critical parts of trees, 90% was due to beta radiation from the deposited radionuclides and 10% to gamma radiation. As early as 1987, recovery processes were evident in the surviving tree canopies and young forests were re-established in the same place as the perished trees by replanting in reclamation efforts [6.20]. In the decimated pine stands, a sudden invasion of pests occurred that later spread to adjoining areas. The deceased pine stands have now been replaced by grassland, with a slow invasion of self-seeding deciduous trees. Four distinct zones of radiation

TABLE 6.2. RADIOACTIVE CONTAMINATION (kBq/kg) OF CONIFEROUS TREES AS A FUNCTION OF DISTANCE FROM THE CHERNOBYL REACTOR (AZIMUTH 205–260°), WITH CORRESPONDING ESTIMATES OF THE AIR DOSE RATE (mGy/h) IN OCTOBER 1987 AND THE ACCUMULATED EXTERNAL DOSE (Gy) [6.21]

Distance from the Chernobyl nuclear power plant (km)	Air dose rate (mGy/h) ^a	External dose (Gy) ^a	Activity concentration in needles (kBq/kg)					
			Cerium-144	Ruthenium-106	Zirconium-95	Niobium-95	Caesium-134	Caesium-137
2.0	2.2	126	13 400	4100	800	1500	1500	4100
4.0	0.10	5	150	60	8	15	17	72
16.0	3.5×10^{-4}	0.014	1.5	0.6	0.1	0.17	0.18	0.55

^a Dose rate and dose of gamma radiation at 1 m height from the soil surface.

induced damage to conifers were discernable (Table 6.3).

6.4. RADIATION EFFECTS ON SOIL INVERTEBRATES

Although between 60% and 90% of the initial fallout was captured by the forest canopy and other plants [6.19], within weeks to a few months the processes of wash-off by rain and leaf fall moved the majority of the contamination to the litter and soil layers (see Section 3.4 for more details), where soil and litter invertebrates were exposed to high radiation levels for protracted time periods. The potential for impact on soil invertebrates was particularly large, since the timing of the accident coincided with their most radiosensitive life stages: reproduction and moulting following their winter dormancy.

Within two months of the accident, the number of invertebrates in the litter layer of forests 3–7 km from the nuclear reactor was reduced by a factor of 30 [6.14], and reproduction was strongly affected (larvae and nymphs were absent). Doses of approximately 30 Gy (estimated from thermoluminescent dosimeters placed in the soil) had catastrophic effects on the invertebrate community, causing mortality of eggs and early life stages, as well as reproductive failure in adults. Within a year, reproduction of invertebrates in the forest litter resumed, due, in part, to the migration of invertebrates from less contaminated sites. After 2.5 years, the ratio of young to adult invertebrates in the litter layer, as well as the total mass of invertebrates per unit area, was no different from control sites;

however, species diversity remained markedly lower [6.14].

The diversity of invertebrate species within the soil facilitates an analysis of community level effects (i.e. changes in species composition and abundance); for example, only five species of invertebrates were found in ten soil cores taken from pine stands in July 1986 at a distance of 3 km from the Chernobyl nuclear power plant, compared with 23 species at a control site 70 km away. The mean density of litter fauna was reduced from 104 individuals per 225 cm² core at the control location to 2.2 at the 3 km site. Six species were found in all ten cores taken from the control site, whereas no species was found in all ten cores from the 3 km location [6.23]. The number of invertebrate species found at the heavily contaminated sites was only half that of controls in 1993, and complete species diversity did not recover until 1995, almost ten years after the accident [6.14].

Compared with invertebrates within the forest litter layer, those residing in arable soil were not affected so much. A fourfold reduction in earthworm numbers was found in arable soils, but no catastrophic mortality of any group of soil invertebrates was observed. There was no reduction in soil invertebrates below a 5 cm depth in the soil. Radionuclides had not yet migrated into deeper soil layers, and the overlying soil shielded the invertebrates from beta radiation, the main contributor (94%) to the total dose. The dose to invertebrates in forest litter was threefold to tenfold higher than that to those residing in surface soil [6.14].

Although researchers are unclear if sterility of invertebrates occurred in the heavily contaminated

TABLE 6.3. ZONES AND CORRESPONDING DAMAGE TO CONIFEROUS FORESTS IN THE AREA AROUND THE CHERNOBYL NUCLEAR POWER PLANT [6.22]

Zone and classification	External gamma dose ^a (Gy)	Air dose rate ^a (mGy/h)	Internal dose to needles (Gy)
Conifer death (4 km ²): complete death of pines, partial damage to deciduous trees	>80–100	>4	>100
Sublethal (38 km ²): death of most growth points, death of some coniferous trees, morphological changes to deciduous trees	10–20	2–4	50–100
Medium damage (120 km ²): suppressed reproductive ability, dried needles, morphological changes	4–5	0.4–2	20–50
Minor damage: disturbances in growth, reproduction and morphology of coniferous trees	0.5–1.2	<0.2	<10

^a Dose rate and dose of gamma radiation at 1 m height from the soil surface.

sites at Chernobyl [6.14], the 30 Gy cumulative dose reported for Chernobyl field studies is within the range of experimental doses used to control pest insects by external irradiation. A recent review indicated that most insect, mite and tick families require a sterilization dose of less than 200 Gy [6.24], although the sterilization dose for some insects and related arthropods is much lower and ranges widely among and within orders. As was found for plants [6.8], radiosensitivity of insects is related to the average interphase nuclear volume [6.24].

6.5. RADIATION EFFECTS ON FARM ANIMALS

Ruminants, both domesticated (cattle, goats, sheep) and wild (elk, deer), generally receive high doses in radioactively contaminated environments because they consume large amounts of vegetation, and many radionuclides accumulate in their bodies; for example, each day a single cow consumes about 30% of the grass from an area of 150 m². Ingestion of radionuclides leads to exposure of the gut, the thyroid and other body organs. Injuries to cattle are a major fallout consequence for rural populations, because of livestock loss but also because of the associated social and psychological implications [6.25, 6.26].

In the period shortly after the accident, domestic livestock within the CEZ were exposed to high levels of radioactive iodine (¹³¹I and ¹³³I, with half-lives of 8 d and 21 h, respectively); this resulted in significant internal and external doses from beta and gamma radiation (Table 6.4). A thyroid dose of 76 Gy from the two isotopes of iodine is sufficient to cause serious damage to the gland [6.27]. The soils of Ukraine and Belarus are naturally low in stable

iodine, cobalt and manganese. In conditions of endemic deficiency of stable iodine, the transfer of radioactive iodine from blood to the thyroid gland may be two to three times higher than normal [6.15]. These conditions accentuated the consequences of the accident.

Depressed thyroid function in cattle was related to the dose received (69% reduction in function with a thyroid dose of 50 Gy, and 82% reduction in animals that received a dose of 280 Gy). The concentration of thyroid hormones in the blood of animals was lower than the physiological norm during the whole lactation period. Radiation damage to the thyroid gland was confirmed by histological studies (i.e. hyperplasia of connective tissue and sometimes adipose tissue, vascular hyperaemia and necrosis of epithelium). Animals with practically no thyroid tissue were observed in Ukraine. Disruptions of the hormonal status in calves born to cows with irradiated thyroid glands were especially pronounced [6.28]. Similar effects were observed in cattle evacuated from the Belarusian portion of the CEZ [6.26].

Although most livestock were evacuated from the area after the accident, several hundred cattle were maintained in the more contaminated areas for a two to four month period. By the autumn of 1986, some of these animals had died; others showed impaired immune responses, lowered body temperatures and cardiovascular disorders. Hypothyroidism lasted until 1989, and may have been responsible for reproductive failures in animals that had received a thyroid dose of more than 180 Gy [6.26]. The offspring of highly exposed cows had reduced weight, reduced daily weight gains and signs of dwarfism. Reproduction returned to normal in the spring of 1989. Haematological parameters were normal for animals kept in areas with ¹³⁷Cs contamination of 0.2–1.4 MBq/m² (5–40 Ci/km²) [6.28].

TABLE 6.4. DOSES TO CATTLE THAT STAYED IN THE 30 km ZONE OF CHERNOBYL FROM 26 APRIL TO 3 MAY 1986 [6.21]

Distance from the Chernobyl nuclear power plant (km)	Surface activity (10 ⁸ Bq/m ²)	Absorbed dose (Gy)		
		Thyroid	Gastrointestinal tract	Whole body internal
3	8.4	300	2.5	1.4
10	6.1	230	1.8	1.0
14	3.5	260	1.0	0.6
12	2.4	180	0.7	0.4
35	1.2	90	0.4	0.2

Chronic radiation damage was observed in over 2000 sheep and 300 horses (3–8 years old) removed from the highly contaminated Khoyniki area of Belarus 1.5 years after the accident [6.26]. Doses were not estimated. In sheep, a depression of general condition, emaciation, heavy breathing, decrease of temperature and other abnormalities were found. Leukopaenia, erythroaenia, thrombocytopaenia and eosinophilia, increase in blood sugar concentrations 1.5–2 times higher than normal, and a significant decrease of thyroid hormone concentrations compared with normal levels were observed. The offspring weight and fleece clip yield of irradiated sheep were half as much as, or less than, those of healthy individuals. In horses, the damage resulted in depression of general condition, oedema, leukopaenia, thrombocytopaenia, eosinophilia and myelocytosis. Seventy per cent of the animals had thyroid hormone concentrations in blood serum that were lower than the detection levels of the assay methods [6.26].

Numerous news reports of radiation induced teratogenesis (birth defects) in cattle and pigs occurred in regions where total doses did not exceed 0.05 Gy/a. Scientific evidence indicates that increased birth defects are not distinguishable from background frequencies at such low doses [6.25]. Additionally, data for 1989 show that livestock birth defects in the contaminated area of the Zhytomyr region were no higher than in the uncontaminated areas of the same region. Photographs of a six footed calf were widely disseminated and the abnormality was attributed to the accident. The calf, however, was born in June 1986, and thus the process of differentiation and organ formation within the womb finished prior to the accident; this much publicized observation of teratogenesis was therefore caused by factors other than radiation from the Chernobyl accident.

6.6. RADIATION EFFECTS ON OTHER TERRESTRIAL ANIMALS

Four months after the accident, surveys and autopsies of wildlife and abandoned domestic animals that remained within the 10 km radius of the Chernobyl nuclear power plant were conducted [6.14]. Fifty species of birds were identified, including some rare species; all appeared normal in appearance and behaviour. No dead birds were found. Swallows and house sparrows were found to be producing progeny that also appeared normal.

Forty-five species of mammals from six orders were observed, and no unusual appearances or behaviours were noted.

Some wildlife and domestic animals were shot and autopsied in August and September 1986. Dogs and chickens showed signs of chronic radiation syndrome (reduced body mass, reduced fat reserves, increase in mass of lymph nodes, liver and spleen, haematomas present in liver and spleen and thickening of the lining of the lower intestine). No eggs were found in the nests of chickens or in their ovaries.

During the autumn of 1986, the number of small rodents on highly contaminated research plots decreased by a factor of two to ten. Estimates of absorbed dose during the first five months after the accident ranged from 12 to 110 Gy for gamma and 580 to 4500 Gy for beta radiation. The numbers of animals were recovering by the spring of 1987, mainly due to immigration from less affected areas. In 1986 and 1987 the percentage of pre-implantation deaths in rodents from the highly contaminated areas increased twofold to threefold compared with controls. Resorption of embryos also increased markedly in rodents from the affected areas; however, the number of progeny per female did not differ from controls [6.29].

6.7. RADIATION EFFECTS ON AQUATIC ORGANISMS

Cooling water for the Chernobyl nuclear power plant was obtained from the 21.7 km² human-made reservoir located south-east of the plant site. The cooling reservoir became heavily contaminated following the accident (see Section 3.5 for details) with over $6.5 \pm 2.7 \times 10^{15}$ Bq of a mixture of radionuclides in the water and sediments [6.30]. Aquatic organisms were exposed to external exposure from radionuclides in water and contaminated bottom sediments and irradiation from contaminated aquatic plants. Internal exposure occurred as organisms took up radioactively contaminated food and water or inadvertently consumed contaminated sediments. The resultant doses to aquatic biota over the first 60 days following the accident are depicted in Fig. 6.5.

The maximum dose rates for aquatic organisms (excluding fish) were reported in the first two weeks after the accident, when short lived isotopes (primarily ¹³¹I) contributed 60–80% of the dose. During the second week, the contribution of

short lived radionuclides to doses to aquatic organisms decreased by a factor of two. Maximum dose rates to fish were delayed (Fig. 6.5), due to the time required for their food webs to become contaminated with longer lived radionuclides (mostly $^{134,137}\text{Cs}$, $^{144}\text{Ce}/^{144}\text{Pr}$, $^{106}\text{Ru}/^{106}\text{Rh}$ and $^{90}\text{Sr}/^{90}\text{Y}$). Differences in dose rates among fish species occurred due to their trophic positions. Non-predatory fish (carp, goldfish, bleak) reached estimated peak dose rates of 3 mGy/d from internal contamination in 1986, followed by significant reductions in 1987. Dose rates in predatory fish (perch), however, increased in 1987 and did not start to decline until 1988 [6.21]. Accumulated doses were highest for the first generation of fish born in 1986 and 1987. Bottom dwelling fish (goldfish, silver bream, bream, carp) that received significant exposure from the bottom sediments received accumulated total doses of approximately 10 Gy.

In 1990 the reproductive capacity of young silver carp was analysed [6.31]. The fish were in live boxes within the cooling pond at the time of the accident. By 1988 the fish reached sexual maturity. Over the entire post-accident period they received a dose of 7–8 Gy. Biochemical analyses of muscles, liver and gonads indicated no difference from the controls. The amount of fertilized spawn was 94%; 11% of the developing spawn were abnormal. Female fertility was 40% higher than the controls, but 8% of the irradiated sires were sterile. The level of fluctuating asymmetry in offspring did not differ

from the controls, although the level of cytogenetic damage (22.7%) significantly exceeded the controls (5–7%). In contrast, Pechkurenkov [6.32] reported that the number of cells with chromosome aberrations in 1986–1987 in carp, flat bream and silver carp was within the norm. It is worth noting that the cooling pond was subject not only to radioactive contamination but also to chemical pollution.

Recent reviews of the chronic effects of ionizing radiation on reproduction in fish, with the Chernobyl data included (Table 6.5), have been summarized.

6.8. GENETIC EFFECTS IN ANIMALS AND PLANTS

Quality data concerning the incidence of Chernobyl related induced mutations in plants and animals are relatively sparse. An increased mutation level was apparent in 1987 in the form of various morphological abnormalities observed in Canada flea-bane, common yarrow and mouse millet plants. Examples of abnormalities include unusual branching of stems, doubling of the number of racemes, abnormal colour and size of leaves and flowers, and development of ‘witches’ brooms’ in pine trees. Similar effects in the 5 km radius circle near the reactor also appeared in deciduous trees (leaf gigantism, changes in leaf shape; see Fig. 6.6).

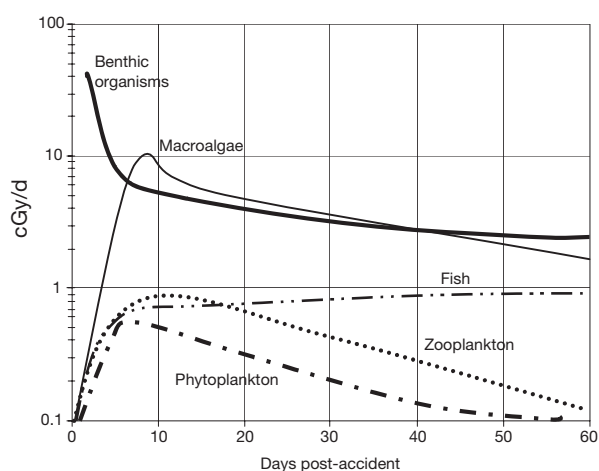


FIG. 6.5. The dynamics of absorbed dose rate (cGy/d) of organisms within the Chernobyl cooling pond during the first 60 days following the accident. Data are model results based on concentrations of radionuclides in the water column and lake sediments [6.21].



FIG. 6.6. Typical morphological abnormality seen on conifer trees. Such enhancement of vegetative growth and gigantism of some plant parts were not uncommon (photograph courtesy of T. Hinton, 1991).

Morphological changes were observed at an initial gamma dose rate of 0.2–0.3 mGy/h. At 0.7–1.3 mGy/h enhancement of vegetative reproduction (heather) and gigantism of some plant species were observed [6.19, 6.20, 6.34, 6.35].

Cytogenetic analysis of cells from the root meristem of winter rye and wheat germ of the 1986 harvest demonstrated a dose dependence in the number of aberrant cells. A significant excess over the control level of aberrations was observed at an absorbed dose of 3.1 Gy, inhibition of mitotic activity occurred at 1.3 Gy and germination was reduced at 12 Gy [6.36]. Analysis of three successive generations of winter rye and wheat on the most contaminated plots revealed that the rate of aberrant cells in the intercalary meristem in the second and third generations was higher than in the first.

From 1986 to 1992 mutation dynamics were studied in populations of *Arabidopsis thaliana* Heynh. (L.) within the CEZ [6.37]. On all study plots in the first two to three years after the accident, *Arabidopsis* populations exhibited an

increased mutation burden. In later years, the level of lethal mutations declined; nevertheless the mutation rate in 1992 was still four to eight times higher than the spontaneous level. The dose dependence of the mutation rate was best approximated by a power function with a power index of less than one.

Zainullin et al. [6.38] observed elevated levels of sex linked recessive lethal mutations in natural *Drosophila melanogaster* populations living under conditions of increased background radiation due to the Chernobyl accident. Mutation levels were increased in 1986–1987 in flies inhabiting contaminated areas with initial exposure rates of 2 mGy/h and more. In the subsequent two years mutation frequencies gradually returned to normal.

Studies of adverse genetic effects in wild mice have been reported by Shevchenko et al. [6.39] and Pomerantseva et al. [6.40]. These involved mice caught during 1986–1991 within a 30 km radius of the Chernobyl reactor with different levels of gamma radiation and in 1992–1993 at a site in the Bryansk region of the Russian Federation. The

TABLE 6.5. CHRONIC EFFECTS OF IONIZING RADIATION ON REPRODUCTION IN FISH, DERIVED FROM THE FASSET DATABASE [6.33]

Dose rate (μGy/h)	Dose rate (mGy/d)	Effects
0–99	0–2.4	Background dose group; normal cell types, normal damage and normal mortality observed
100–199	2.4–4.8	No data available
200–499	4.8–12	Reduced spermatogonia and sperm in tissues
500–999	12–24	Delayed spawning, reduction in testes mass
1000–1999	24–48	Mean lifetime fecundity decreased, early onset of infertility
2000–4999	48–120	Reduced number of viable offspring Increased number of embryos with abnormalities Increased number of smolts in which sex was undifferentiated Increased brood size reported Increased mortality of embryos
5000–9999	120–240	Reduction in number of fish surviving to one month of age Increased vertebral abnormalities
>10 000	>240	Interbrood time tending to decrease with increasing dose rate Significant reduction in neonatal survival Sterility in adult fish Destruction of germ cells within 50 days in medaka fish High mortality of fry; germ cells not evident Significant decrease in number of male salmon returning to spawn After four years, female salmon had significantly reduced fecundity

estimated total doses of gamma and beta radiation varied widely and reached 3–4 Gy per month in 1986–1987. One endpoint was dominant lethality, measured by embryo mortality of the offspring of wild male mice mated to unexposed female laboratory mice. The dominant lethality rate was elevated for a period of a few weeks following capture for mice sampled at the most contaminated site. At dose rates of about 2 mGy/h, two of 122 captured males produced no offspring and were assumed to be sterile. The remainder showed a period of temporary infertility and reduced testes mass, which, however, recovered with time after capture.

The frequencies of reciprocal translocations in mouse spermatocytes were consistent with previous studies. For all collected mice, a dose rate dependent increased incidence of reciprocal translocations (scored in spermatocytes at meiotic metaphase I) was observed. The frequency of mice harbouring recessive lethal mutations decreased with time post-accident [6.40]. Radiation related gene mutation is unlikely to have any adverse effect on populations at the dose rates that prevail now.

Advances in the sophistication and associated technologies of detecting molecular and chromosomal damage have occurred since the early genetic studies prior to the Chernobyl accident. Such advances have allowed researchers on the genetic consequences of the Chernobyl accident to examine endpoints not previously considered. Most prominent, and controversial, is the mutation frequencies in repeat DNA sequences termed ‘minisatellite loci’ or expanded simple tandem repeats (ESTRs). These are repeat DNA sequences that are distributed throughout the germline and that have a high background (spontaneous) mutation rate. At present, ESTRs are considered to have no function, although this is a matter of much interest and discussion [6.41, 6.42]. Minisatellite mutations have only rarely been associated with recognizable genetic disease [6.43].

Although laboratory examination of mutations in mouse ESTR loci shows clear evidence of a mutational dose response [6.44, 6.45], no convincing data on elevated levels of minisatellite mutations in plants or animals residing in the Chernobyl affected areas appear to have been published so far in the peer reviewed scientific literature. In general, quantitative interpretation of the ESTR data is difficult because of conflicting findings, their weak association with genetic disease, dosimetric uncertainties and methodological

problems [6.42]. This is an area of science that requires additional research.

6.9. SECONDARY IMPACTS AND CURRENT CONDITIONS

Prior to the accident, much of the area around Chernobyl was covered in 30–40 year old pine stands that, from a successional standpoint, represented mature, stable ecosystems. The high dose rates from ionizing radiation during the first few weeks following the accident altered the balanced community by killing sensitive individuals, altering reproduction rates, destroying some resources (e.g. pine stands), making other resources more available (e.g. soil water) and opening niches for immigration of new individuals. All these components, and many more, were interwoven in a complex web of action and reaction that altered populations and communities of organisms.

Exposure to ionizing radiation is an environmental stress, in many ways similar to other environmental stresses such as pollution by metals or the destruction caused by forest fires. If such stressors are sufficient, the community organization is changed and generally reverts to an earlier successional state. However, when the stress is subsequently reduced and sufficient time passes, recovery occurs and the ecosystem again regains stability, advancing towards a more mature state. The change in species diversity observed within the soil invertebrate communities presented above is perhaps the most obvious published example of community level change and subsequent recovery following the Chernobyl accident. The death of pine stands close to the Chernobyl reactor and the subsequent establishment of grasslands and deciduous trees are striking visual examples.

Age and sex distributions, diversity and the abundance and gross physiological conditions of small mammal populations in the CEZ appear to be similar to background locations in other parts of Ukraine [6.46–6.48]. Reports on the current genetic conditions of rodents within the zone are contradictory; for example, Shevchenko et al. [6.39] found significant disorders in spermatogenesis, while Baker et al. [6.46] found no reproductive inhibition or germ line mutations.

Layered on top of the impacts of the radiation exposure was the abrupt and drastic change that occurred when humans were removed from the CEZ. The town adjacent to the Chernobyl reactor,

Pripyat, was abandoned when over 50 000 people were evacuated. Agricultural activity, forestry, hunting and fishing within the CEZ were stopped because of the radioactive contamination of the products. Only activities designed to mitigate the consequences of the accident were carried out, as well as those supporting the living conditions of the cleanup workers, including substantial road construction.

For some years after the accident, the agricultural fields still yielded domesticated produce, and many animal species, especially rodents and wild boars, consumed the abandoned cereal crops, potatoes and grasses as an additional source of forage. This advantage, along with the special reserve regulations established in the CEZ (e.g. a ban on hunting), tended to compensate for the adverse biological effects of the radiation and promoted an increase in the populations of wild animals. Significant population increases of game mammals (wild boar, roe deer, red deer, elk, wolves, foxes, hares, beavers, etc. (Fig. 6.7)) and bird species (black grouse, ducks, etc.) were observed soon after the Chernobyl accident [6.49, 6.50].

More than 400 species of vertebrate animals, including 67 ichthyoids, 11 amphibians, 7 reptiles, 251 birds and 73 mammals, inhabit the territory of the evacuated town of Pripyat and its vicinity; more than 50 of them belong to a list of those protected according to national Ukrainian and European Red Books. The CEZ has become a breeding area for white tailed eagles, spotted eagles, eagle owls, cranes and black storks (Fig. 6.8) [6.51].

In the Pripyat River floodplain a developed system of artificial drainage channels now supports about a hundred families of beavers. Recognizing the value of the abandoned land around Chernobyl, 28 endangered Przewalsky wild horses were introduced in 1998. After six years their number had doubled [6.51]. In both the Ukrainian and Belarusian parts of the CEZ, State radioecological reserves have been created with a regime of nature protection.

As has been shown many times before, when humans are removed, nature flourishes. This phenomenon exists in US National Parks such as Yellowstone and the Grand Tetons, and at large US Department of Energy sites where the general public has been excluded for over 50 years. Human presence in any environment is a disturbance to the natural biota. Normal activities of farming, hunting, logging and road building, to name but a few, fragment, pollute and generally stress the processes

and mechanisms of natural environments. The removal of humans alleviates one of the more persistent and ever growing stresses experienced by natural ecosystems.

(a)



(b)



FIG. 6.7. Wild boar (a) and wolves (b) inhabiting the CEZ are not afraid of people because of long term hunt prohibition (photographs courtesy of S. Gaschak, 2004).



FIG. 6.8. A white tailed eagle chick observed recently in the CEZ. Before 1986 these rare predatory birds had rarely been found in this area (photograph courtesy of S. Gaschak, 2004).

On the other hand, the absence of forest management, and the associated increase in forest fires, have substantial impacts on natural communities. After the human population was evacuated, both wood cutting and the construction of mineralized fire prevention strips ceased. The number of dead trees increased and created conditions that enhanced the development of forest diseases and pests (borers, bark beetles, etc.). The amount of dead wood and brushwood has gradually increased in the unmanaged forests. The degradation of the forests resulted in enormous forest fires during the dry summer period of 1992, when the area of burnt forest amounted to 170 km² (i.e. about one sixth of the woodlands) [6.52].

Without a permanent residence of humans for 20 years, the ecosystems around the Chernobyl site are now flourishing. The CEZ has become a wildlife sanctuary [6.47], and it looks like the nature park it has become.

6.10. CONCLUSIONS AND RECOMMENDATIONS

6.10.1. Conclusions

- (a) Radiation from radionuclides released by the Chernobyl accident caused numerous acute adverse effects in the biota located in the areas of highest exposure (i.e. up to a distance of a few tens of kilometres from the release point). Beyond the CEZ, no acute radiation induced effects on biota have been reported.
- (b) The environmental response to the Chernobyl accident was a complex interaction among radiation dose, dose rate and its temporal and spatial variations, and the radiosensitivities of the different taxons. Both individual and population effects caused by radiation induced cell death have been observed in plants and animals as follows:
 - (i) Increased mortality of coniferous plants, soil invertebrates and mammals;
 - (ii) Reproductive losses in plants and animals;
 - (iii) Chronic radiation syndrome in animals (mammals, birds, etc.).

No adverse radiation induced effects have been reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy during the first month after the radionuclide fallout.

- (c) Following the natural reduction of exposure levels due to radionuclide decay and migration, populations have been recovering from the acute radiation effects. By the next growing season after the accident, the population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from the major radiation induced adverse effects in plants and animals.
- (d) The acute radiobiological effects observed in the Chernobyl accident area are consistent with radiobiological data obtained in experimental studies or observed in natural conditions in other areas affected by ionizing radiation. Thus rapidly developing cell systems, such as meristems of plants and insect larvae, were predominantly affected by radiation. At the organism level, young plants and animals were found to be the most sensitive to the acute effects of radiation.
- (e) Genetic effects of radiation, in both somatic and germ cells, were observed in plants and animals in the CEZ during the first few years after the accident. Both in the CEZ and beyond, different cytogenetic anomalies attributable to radiation continue to be reported from experimental studies performed on plants and animals. Whether the observed cytogenetic anomalies have any detrimental biological significance is not known.
- (f) The recovery of affected biota in the CEZ has been confounded by the overriding response to the removal of human activities (e.g. termination of agricultural and industrial activities and the accompanying environmental pollution in the most affected area). As a result, the populations of many plants and animals have expanded, and the present environmental conditions have had a positive impact on the biota in the CEZ.

6.10.2. Recommendations for future research

- (a) In order to develop a system of environmental protection against radiation, the long term impact of radiation on plant and animal populations should be further investigated in the CEZ; this is a globally unique area for

radioecological and radiobiological research in an otherwise natural setting.

- (b) In particular, multigenerational studies of radiation effects on the genetic structure of plant and animal populations might bring fundamentally new scientific information.
- (c) There is a need to develop standardized methods for biota-dose reconstruction, for example in the form of a unified dosimetric protocol.

6.10.3. Recommendations for countermeasures and remediation

- (a) Protective actions for farm animals in the event of a nuclear or radiological emergency should be developed and internationally harmonized based on modern radiobiological data, including the experience gained in the CEZ.
- (b) It is likely that any technology based remediation actions aimed at improving the radiological conditions for plants and animals in the CEZ would have adverse impacts on biota.

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7. ENVIRONMENTAL AND RADIOACTIVE WASTE MANAGEMENT ASPECTS OF THE DISMANTLING OF THE CHERNOBYL SHELTER

The destruction of the unit 4 reactor at the Chernobyl nuclear power plant created radioactive contamination and radioactive waste³ in the unit, the Chernobyl nuclear power plant site and the surrounding area (further referred to as the CEZ). The future development of the CEZ depends on the strategy for the conversion of unit 4 into an ecologically safe system (i.e. the development of the NSC, the dismantlement of the current shelter, removal of FCM, and eventual decommissioning of the reactor site).

In particular, the long term strategy for unit 4 involves implementation of the NSC concept to cover the unstable shelter and the related radioactive waste management activities at the Chernobyl nuclear power plant site and the CEZ. Currently units 1, 2 and 3 (1000 MW RBMK reactors) are shut down awaiting decommissioning; two additional reactors (units 5 and 6) that had been near completion were abandoned in 1986 following the accident.

This section addresses the current status of unit 4 and the existing and future environmental impact associated with it and the management of the radioactive waste from the accident at the Chernobyl nuclear power plant site and in the CEZ.

7.1. CURRENT STATUS AND THE FUTURE OF UNIT 4 AND THE SHELTER

7.1.1. Unit 4 of the Chernobyl nuclear power plant after the accident

In the course of the 1986 accident, a small part of the nuclear fuel (3.5% according to past estimates [7.1] or 1.5% according to recent estimates [7.2]) and a substantial fraction of volatile radionuclides (see Section 3.1) were released from the damaged unit 4. The remainder of the damaged

nuclear fuel, more than 95% of the fuel mass at the moment of the accident, i.e. about 180 t, was left in the remains of the reactor [7.1]. The uncertainty in this estimate is discussed in Section 7.1.5.

The first measures taken after the accident to control the fire and the radionuclide releases consisted of dumping neutron absorbing compounds and fire control material into the crater formed by the destruction of the reactor [7.1] (see Fig. 7.1). The total amount of material dumped on the reactor was approximately 5000 t, including about 40 t of boron compounds, 2400 t of lead, 1800 t of sand and clay and 600 t of dolomite, as well as sodium phosphate and polymer liquids [7.1].

At the Chernobyl nuclear power plant site in mid-May 1986 there were high levels of air radiation dose rate and air activity concentration, caused by relatively uniform contamination of the area with finely dispersed nuclear fuel and aerosols of short lived radionuclides, and also the presence of dispersed nuclear fuel particles or fragments. These fragments consisted of discrete and non-uniform material from the reactor core, reactor constructional material and graphite.

After the accident, the debris of the destroyed reactor building was collected, along with fragments of the reactor core, etc., and the soil surface layer. Thousands of cubic metres of radioactive waste generated by this work were disposed of in the pioneer wall and the cascade wall. Construction of walls around the damaged reactor reduced the radiation dose rates by a factor of 10–20 [7.3]. The completion of the pioneer wall and the cascade wall and a significant reduction in radiation levels allowed the shelter to be constructed.

The shelter, which was intended to provide the environmental containment of the damaged reactor, was erected within an extremely short period of time, between May and November 1986, under conditions of high radiation exposure of the personnel. The steps taken to save time and cost during the construction, and the high dose rates inside the structure, resulted in a lack of reliable and comprehensive data on the stability of the damaged older structures, a need for remote control

³ The radioactive waste in the CEZ does not include the waste associated with the decommissioning of Chernobyl nuclear power plant units 1, 2 and 3.



FIG. 7.1. The destroyed reactor after the accident in 1986.

concreting and the impossibility of carrying out welding in some specific situations.

7.1.2. Current status of the damaged unit 4 and the shelter

The shelter [7.4] was constructed using steel beams and plates as structural elements. Its foundation rests at some points on the original structural elements of unit 4, whose structural integrity, following the accident, is not well known. At other points it rests on debris remaining from the accident. Thus the ability of the shelter structure to withstand natural events such as earthquakes and tornados is known only with large uncertainties. In addition to uncertainties on the structural stability at the time of its construction, structural elements of the shelter have degraded as a result of moisture induced corrosion during the nearly 20 years since the accident.

The shelter has approximately 1000 m² of openings in its surface. These openings allow approximately 2000 m³/a of precipitation to

percolate through the radioactively contaminated debris and eventually to pool in rooms in the lower levels of unit 4 (see Fig. 7.2) [7.5]. Condensation within unit 4 of approximately 1650 m³/a of water and the residues from periodic spraying of 180 m³/a of liquid dust suppressant contribute to the quantities of water percolating through the unit 4 debris and collecting in its basement. The collected water is contaminated with ¹³⁷Cs, ⁹⁰Sr and transuranic elements, resulting in average concentrations of 1.6×10^{10} Bq/m³ of ¹³⁷Cs, 2.0×10^9 Bq/m³ of ⁹⁰Sr, 1.5×10^5 Bq/m³ of plutonium and 6 mg/L of uranium. About 2100 m³/a of the collected water evaporates, and about 1300 m³/a leaks through the foundation into the soil beneath unit 4 [7.6]. The existing Chernobyl nuclear power plant radioactive waste management system is not capable of treating liquid radioactive waste that contains transuranic elements.

The inside conditions of unit 4 (Fig. 7.3) are hazardous and present significant risks to workers and the environment. General area radiation dose rates range from 2 µSv/h to 0.1 Sv/h inside the



FIG. 7.2. Opening in the shelter allowing infiltration of atmospheric water.

shelter [7.5]. Individual occupational radiation exposures during current operations at unit 4 are controlled so that they do not exceed the dose limit of 20 mSv/a [7.7].

Unit 4 is ventilated during current activities through a monitored exhaust above the reactor room. The unfiltered exhaust air is normally below the permitted limits for atmospheric discharge, and a filtration system exists for use should the exhaust air levels approach the permitted discharge limits. The ventilation system is zoned so that air flows from outside the shelter through spaces with increasing levels of contamination.

Unit 4 and the associated cascade walls have an accumulation of FCM, including large core fragments that could conceivably lead to criticality under flooded conditions. Such a criticality accident is considered unlikely; however, if criticality should occur, it might lead to the exposure of some workers inside unit 4 to an external dose of only a few millisieverts, because workers tend to avoid the spaces with criticality risk. It has been estimated that, in such a case, there would be no significant



FIG. 7.3. Reactor room of unit 4 after the accident.

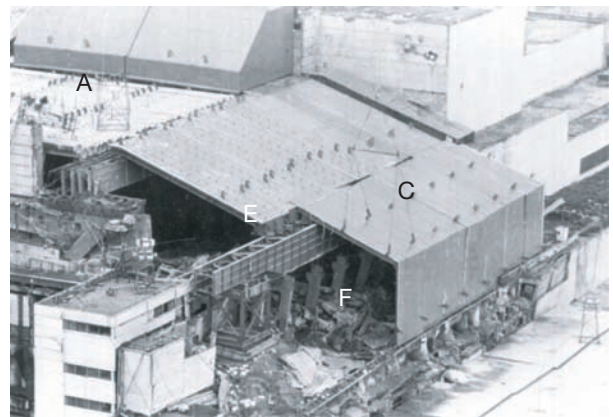


FIG. 7.4. Major structural components of the Chernobyl shelter: (A) pipe roofing; (B) southern panels; (C) southern hockey sticks; (D) B1/B2 beams; (E) mammoth beam; (F) octopus beam.

consequences inside and outside the CEZ [7.5, 7.8, 7.9].

A number of activities have been performed in recent years to stabilize and improve the conditions of the shelter. These include: repair of the unit 3/4 ventilation stack foundation and bracing; reinforcement of the B1 and B2 beams (Fig. 7.4); improvement of the physical protection and access control system; design of an integrated automated control system (control of building structure conditions, seismic control, nuclear safety control and radiation control); modernization of the dust suppression system; and additional structural stabilization. Computerized control systems were installed in the shelter [7.9] to monitor gamma radiation, neutron flux, temperature, heat flux, concentrations of hydrogen, carbon oxide and air

moisture, mechanical stability of structures, etc. This has been achieved with significant support from Ukraine and donor countries⁴.

The magnitude and importance of possible future radioactive releases from the shelter (in the event of its collapse) significantly depend on the radiological and physicochemical properties of the radioactive material, including dust that may arise from the area inside the shelter. Now, nearly 20 years after the accident, dust has penetrated concrete walls, floors and ceilings, and is in the air in the form of aerosols. Thus in a number of shelter premises the fuel-containing dust has become the main source of radiation hazard. Research [7.5, 7.10] shows that the typical size of these particles (activity median aerodynamic diameter) is from 1 to 10 µm. Hence most of the material is expected to be respirable, which increases its potential inhalation hazard. The potential for inhalation hazard is increased by the winds that may be generated if the shelter roof were to collapse.

Should the shelter collapse, it would also complicate continuing accident recovery efforts, and the resulting radioactive dust cloud would have adverse environmental impacts. Further analysis of the environmental release is sensitive to the source term assumed in the dust cloud that would be generated as a result of the collapse. Different studies give different possible radioactive dust releases to the environment, ranging from about 500 to 2000 kg of particulate dust, which could contain from 8 to 50 kg of finely dispersed nuclear fuel. Regardless of the source term assumption, almost all material that might be raised into the atmosphere by a shelter collapse is expected to be deposited within the CEZ [7.11, 7.12].

Another concern related to the FCM is its possible transport out of the shelter into groundwater through the accumulated water. The potential for FCM to dissolve in the accumulated water was confirmed when bright yellow stains and faded pieces of FCM were found on the surface of solidified fuel-lava streams in unit 4 [7.3]; subsequent analysis proved the presence of soluble

uranium compounds. Until recently, this FCM was considered to be a glassy mass that was very insoluble. The possibility of leaching of radionuclides from the FCM and of mobile radionuclides such as ⁹⁰Sr migrating and reaching the Pripjat River was expected to be very low [7.9]. The expected significance of this phenomenon is not known, and therefore monitoring of the evolving groundwater situation at and around the shelter is important.

Additional studies of the water table showed that it has risen by up to 1.5 m in a few years to about 4 m from the ground level, and may still be rising. This effect is considered to have occurred mainly as a result of the construction of a 3.5 km long and 35 m deep wall around unit 4 that aimed to protect the Kiev reservoir from potential contamination through groundwater [7.9].

The main potential hazard associated with the shelter is a possible collapse of its top structures and the release of radioactive dust into the environment; therefore a dust suppression system was installed beneath the shelter roof that periodically sprays dust suppression solutions and fixatives. The system has operated since January 1990, and more than 1000 t of dust suppressant has been sprayed during this period.

7.1.3. Long term strategy for the shelter and the new safe confinement

In order to avoid a collapse of the shelter, some measures have been implemented and additional measures are planned to strengthen unstable parts of the shelter and to extend their stability from 15 to 40 years [7.13]. In addition, the NSC is planned to be built as a cover over the existing shelter as a longer term solution (see Fig. 7.5). The Ukrainian Government supports the concept of a multifunctional facility with at least 100 years service life. This facility aims to reduce the probability of shelter collapse, reduce the consequences of a shelter collapse, improve nuclear safety, improve worker and environmental safety, and convert unit 4 into an environmentally safe site. The construction of the NSC is expected to allow for the dismantlement of the current shelter, removal of FCM from unit 4 and the eventual decommissioning of the reactor.

The specific operational aspects related to the construction and operation of the NSC, including maintenance in the long term, have not yet been identified. It is important to note that the NSC

⁴ Contributors to the work of the Chernobyl Shelter Fund include Austria, Belgium, Canada, Denmark, the European Commission, Finland, France, Germany, Greece, Ireland, Italy, Kuwait, Luxembourg, the Netherlands, Norway, Poland, Spain, Sweden, Switzerland, Ukraine, the UK and the USA. Additional donors to the Fund include Iceland, Israel, Korea, Portugal, Slovakia and Slovenia.

design is based on the current plans for removal of the FCM that depend on the availability of a final geological disposal facility about 50 years from now [7.13]. This extended dormancy period could result in the dispersal of the special human resources needed to remove and dispose of the FCM safely. Accordingly, there are good reasons for removing the FCM and structural material as soon as possible after the construction of the NSC.

7.1.4. Environmental aspects

7.1.4.1. Current status of the shelter

At present, the environmental contamination around the Chernobyl nuclear power plant site is due to the initial radioactive contamination of the area from the accidental release of 1986, the routine releases of radionuclides through the ventilation system of the shelter and the engineering and other activities carried out in the CEZ. The main dose contributing radionuclides within the CEZ around the Chernobyl nuclear power plant site are ^{137}Cs , ^{90}Sr , ^{241}Am and $^{239,240}\text{Pu}$ (see also Section 3); the distribution of these radionuclides is shown in Fig. 7.6 [7.2].

7.1.4.2. Impact on air

Currently, radioactive aerosol releases into the atmosphere from the shelter are considered to result from two main sources: controlled releases from the central hall of unit 4 into the environment through the exhaust ventilation system and

ventilation stack No. 2, and uncontrolled releases through the leaks in the roof and walls. Ventilation stack No. 2 releases 4–10 GBq/a, which is many times lower than the regulatory limit of 90 GBq/a [7.9]. The uncontrolled releases depend on the locations and areas of the openings in the external structures and the air transfer rate through them, which depends on many factors, such as temperature, barometric pressure, humidity and wind speed and direction.

As a result, the air in the immediate vicinity of the shelter contains finely dispersed fuel particles with concentrations of up to 40 mBq/m³ of ^{137}Cs at distances less than 1 km and 2 mBq/m³ at about 3 km from the shelter. The aerosol particles have radioactive compositions similar to those of the fuel; the primary beta emitters are ^{90}Sr and ^{137}Cs , while the alpha emitters are mostly plutonium and ^{241}Am . Inhalation doses to individuals outside the shelter result from a combination of the ongoing shelter releases and resuspended material from the initial accident. If a person (worker) were to spend an entire year adjacent to the shelter, a recent inhalation dose assessment indicates that releases would result in an annual dose of about 0.5 mSv, which would decrease to about 0.0002–0.0005 mSv beyond a distance of 10 km [7.14]. Inhalation doses from the ongoing releases outside the CEZ are significantly less than the dose limits for the population [7.7].

7.1.4.3. Impact on surface water

The average concentrations of radionuclides in surface water bodies are declining. In the Pripjat River in 2003, for example, concentrations were observed to be 0.05 (max. 0.12) Bq/L for ^{137}Cs and 0.15 (max. 0.35) Bq/L for ^{90}Sr [7.15]. The main sources of radionuclides in the rivers in the CEZ during ordinary and high water seasons continue to be runoff from the watersheds situated outside the immediate Chernobyl nuclear power plant area, infiltrating waters from the Chernobyl nuclear power plant cooling pond and old water reclamation systems in the heavily contaminated territories. During winter and low water seasons, the radionuclide fluxes from regional groundwater contribute the majority of the radionuclide migration to the Pripjat River from this area. However, the values of radionuclide flux from all groundwater into surface water are still relatively low, and the contribution of groundwater contamination plumes from the temporary

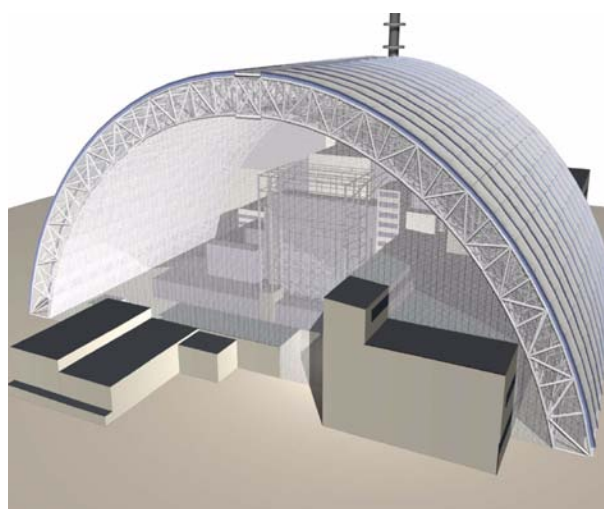
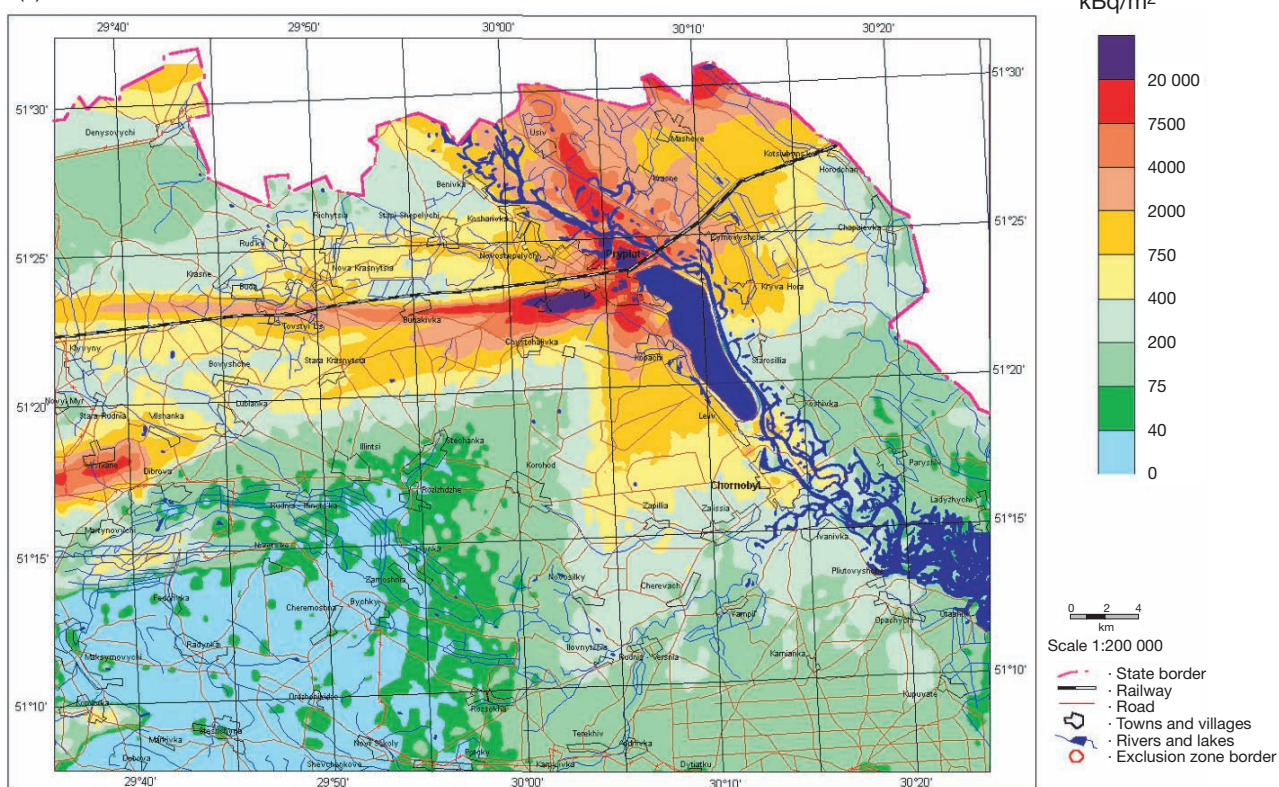


FIG. 7.5. Planned NSC.

(a)



(b)

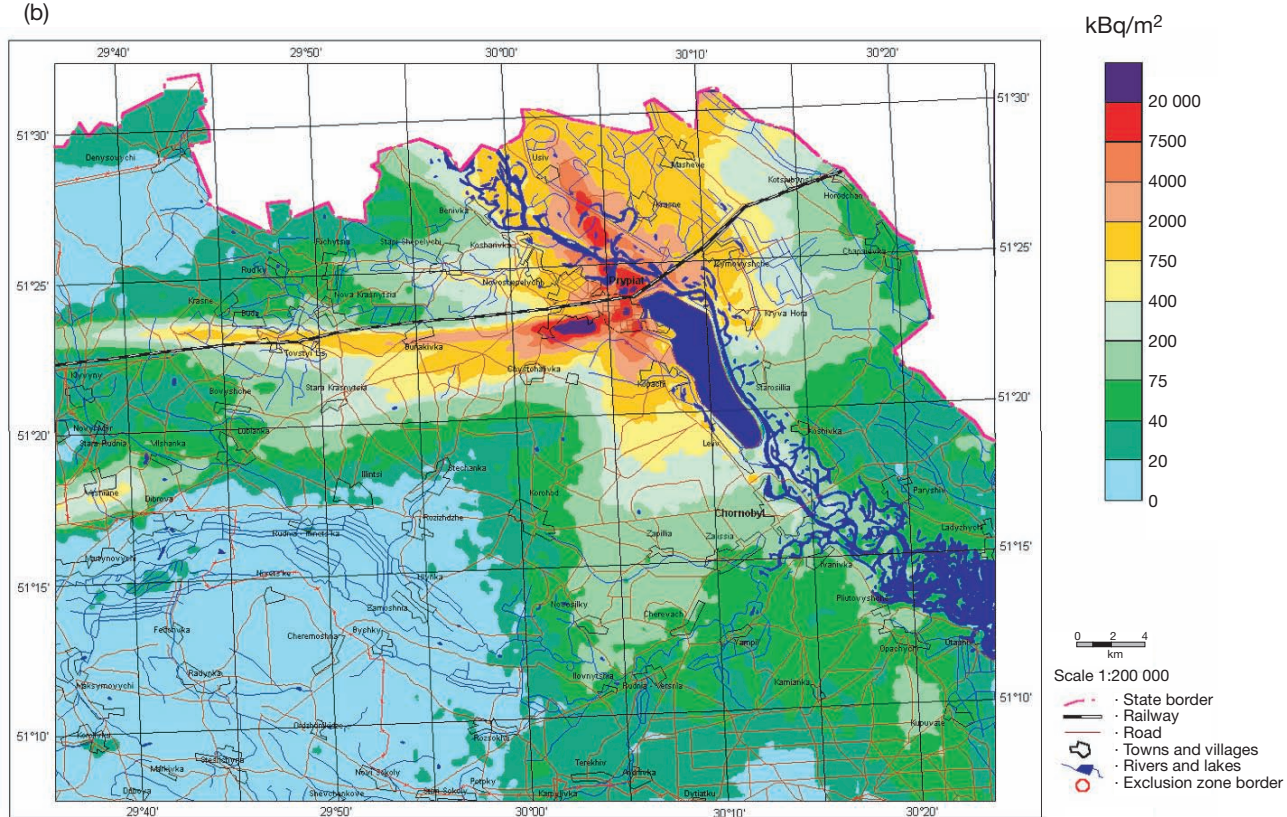
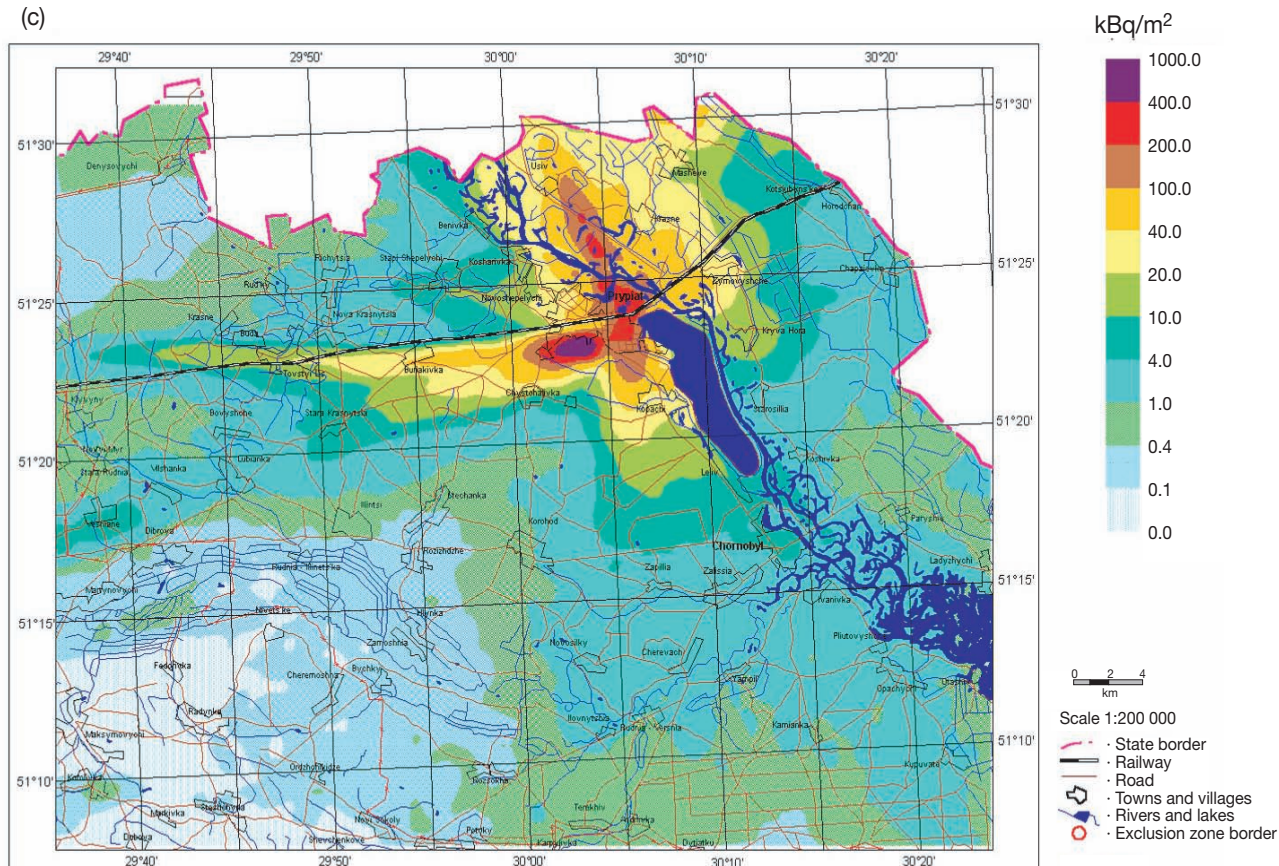
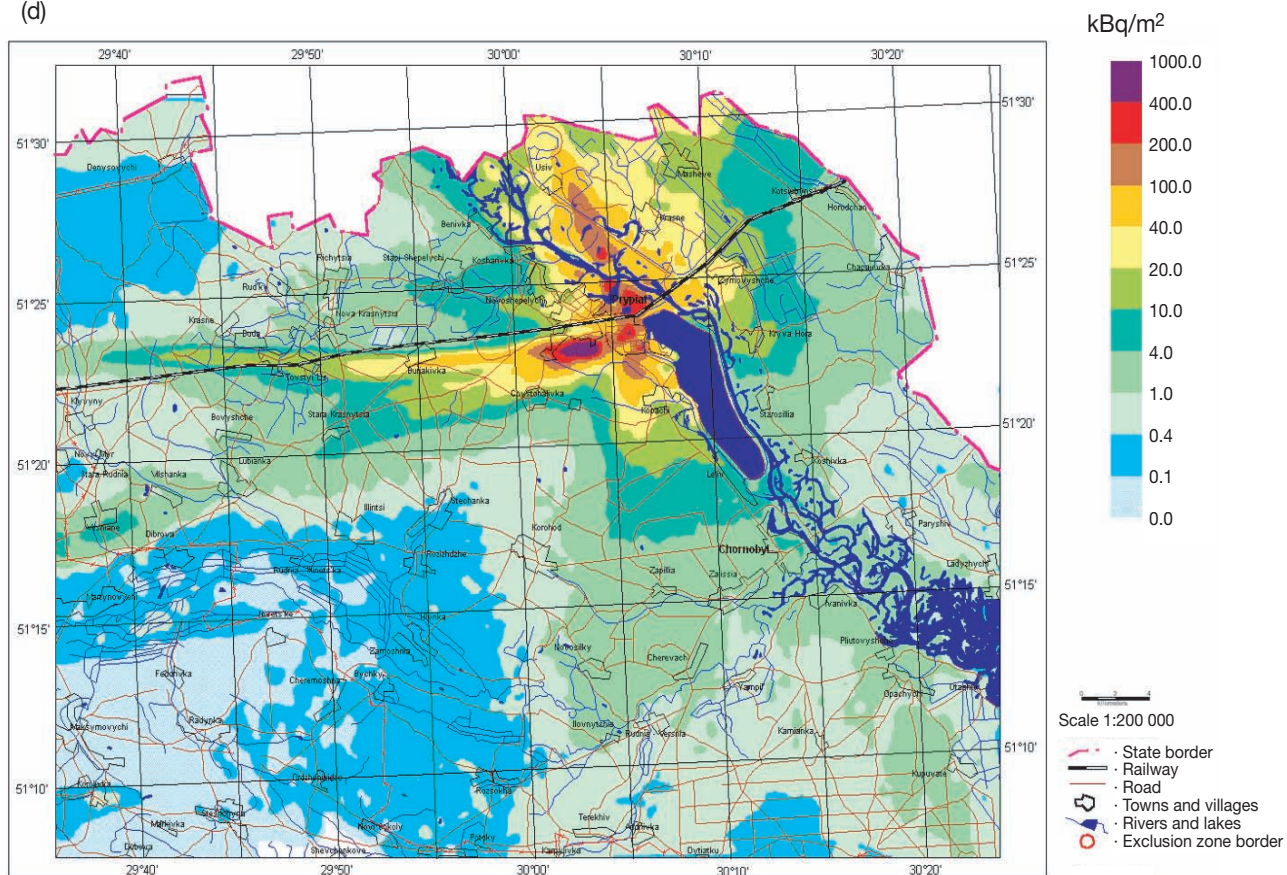


FIG. 7.6. Surface contamination by radioactive fallout within the CEZ [7.2]. (a) Caesium-137 in soils of the CEZ in 1997 (kBq/m²); (b) ^{90}Sr in soils of the CEZ in 1997 (kBq/m²); (c) ^{241}Am in soils of the CEZ in 2000 (kBq/m²); (d) $^{239,240}\text{Pu}$ in soils of the CEZ in 2000 (kBq/m²).

(c)



(d)



radioactive waste facilities and the shelter area has been identified as about 3–10% [7.15] of the annual migration of radionuclides into the Pripjat–Dnieper River system from the CEZ (see also Section 3.5).

7.1.4.4. *Impact on groundwater*

Surface contamination around the Chernobyl nuclear power plant site is the cause of groundwater contamination, with groundwater levels of 100–1000 Bq/m³ for ⁹⁰Sr and about 10–100 Bq/m³ for ¹³⁷Cs. Radionuclide contamination of the groundwater at the shelter site is much higher. In recent studies, the primary source term for radionuclide contamination of the groundwater is considered to be water accumulating inside the underground rooms of unit 4 (as a result of precipitation), groundwater accumulated near the pioneer wall (because of absence of a drainage system) and other water infiltrating from the nuclear power plant site.

In some places, ¹³⁷Cs in groundwater in the subsurface horizons near the shelter reaches 100 Bq/L and even 3000–5000 Bq/L. However, in the majority of the shelter area, ¹³⁷Cs concentrations in groundwater are more or less similar and vary from 1 to 10 Bq/L. Typical concentrations of ⁹⁰Sr in groundwater around the shelter site are in the range from 2 to 160 Bq/L, with maximum concentrations observed during the past five years ranging from 1000 to 3000 Bq/L. Estimated concentrations of transuranic elements in the groundwater of this area also vary over a wide range, from 0.003 to 3–6 Bq/L for ²³⁸Pu and ^{239,241}Pu, and from 0.001 to 8–10 Bq/L for ²⁴¹Am [7.16, 7.17].

7.1.4.5. *Impacts of shelter collapse without the new safe confinement*

Owing to concerns about the long term stability of the shelter, estimates have been made of the probability of its collapse. Depending on the mechanisms considered, the probability ranges from about 0.001 to 0.1/a [7.5, 7.18], and therefore an analysis (summarized from Ref. [7.6]) of the potential impacts of a shelter collapse has been performed for scenarios without and with the NSC in place.

(a) *Impact on air*

Collapse of the shelter could raise a large cloud of fine dust (up to 500–2000 kg) containing 8–

50 kg of nuclear fuel particles with an activity of about 1.6×10^{13} Bq. This could lead to an additional annual inhalation dose of up to 0.4 Sv near the shelter. The estimated annual doses outside the CEZ could reach 2 mSv [7.6], which would exceed the established dose limits for the public in Ukraine [7.7].

Within the boundaries of the CEZ, the depositions of radionuclides from such a collapse would be, in all cases, a small fraction of the existing contamination levels caused by the original Chernobyl accident. Typical results are shown in Fig. 7.7 [7.8]. The highest relative increase in soil contamination would occur if the wind were to blow the plume from a shelter collapse to the south-west towards the area that received the least impact from the original accident. In this case, the additional deposition might add about 10% to the existing soil contamination levels. Outside the CEZ boundaries, at 50 km from the shelter, additional surface contamination with ¹³⁷Cs, ⁹⁰Sr and ^{238,239,240}Pu due to a shelter collapse would contribute from a few to 10%.

(b) *Impact on surface water*

In the event of a shelter collapse, additional radioactive material could also be deposited in and near the rivers.

As shown in Fig. 7.7, radionuclide depositions into the Pripjat River could be as high as 1.1×10^{12} Bq of ⁹⁰Sr, 2.4×10^{12} Bq of ¹³⁷Cs, 1.6×10^{10} Bq of ²³⁸Pu, 4.0×10^{10} Bq of ^{239,240}Pu and 5.0×10^{10} Bq of ²⁴¹Am. Estimates of the maximum possible concentrations of these radionuclides in the Dnieper reservoirs show that the peak concentration of ⁹⁰Sr can be expected in the Kiev reservoir on the 41st day after the accident happens, and would be about 700 Bq/m³. The maximum concentration of ⁹⁰Sr in the Kakhovka reservoir would be about 200 Bq/m³ or less. This confirms that the normative values of ⁹⁰Sr in potable water (2000 Bq/m³ [7.7]) would not be exceeded if an accident leading to the maximum impacts were to occur at the shelter.

The maximum possible concentrations of ¹³⁷Cs that can be expected in the Kiev and Kaniv reservoir water, even in the worst simulated scenarios, are three to ten times lower than the limits for potable water. Such a collapse would not affect the concentrations of ²³⁸Pu, ^{239,240}Pu and ²⁴¹Am in the Pripjat and Dnieper Rivers [7.6].

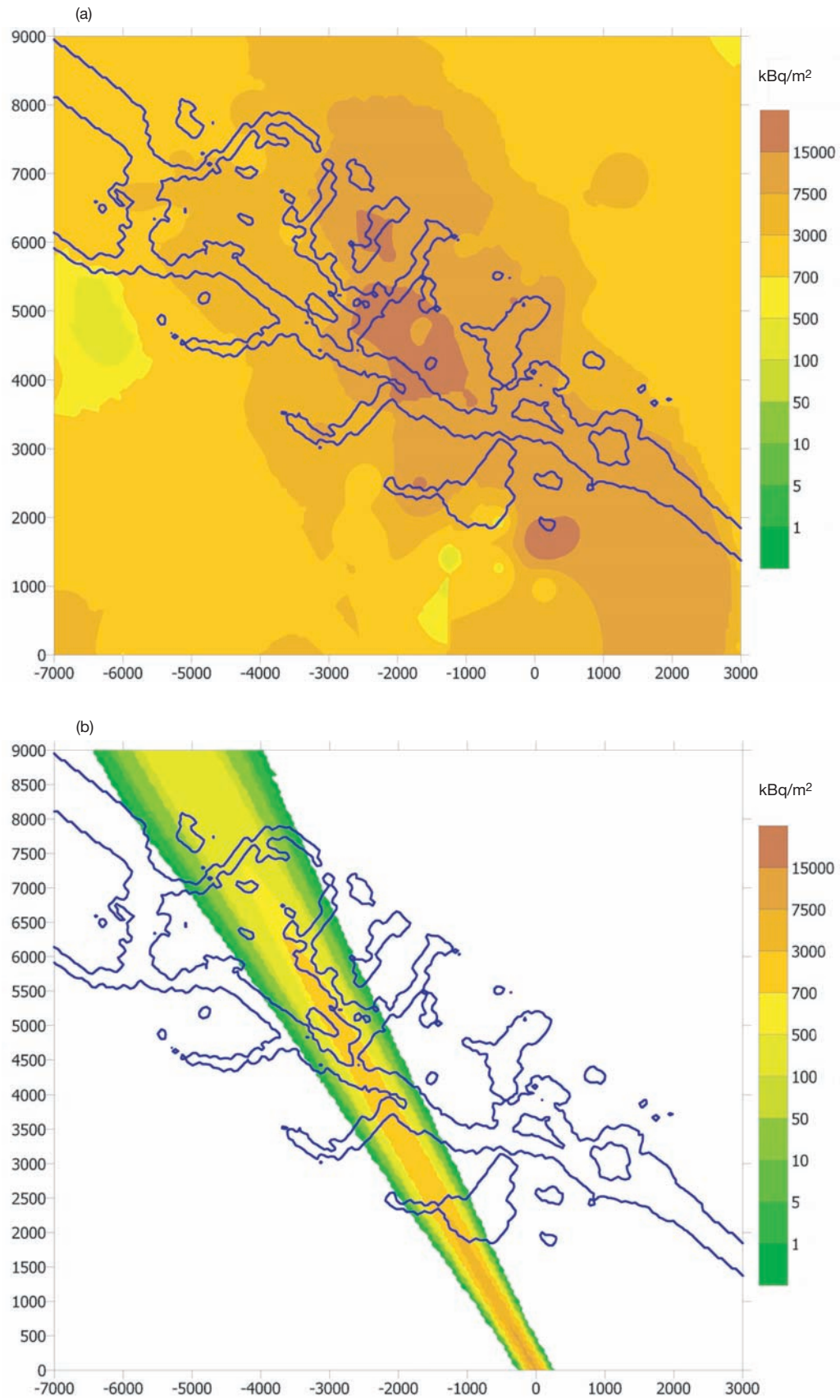


FIG. 7.7. Strontium-90 soil density of Chernobyl fallout (a) upstream of Yanov bridge, 1999, and (b) predicted from a shelter collapse [7.6]. The distance from the shelter is given on both axes.

Releases from a shelter collapse could lead to some increased exposure of people living downstream of the most impacted area in the CEZ and who consume water and fish from the reservoirs. Radiation doses to individuals are discussed in Ref. [7.6], in which the highest values are predicted to be for professional fishermen and typical consumers.

(c) Impact on groundwater

Rainwater infiltration and condensation within the existing shelter have also been studied [7.6]. The radiological significance of the large pool of water in the basement of the shelter was confirmed. The leakage of the heavily contaminated water from this pool through the concrete walls and floor of the room is a main source of the contamination of the vadose zone and groundwater beneath the shelter. Under existing conditions, a positive water balance exists and water collects in the basement rooms.

The results of an assessment of groundwater contamination without the NSC show that a concentration of ^{90}Sr in the groundwater of about $4 \times 10^9 \text{ Bq/m}^3$ is expected to occur at distances less than 100 m from the shelter, and would decline to 100 Bq/m^3 at 600 m from the shelter. The contamination is predicted to reach the Pripyat River in 800 years. However, the infiltration fluxes of ^{90}Sr from the shelter even without the NSC are not expected to cause significant impacts on the Pripyat River.

7.1.4.6. Impacts of shelter collapse within the new safe confinement

(a) Impact on air

Placement of the NSC over the shelter is expected to reduce the release of dust on to the site resulting from a collapse, thus reducing the magnitude of inhalation doses. The dust would largely settle within the NSC and not be released to the environment except through normal ventilation pathways. The amount of transported dust would depend on the ventilation and the confinement capability designed into the NSC. The doses are expected to be reduced by factors of seven to 70 compared with the estimated doses in the event of a shelter collapse without the NSC, depending on the capacity of the NSC ventilation system [7.6]. This leads to an expected decrease of outdoor workers' exposure by a factor of two in comparison with the

scenario of a shelter collapse without the NSC. However, some workers might be inside the NSC at the time of the collapse; doses to these workers might be increased because of containment of the dust.

For the small number of individuals who have chosen to reside within the CEZ, inhalation doses are expected to be reduced by factors of 50 to 500, to no more than 1 or 2 mSv [7.6]. Even assuming the worst (95th percentile) meteorological conditions and also assuming that the dust cloud passes over one of the larger cities, such as Slavutych, an increase of latent fatal cancer risk projected for the population in the event of a collapse with the NSC is not expected.

Very minor additions to soil contamination would be caused by the discharge and deposition of airborne radionuclides should the shelter collapse inside the NSC. Within the boundaries of the CEZ, the radionuclide deposition would be in all cases a small fraction of the existing levels caused by the original Chernobyl accident. The highest relative increase would occur if the wind were to blow the plume from a shelter collapse to the south-west towards the area that received the least impact from the original accident; in this case, the additional deposition might add less than 0.2% to the existing soil contamination levels.

(b) Impact on surface water

Emplacement of the NSC would ensure that, in the event of a collapse, additional deposition of radionuclides on surface water would be minimal. The depositions illustrated in Fig. 7.7 would be reduced by factors of 50 to 500 [7.6], and the resulting concentrations in downstream waters would not exceed the Ukrainian norms.

(c) Impact on groundwater

The dynamics of radionuclide migration into the groundwater with the presence of the NSC was evaluated assuming that the water level is reduced to zero in the basement one and a half years after the NSC is constructed. After NSC construction, the precipitation fluxes are expected to be minimized and evaporation fluxes will be higher than fluxes from dust suppression and condensation. This means that the water level in the basement is expected to diminish due to seepage through the walls, and the room would therefore be empty in less than two years.

7.1.5. Issues and areas for improvement

7.1.5.1. Influence of the source term uncertainty on environmental decisions

There is still considerable uncertainty regarding the amount of nuclear fuel remaining in unit 4. One estimate [7.1, 7.19] is that inside unit 4 there is approximately 95% of the 190 t of nuclear fuel (as uranium) that was in the reactor at the time of the accident. Another estimate [7.12] is that there is 60% of the original core plus the fuel in the decay pool and in the central room remaining in the facility (212 t total, less 80 t of FCM, less 6 t of blown out fuel = 126 t remaining). The estimated radioactivity inside the shelter in 1995 was approximately 7×10^{17} Bq [7.3]. Despite these and other studies, to date there is no comprehensive information regarding the amount and distribution of fuel inside the shelter. This lack of knowledge is an important factor in the evaluation of the safety and environmental consequences of unit 4 and the shelter evolution, as well as for the selection of adequate solutions for the long term management of the associated radioactive waste.

7.1.5.2. Characterization of fuel-containing material

The physical state of the FCM appears to be changing with time. It appears that the FCM has begun to oxidize and may be decomposing into fine particulate matter with an unknown oxidation rate, particle size and behaviour. Another related important uncertainty is on the dust distribution in the shelter, and more specifically in the NSC atmosphere over long term operation of the facility. As estimates of the environmental impacts (e.g. transport and inhalation calculations) of long term shelter development are sensitive to the assumptions about these source term parameters, it is necessary that these parameters be further investigated. This would contribute to increased confidence in the safety assessment results and the selection of appropriate protective measures for workers, the public and the environment.

7.1.5.3. Removal of fuel-containing material concurrent with development of a geological disposal facility

The stabilization of the shelter and construction of the NSC is expected to generate significant amounts of long lived radioactive waste,

some of which would contain FCM. However, there are no plans for removal of the FCM until a geological disposal facility is constructed and commissioned. A long term management strategy for the FCM and long lived radioactive waste therefore needs to be developed to ensure safe management of this waste.

It can be concluded that there is no technical reason to delay removal of the FCM until a geological disposal facility is available. Removal of FCM could commence following dismantlement of the unstable structures of the shelter, continuing with radioactive waste predisposal management and temporary storage on the Chernobyl nuclear power plant site until the geological disposal facility becomes available. Due to the high content of long lived radionuclides there is also no significant worker dose benefit to be obtained from waiting for the availability of a geological disposal facility. Whether retrieved now or after 50 years, remote retrieval and radioactive waste management techniques will be required to remove the FCM and restore the unit 4 site.

7.2. MANAGEMENT OF RADIOACTIVE WASTE FROM THE ACCIDENT

In the course of remediation activities, both at the Chernobyl nuclear power plant site and in its vicinity, large volumes of radioactive waste were generated and placed in temporary near surface waste storage facilities located in the CEZ (Fig. 7.8) at distances of 0.5–15 km from the nuclear power plant site. Sites for temporary waste storage of the

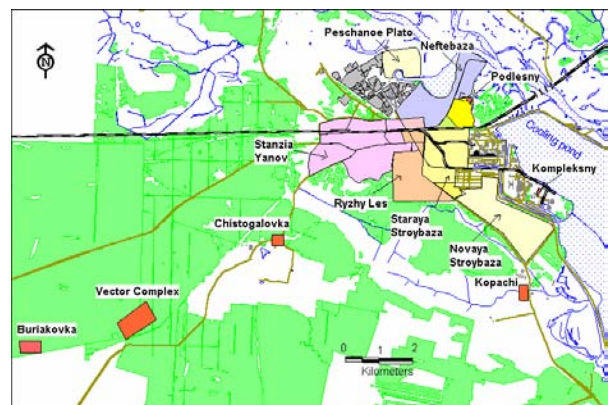


FIG. 7.8. Temporary radioactive waste disposal facilities in the territory of the CEZ.

TABLE 7.1. UKRAINIAN SOLID RADIOACTIVE WASTE CATEGORIZATION [7.21]

	Range of specific activity (kBq/kg)			
	Group 1 ^a	Group 2 ^a	Group 3 ^a	Group 4 ^a
Low activity	10 ⁻¹ –10 ¹	10 ⁰ –10 ²	10 ¹ –10 ³	10 ³ –10 ⁵
Intermediate activity	10 ¹ –10 ⁵	10 ² –10 ⁶	10 ³ –10 ⁷	10 ⁵ –10 ⁸
High activity	>10 ⁵	>10 ⁶	>10 ⁷	>10 ⁸

^a Group 1: transuranic alpha radionuclides; group 2: alpha radionuclides (excepting transuranium); group 3: beta and gamma radionuclides (excluding those in group 4); group 4: ³H, ¹⁴C, ³⁶Cl, ⁴⁵Cf, ⁵³Mn, ⁵⁵Fe, ⁵⁹Ni, ⁶³Ni, ^{93m}Nb, ⁹⁹Tc, ¹⁰⁹Cd, ¹³⁵Cs, ¹⁴⁷Pm, ¹⁵¹Sm, ¹⁷¹Tm and ²⁰⁴Tl.

trench and landfill type were created from 1986 to 1987, intended for radioactive waste generated after the accident as a result of the cleanup of contaminated areas, to avoid dust spread, reduce radiation levels and provide better working conditions at unit 4 and its surroundings. These facilities were established without proper design documentation, engineered barriers or hydrogeological investigations, which are required by contemporary waste safety requirements.

During the years following the accident, economic and human resources were expanded to provide a systematic analysis and an acceptable strategy for the management of existing radioactive waste. However, as reported in some Ukrainian studies [7.20], to date a broadly accepted strategy for radioactive waste management at the Chernobyl nuclear power plant site and the CEZ, and especially for high level and long lived waste, has not been developed. Some of the reasons are the large number of and areas covered by the radioactive waste storage and disposal facilities, of which only half are well studied and inventoried. This results in large uncertainties in the documented radioactive waste inventories (volume, activity, etc.).

The existing radioactive waste from the accident and potential radioactive waste to be generated during the NSC construction, shelter dismantling, FCM removal and decommissioning of unit 4 can be categorized as:

- Radioactive waste from the shelter and the nuclear power plant site that will be created by construction of infrastructure and the NSC;
- Accident generated transuranic waste that has been mixed with radioactive waste from operations at Chernobyl nuclear power plant units 1, 2 and 3;

TABLE 7.2. CLASSIFICATION OF RADIOACTIVE WASTE WITH UNKNOWN SPECIFIC ACTIVITY USING THE DOSE RATE AT 0.1 m DISTANCE [7.21]

	Dose rate (μGy/h)
Low activity	1–100
Intermediate activity	100–10 000
High activity	>10 000

- Radioactive waste in temporary radioactive waste facilities located throughout the CEZ;
- Radioactive waste in existing radioactive waste disposal facilities.

The safety and environmental issues related to each of these categories of radioactive waste are presented in this section. The radioactive waste expected to be generated during the decommissioning of the Chernobyl nuclear power plant units 1, 2 and 3 represents an additional category that is not the subject of this report.

The current Ukrainian legislation applies a categorization of radioactive waste in accordance with its specific activity and radiotoxicity, specified in Table 7.1 [7.21].

For waste contaminated with unspecified mixtures of radionuclides emitting gamma radiation, use of the classification ‘low’, ‘intermediate’ and ‘high’ activity is allowed using the air dose rate at a distance of 0.1 m, as specified in Table 7.2 [7.21].

Current radioactive waste management practice in Ukraine does not fully comply with the above classification; measures are therefore being taken to bring it into conformity with the new regulations [7.22].

7.2.1. Current status of radioactive waste from the accident

7.2.1.1. Radioactive waste associated with the shelter

The shelter is considered to be “the destroyed unit 4 after a radiological accident” and “a near surface storage facility for unconditioned radioactive waste at a stage of stabilization and reconstruction” [7.22, 7.23]. The amount and type of waste, debris and other radioactive material inside the shelter is presented in Table 7.3.

In addition, soil that was heavily contaminated by the deposition of fuel fragments and with radio-nuclides and debris from the accident (metal pieces, concrete rubble, etc.) was also collected and stored in the vicinity of unit 4:

- (a) Three pioneer walls (west, north and south of the shelter), where contaminated soil, concrete and containers are stored and which contain an estimated 1700–4900 m³ of high level waste⁵ and up to 72 000 m³ of low and intermediate level waste [7.25, 7.26].
- (b) The cascade wall north of the shelter, where core fragments, metal, concrete, core pit

equipment and accident cover material are stored (16 600 m³ of high level waste, 117 t of reactor core elements and 53 400 m³ of low and intermediate level waste) [7.25].

- (c) The industrial site around the shelter, where concrete, gravel, sand, clay and contaminated soil are stored that contain 7000 m³ of high level waste and 286 000 m³ of low and intermediate level waste [7.27]. Other studies show that fuel, graphite, etc., are located in the contaminated soil [7.26].

The radioactive waste inside the pioneer and cascade walls was later covered with concrete. This material is considered to be high level waste that is not acceptable to be disposed of in near surface disposal facilities. Since it cannot be retrieved easily for conditioning, the radioactive waste recovered from these walls is to be part of a global strategy for the decommissioning of unit 4.

⁵ High level waste falls into two subcategories: low temperature waste with a heating rate of less than 2 kW/m³ and heat generating waste with a heating rate higher than 2 kW/m³ [7.24].

TABLE 7.3. ESTIMATED INVENTORY IN THE SHELTER [7.25]

	Type of radioactive waste and criteria of assessment	Category of radioactive waste	Amount
FCM	Fresh fuel assemblies, spent fuel assemblies, lava type material, fuel fragments, radioactive dust	High level	About 190–200 t, 700 t of graphite
Solid radioactive waste with less than 1% nuclear fuel (mass)	Fragment of the core with a dose rate at 10 cm of more than 10 mSv/h		
Liquid radioactive waste	Changing inventory based on precipitation (e.g. pulp, oils, suspensions with soluble uranium salts)	Low level (up to 3.7 × 10 ⁵ Bq/L)	2500–5000 m ³
		Intermediate level (more than 3.7 × 10 ⁵ Bq/L)	500–1000 m ³
Solid radioactive waste	Metal equipment and building material, for example concrete, dust, non-metal material (organic, plastic)	High level	38 000 m ³ (building material), 22 240 t (metal constructions)
		Low and intermediate level	300 000 m ³ (building material and dust), 5000 m ³ (non-metal)



FIG. 7.9. Existing above ground storage facility for solid radioactive waste at the Chernobyl nuclear power plant site.

It is estimated that the current and expected radioactive waste from unit 4 can be categorized as short lived low and intermediate level waste (soil from the construction of the NSC, construction material, concrete, metal constructions, etc.) and high level waste (e.g. FCM) according to Ukrainian legislation [7.28, 7.36].

7.2.1.2. *Mixing of accident related waste with operational radioactive waste*

During 1986–1993, some low and intermediate level radioactive waste and high level waste with transuranic elements were stored together with some operational radioactive waste from units 1, 2 and 3 in an above ground storage facility (see Fig. 7.9) at the Chernobyl nuclear power plant site.

This waste amounts to about 2500 m³, with a total radioactivity of about 131 TBq [7.19], and is stored unconditioned. Once filled, the storage facility was backfilled with concrete grout and covered with a concrete roof to reduce radiation levels and water infiltration. Thus the retrieval of the radioactive waste stored in this facility cannot be easily achieved and will require particular care. Plans for such retrieval are currently under study. At present, this facility is being extended and is intended to be used for the disposal of radioactive waste produced during the decommissioning of units 1, 2 and 3.

7.2.1.3. *Temporary radioactive waste storage facilities*

The largest volumes of radioactive waste generated by unit 4 remediation activities are

located in the CEZ (see Fig. 7.8). Sites for temporary storage of radioactive waste, of the trench and landfill type, were constructed shortly after the accident at distances of 0.5–15 km from the nuclear power plant site. They were created from 1986 to 1987 and intended for radioactive waste generated after the accident as a result of the cleanup of contaminated areas to avoid dust spread, reduce radiation levels and provide better working conditions at unit 4. These facilities were established without design documentation, engineered barriers or hydrogeological investigations.

The total area of temporary radioactive waste facilities is about 8 km², with the total volume of disposed radioactive waste estimated to be over 10⁶ m³. The main inventories of activity are concentrated in the Stroibaza and Ryzhy Les temporary radioactive waste facilities along the western trace of the Chernobyl fallout (see Fig. 7.8). The specific activity of the radioactive waste in the temporary radioactive waste facility at Ryzhy Les is 10⁵–10⁶ Bq/kg of ⁹⁰Sr and ¹³⁷Cs and 10³–10⁴ Bq/kg of plutonium isotopes (total).

Most of the facilities are structured in the form of trenches 1.5–2.5 m deep in the local sandy soil. The radioactive material (soil, litter, wood and building debris) is overlain by a layer of alluvial sand 0.2–0.5 m thick. The majority of the temporary radioactive waste facilities consist of trenches in various types of geological setting, in which waste was stacked and covered with a layer of soil from the nearby environment. These facilities are therefore very variable with regard to their potential for release, which depends on the total radioactivity stored, the waste form (in particular timber), the retention capacity of the substratum along migration pathways and the location of the sites in hydrogeological settings. At least half of these temporary radioactive waste facilities have been studied (see Table 7.4) [7.19, 7.29].

There are also many other temporary radioactive waste facilities, estimated to comprise about 800 trench facilities each with waste disposal volumes in the range of 8 × 10² to 2 × 10⁶ m³ [7.29, 7.30]. The inventories of these facilities are known for about half of them. The facilities are not under regulatory control. Estimates made for a few sites show that their radioactive contents can be high (10–1000 TBq), sometimes of an order of magnitude comparable with the total radioactivity present in soil in the CEZ (about 7000 TBq) [7.30].

7.2.1.4. Radioactive waste disposal facilities

The main radioactive waste disposal facilities for accident waste are the Buriakovka, Podlesny and Kompleksny sites, which are under regulatory control. These three near surface disposal sites were established after the accident to dispose of radioactive waste from remediation actions carried out during the first year following the accident. These sites were chosen and designed for the disposal of higher level accident waste than the radioactive waste located in the temporary radioactive waste facilities [7.19].

Buriakovka, built in 1987, is the only disposal facility currently in operation in the CEZ. It comprises 30 trenches covered with a 1 m clay layer and is located on 23.8 ha. Up to 652 800 m³ of radioactive waste has been disposed of. After in situ

compaction, this was reduced to 530 000 m³, with a total radioactivity of 2.5×10^{15} Bq of solid short lived low and intermediate level waste. It consists of metal, soil, sand, concrete and wood contaminated with ⁹⁰Sr, ¹³⁷Cs, ¹³⁴Cs, ^{238,239,240}Pu, ^{154,155}Eu and ²⁴¹Am. Radioactive waste with dose rates at 10 cm from the surface in the range of 0.003–10 mGy/h was accepted in this facility.

The Podlesny vault type disposal facility was commissioned in December 1986 and closed in 1988. The facility was designed for the disposal of high level waste with a dose rate 10 cm from the surface in the range of 0.05–2.5 Gy/h. Material with dose rates above this was also disposed of in the facility. The total radioactive waste volume of 11 000 m³ of building material, metal debris, sand, soil, concrete and wood was placed in two vaults. The disposal facility was covered with concrete at its

TABLE 7.4. STATUS OF TEMPORARY RADIOACTIVE WASTE FACILITIES [7.19, 7.29]

	Size (ha)	Number of trenches	Number of landfills	Radioactive waste type	Radioactive waste volume (10 ³ m ³)	Total activity (Bq)
<i>Sites with well known inventories</i>						
Neftebaza	53	221	4	Soil, plants, metal, concrete and bricks	104	4×10^{13}
Peschannoe Plato	78	2	82	Short lived ^a low and intermediate level waste of soil, rubble and concrete	57	7×10^{12}
<i>Partially investigated sites</i>						
Stantzia Yanov	128	Known: more than 36	—	Soil, plants, metal, concrete and bricks	30	$>4 \times 10^{13}$
Ryzhy Les	227	Estimated at more than 61	Estimated at more than 8	Mainly soil, some construction and domestic material	500	Up to 4×10^{14}
Staraya Stroibaza	130	More than 100	—	Soil, metal, concrete and wood	171	1×10^{15}
Novaya Stroibaza	122	—	—	Soil, plants, metal, concrete and bricks	150	2×10^{14}
Pripyat	70	—	—	Contaminated vehicles, machinery, wood and construction waste	16	3×10^{13} Bq (1990)
Chistogalovka	6	—	—	Material from demolition of buildings, soil, wood and work clothes	160	4×10^{12}
Kopachi	125	—	—	Construction waste from demolition	110	3×10^{13}

^a According to Ukrainian legislation, short lived waste is radioactive waste whose release from regulatory control is achieved earlier than 300 years after disposal; long lived waste is radioactive waste whose release from regulatory control is achieved later than 300 years after disposal [7.21].

closure. In 1990 the estimated total radioactivity of the disposed waste was 2600 TBq. In 2002 a re-evaluation of the facility status showed reasons to believe that the total activity of waste disposed at this site may be higher than initially estimated, and a need for a re-estimation of the current inventory was identified. Due to the uncertainties in the inventory, it is assumed that various types of waste were disposed of, including FCM.

The Kompleksny vault type facility was based on reconstructed facilities of the unfinished units 5 and 6 at the Chernobyl nuclear power plant site. Kompleksny was in operation from October 1986 until 1988 and was designed for low and intermediate level waste corresponding to dose rates up to 0.01 Gy/h at 10 cm from the surface of the waste container. More than 26 200 m³ of solid waste with a total activity of 4×10^{14} Bq was disposed of in 18 000 containers and later covered with sand and clay. This waste is mainly sand, concrete, metal, construction material and bricks. Due to the high level of groundwater at different periods of the year, the facility is flooded 0.5–0.7 m above its bottom. Significant uncertainties exist associated with the radionuclide inventory because of the lack of data about the radioactive waste disposed of at the site.

At present, a new near surface facility, the Vektor complex, for low and intermediate level radioactive waste processing, storage and disposal, is under development. This complex will include [7.19]:

- (a) An engineering facility for the processing of all types of solid radioactive waste (capacity of 3500 m³/a);
- (b) A disposal facility for short lived solid radioactive waste (55 000 m³ total capacity);
- (c) A storage facility for long lived solid radioactive material;
- (d) A storage facility for FCM;
- (e) Intermediate storage for high level conditioned radioactive waste to be prepared for final disposal at the deep geological disposal facility.

7.2.2. Radioactive waste management strategy

At present, no further dismantlement and cleanup of unit 4 is planned. However, estimates of the radioactive waste generation and subsequent management options have been performed for the construction of the NSC and the dismantlement phase of the unstable structures of the shelter. The

preparation phase is expected to generate about 390 t of solid radioactive waste and about 280 m³ of liquid [7.6]. It also requires the removal of 100 000 m³ of contaminated soil around unit 4, which may still contain fuel fragments. Preliminary studies for the dismantlement of the shelter superstructure predict that about 1200 t of steel, with an estimated volume of radioactive waste of 1800 m³ [7.14], mainly metal and large concrete pieces, will be removed. This waste is planned to be sorted based upon its radiation level. High level waste, which is expected to be only a small part, is planned to be placed in containers and stored within the NSC.

According to Ukrainian legislation [7.31], all industrial radioactive waste is classified according to the scheme shown in Fig. 7.10: high level and long lived waste must be disposed of in a deep geological disposal facility; low and intermediate level and short lived radioactive waste in a near surface disposal facility. Following these criteria, a strategy for the management of radioactive waste from the 1986 accident needs to be developed, and in particular for the management of high level and long lived radioactive waste.

The planned options for low level waste are to sort the waste according to its physical characteristics (soil, concrete, metal, etc.) and, possibly, to decontaminate it and/or condition it for beneficial reuse (reuse of soil for NSC foundations, melting of metal pieces) or send it for disposal in a new extension of the Buriakovka disposal facility [7.19] or the Vektor disposal site.

The long lived waste is planned to be placed in interim storage. Different storage options are being considered at the Chernobyl nuclear power plant or the Vektor site, and a decision has not yet been made. After construction of the NSC, decommissioning of

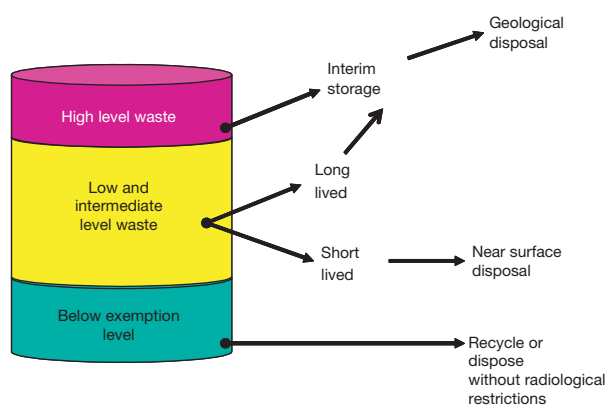


FIG. 7.10. Planned management of radioactive waste at the Chernobyl nuclear power plant site [7.19].

the shelter facilities is envisaged, including shelter dismantlement and further removal of FCM. High level radioactive waste will be partially processed in place and stored at a temporary storage site until a deep geological disposal site is ready. At present, this strategy is considered as the preferred option for high level radioactive waste and FCM [7.19]. To implement this strategy, it is planned to organize a system for processing and temporary storage of the high level and long lived radioactive waste at the Vektor facility complex that is now being developed. When the Vektor facility is in full operation, it may be possible to begin the work of removing FCM and other radioactive waste from the shelter under cover of the NSC.

Such a strategic approach is foreseen in the comprehensive programme on radioactive waste management that was approved by the Ukrainian Government [7.25]. Prior to elaboration of such a programme, special field studies and geological investigations must be carried out in the CEZ and its surrounding area, and in particular in the areas with crystalline rocks that have a depth of more than 500 m. According to Ref. [7.25], it is considered reasonable to begin an investigation for exploring the most appropriate geological site in this area in 2006. Following such planning, the construction of a deep geological disposal facility might be completed before 2035–2040.

Management of future liquid radioactive waste from the shelter is planned to be performed at the new liquid radioactive waste treatment plant at the Chernobyl nuclear power plant site. However, the management of liquid waste containing transuranic elements remains an issue to be resolved.

In addition, in the strategy for management of radioactive waste from the accident, account should be taken of the management of other storage sites containing about 2000 pieces of contaminated equipment (transport vehicles, helicopters, tanks,

etc.) that were used in the first months after the accident and for which the final disposition has not been determined.

7.2.3. Environmental aspects

Safety concerns in relation to most of the temporary radioactive waste facilities in the CEZ need to be viewed within the context that most of these facilities are located in very contaminated areas, with surface levels of ^{90}Sr in the range of 400–20 000 kBq/m², 700–20 000 kBq/m² for ^{137}Cs and 40–1000 kBq/m² for $^{239,241}\text{Pu}$. In this same territory, the temporary radioactive waste facilities occupy a relatively small volume covered with several metres of soil and other geological material.

The major concern is the risk of increased contamination of groundwater and the possibility, in the future, that such contamination reaches major water sources used as water supplies. The measurements reported in the French–German initiative [7.32] (see Table 7.5) clearly show that some temporary radioactive waste facilities have a significant influence on groundwater. In particular, flooded and partially flooded trenches are giving rise to enhanced migration, due to the absence of engineered safety features. More favourable settings, such as the Buriakovka site, lessen the radionuclide release variations and maintain concentrations in groundwater at comparatively low levels.

For a part of the year, some temporary radioactive waste facilities are very near or in the groundwater table, which can affect radionuclide dispersion. It is noticeable that water table levels at the trenches and landfills vary from about 1 to 7 m depth and vary depending on the season. Part of the facilities at Stantzia Yanov and Neftebaza are constantly flooded. Flooding is also an important concern at the Kompleksny disposal site, where the waste containers are flooded from 0.5 to 0.7 m from

TABLE 7.5. CONTAMINATION OF GROUNDWATER NEAR SELECTED TEMPORARY RADIOACTIVE WASTE STORAGE FACILITIES IN 1994–1995 [7.16] AND IN 1999 [7.23]

	Strontium-90 (Bq/L)		Caesium-137 (Bq/L)		Plutonium-239, 240 (Bq/L)
	1994–1995	1999	1994–1995	1999	1994–1999
Ryzhy Les	100–120 000	100–230	0.1–100	0.1–2.5	0.4–0.6
Stroibaza	3–200	30–50	1–20	0.02–0.004	No data
Peschannoe Plato	3–10	2–40	0.7–3	0.02–0.1	No data

the bottom of the disposal facility [7.19]. The degree of contamination is monitored in these disposal sites using a monitoring system, established in 1986–1989, that needs upgrading.

Monitoring results of groundwater contamination around the temporary storage facilities indicated concentrations of ^{90}Sr in the range of 100–100 000 Bq/m³ [7.19, 7.33]. The highest levels of contamination are detected at the northern part of the Chernobyl nuclear power plant site, groundwater from which also runs into the Pripjat River. Therefore, actual and potential impacts from radionuclides exist for those radioactive waste facilities located immediately next to the riverside in alluvial soils and which might be at regular risk of flooding during high water periods [7.20, 7.32]. These types of disposal facility have been studied during the past five years and continue to be studied as a basis for their step by step removal and relocation to the properly established disposal facilities.

As mentioned above, the rate of radionuclide migration with groundwater is much lower than the hydraulic transport of the water itself. This means that, due to retardation factors and geochemical processes, the majority of radionuclides being released from the body of the temporary radioactive waste facilities are accumulating in the geological media. Taking into account the adsorption capacity of the soils and geological media surrounding the temporary radioactive waste

facilities, several studies have shown that a significant fraction of ^{90}Sr is still associated with the fuel matrix, which delays its release to the pore water in the soil for many years. As a result, radionuclide concentrations in groundwater, even for such mobile radionuclides as ^{90}Sr , are very low. Plutonium isotopes (and ^{241}Am associated with them) have not yet been adequately studied; however, it is well known that their migration beyond the temporary radioactive waste sites is negligible (Fig. 7.11).

Studies of the vertical and lateral transfer rates of radionuclides demonstrated that, for the local soil, there is a low risk of radionuclide contamination in groundwater and therefore a proportionately low risk of significant contamination of the Pripjat River in the future, as discussed also in Section 3.5 (see Fig. 3.58). It has been shown that the leading edge of contaminated groundwater from most of the significant temporary radioactive waste facilities may reach regional surface water within 100 or more years, making this issue of minimal importance in terms of radiological impact for populations living downstream of the Pripjat River system [7.17, 7.34]. However, for the CEZ, groundwater is still an important potential source for radionuclide migration in the environment, and therefore the waste facilities have to be under regular monitoring and institutional control.

The long term strategy for the temporary facilities is related to the management of the

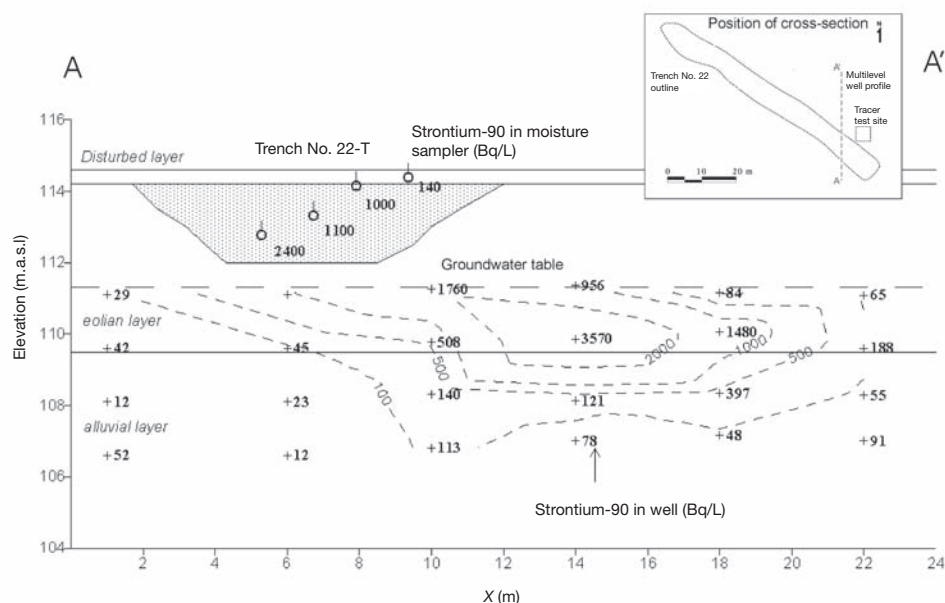


FIG. 7.11. Spatial distribution of ^{90}Sr (Bq/L) in the groundwater near surface trench No. 22 of the Ryzhy Les facility in October 1998 [7.34].

associated radiological risks. The ultimate goal should be that waste is disposed of or left in temporary radioactive waste facilities that ensure sufficient confinement of ^{137}Cs and ^{90}Sr to allow their decay without having generated significant impacts on potential critical groups. For those temporary radioactive waste facilities located near the banks of the Pripjat River that could be inundated by floodwaters, the preferred strategy is to remove and relocate the waste into the properly established disposal facilities.

For the temporary radioactive waste facilities in the CEZ whose inventory is not known, and for which the potential for future contamination of surrounding groundwater and surface water is uncertain, safety assessments need to be performed, taking into account radioactive decay and natural attenuation. There is clearly a need to assess, with an increased level of confidence, the migration of contamination plumes and their interface with major water resources and supply areas (aquifers, rivers, reservoirs, local supplies for the nuclear power plant and the CEZ). Such assessments need to consider all sources of release likely to affect these water resources.

The safety assessment results will guide decisions on appropriate remediation or institutional control measures at the temporary sites. Operational waste acceptance criteria (e.g. activity concentrations) also need to be established to ensure that potential exposures from various scenarios remain acceptable, on the hypothesis that resettlement in the CEZ occurs after some hundreds of years. It is obvious that institutional control at such disposal sites will need to be maintained for a period of a few hundred years to allow ^{137}Cs and ^{90}Sr activities to decay to insignificant levels. This will require significant resources for monitoring, implementation of recovery actions and probably major restrictions on resettlement. However, long term institutional controls should not be considered as an alternative to recovery actions to improve overall safety in the CEZ.

7.2.4. Issues and areas of improvement

7.2.4.1. *Radioactive waste management programme for the exclusion zone and the Chernobyl nuclear power plant*

A comprehensive programme for radioactive waste management has not yet been established for

further cleanup of contaminated areas or temporary radioactive waste facilities at the Chernobyl nuclear power plant and within the CEZ. As mentioned earlier, the ongoing strategy is to monitor the temporary waste sites with the highest radiological risk to the environment, so as to assess whether cleanup or environmental protection actions are needed. In addition, options for the long term processing, storage and disposal of long lived and high level waste from the Chernobyl nuclear power plant and the CEZ, as well as management of liquid waste contaminated with transuranic elements, are to be selected and the necessary facilities developed. Development of such a programme could ensure the consistent and coordinated long term management of all types of accident waste and hence provide protection of workers, the public and the environment.

7.2.4.2. *Decommissioning of unit 4*

Two main factors need to be addressed within the strategy for dismantlement of the shelter and decommissioning of unit 4: the safety implications of the management of associated radioactive waste (in particular of the high level waste) and the safety implications of delaying recovery operations. The strategy for the management of radioactive waste that cannot be disposed of in near surface facilities needs to be developed. Specifically, there is a need for new waste management facilities (e.g. storage of long lived waste, geological disposal), with consideration given to the capacity of these facilities and also the possibility of using the existing facilities for the decommissioning of the Chernobyl nuclear power plant. Particular attention needs to be given to the establishment of an adequate infrastructure and facilities for the management of long lived waste (in particular large quantities of soil, transuranic liquid waste and contaminated metal) and high level waste (i.e. FCM) and their subsequent disposal.

7.2.4.3. *Waste acceptance criteria*

The waste management programme being implemented does include criteria for the categorization of accident radioactive waste, which are needed for the selection of an appropriate management option for individual radioactive waste streams. Adoption of criteria for waste management, based on ^{137}Cs and alpha specific radioactivity levels in the waste, is under

development. Although such criteria are more adapted to appraising the potential for waste to be accepted in near surface facilities, the question of estimating the acceptable specific activities for existing waste, especially in temporary radioactive waste facilities, remains difficult to solve. The development of waste acceptance criteria is important in order to ensure protection of workers and the environment, as well as the public, in the long term.

7.2.4.4. Long term safety assessment of existing radioactive waste storage sites

There is a need to identify the remaining temporary radioactive waste storage facilities and to appropriately mark them to prevent inadvertent intrusion. The long term impact of these facilities on the environment also needs to be evaluated in order to estimate the need, where necessary, for implementation of upgrading or remedial actions.

Taking into account the large number of facilities, there is also a need to prioritize the needs for safety assessment. These assessments should evaluate safety in the present conditions and with consideration of possible future resettlement. Consideration should be given to the need to restrict the number of sites that are flooded or will, in the future, need extensive control over some hundreds of years.

In order to select those facilities with higher radiological risk it is important to improve methods for assessing the radioactive content of the waste in the temporary facilities, especially of long lived radionuclides. For pragmatic reasons, this assessment should be based on a limited number of parameters and measures. In this way, uncertainties that affect present estimates of the potential impact of individual facilities on the environment will be reduced, and a consistent assessment that takes into account all existing and potential sources of contamination in the CEZ will become feasible.

7.2.4.5. Potential recovery of temporary waste storage facilities located in the Chernobyl exclusion zone

Work is under way on the development of a strategy for the management of temporary waste storage facilities; this envisages three options for the different facilities, depending on their status and radiological hazard to the environment [7.19, 7.29]:

- (a) Retrieval of waste and disposal in the short term in order to minimize environmental consequences and improve the safety of workers; for example, industrial sites, the shelter, the flooded temporary storage facilities and the Kompleksny disposal facility.
- (b) Possible temporary storage of waste under institutional control in accordance with radiation protection requirements with a view to future disposal; for example, the Podlesny disposal facility and contaminated equipment from the activities aimed at mitigation of the Chernobyl accident.
- (c) Investigation of facilities that need to be studied in order to decide on adequate intervention measures; for example, temporary radioactive waste facilities and soil from the construction of the NCF.

7.3. FUTURE OF THE CHERNOBYL EXCLUSION ZONE

The long term development of the CEZ is an important and complex task that must consider various technical, economic, social and other factors; various options have been considered for the evolution of this zone. According to Likhtarev et al. [7.35], after 2015 about 55% of the territory around the Chernobyl nuclear power plant could be considered for release from radiological limitations according to Ukrainian legislation. However, the final decision on permitting people to return to this zone must take into account the inhomogeneous character of the contaminated land, specific features of radionuclide migration and accumulation in different portions of the local landscape, and the routine habits of the population living in this region (hunting, fishing, berry picking, mushroom gathering, etc.).

The overall plan for the development of the CEZ is to recover the affected areas of the CEZ, redefine the CEZ and make the non-affected areas available for resettlement by the public. This will require well defined administrative controls as to the nature of activities that may be performed in the resettled areas, prohibition of growing of food crops and cattle grazing and the use of only clean feed for cattle. Accordingly, these resettled areas are best suited for an industrial site rather than for a residential area.

For the reasons given above, the activities focused on decontamination and dismantlement of the

shelter and on radioactive waste management in this territory are expected to continue, which requires optimal management of this area. The new concept foresees division of the CEZ into different sections:

- (a) The industrial zone is planned to include the most contaminated areas, where the Chernobyl nuclear power plant, facilities for processing radioactive waste and main radioactive waste storage areas are situated. Primarily industrial activities are envisaged to be carried out here, specifically the construction of the NSC facilities. To provide the infrastructure for NSC construction, new roads, shipping yards, railways and other support structures are planned. The town of Chernobyl has been considered as an option for such infrastructure development [7.6]. If the CEZ is selected as the site for construction of the geological repository for high activity and long lived radioactive waste, a significant amount of drilling and mining work will have to be performed, which will also require specific development of the engineering infrastructure.
- (b) The sanitary restricted zone is considered to be a buffer area between industrial and nature reserve areas.
- (c) The nature reserve areas are planned to be located where most industrial and human activities are prohibited, with the aim of preservation of the basic natural landscapes and biodiversity of the region.

The rehabilitation of the CEZ is expected to create optimal conditions for industrial activity and environmental protection for a long period of time; for example, the NSC is expected to be operational for at least 100 years. Different types of radioactive storage facility must provide safe storage for 300 or more years. A possible activity in this area may be construction of the main geological disposal facility for radioactive waste. A national engineering centre may be established for processing all categories of radioactive material and waste to be delivered to the geological repository from different parts of Ukraine.

Continued monitoring and support studies in the CEZ are needed to form a basis for the review and optimization of the management strategy in the contaminated territories, and also for developing basic and practical knowledge about the dynamics and evolution of radionuclide migration, the need

for additional engineering barriers and the implementation of environmental remediation technologies.

In summary, the future of the CEZ for the next hundred years and more is envisaged to be associated with the following activities:

- (i) Construction and operation of the NSC and relevant engineering infrastructure;
- (ii) De-fuelling, decommissioning and dismantling of units 1, 2 and 3 of the Chernobyl nuclear power plant and shelter;
- (iii) Construction of facilities for the processing and management of radioactive waste, in particular a deep geological repository for high activity and long lived radioactive material;
- (iv) Development of nature reserves in the area that remains closed to habitation;
- (v) Maintenance of environmental monitoring and research activities.

7.4. CONCLUSIONS AND RECOMMENDATIONS

7.4.1. Conclusions

It can be concluded that the existing uncertainties associated with the stability of the shelter structures, the radioactive inventory, the insufficient confinement, the evolving characteristics of the FCM and the conditions inside and around the shelter (e.g. groundwater conditions) create uncertain safety conditions from the point of view of protection of workers, the public and the environment in the future. Therefore, continuation of the stabilization measures at the shelter and construction of the NSC are expected to improve safety and prevent or mitigate accident scenarios that would be expected to have consequences outside the CEZ.

It is also required that prompt solutions be found for the safe predisposal and disposal management of the radioactive waste to be generated during this period, in particular for the management of long lived and high level waste. Planning and evaluation of safety for the decommissioning of unit 4 after the construction of the NSC is needed in order to develop appropriate measures and to allocate necessary resources for the conversion of the shelter into a safe environmental system.

The decommissioning of unit 4 will generate significant amounts of radioactive waste with a wide range of characteristics that will need to be safely managed as part of the decommissioning and waste management activities at the Chernobyl nuclear power plant and the CEZ. A comprehensive strategy for the management of all waste streams is needed to ensure adequate infrastructure and capabilities for the processing, storage and disposal of this waste. Such a strategy will also need to take into account the future development of underground and on-surface storage and disposal facilities, some of which are flooded.

At present, studies show that the known waste facilities do not present an unacceptable hazard to the public; however, an assessment of their long term impact on the public and the environment is needed. This should be done taking into account the remaining sources of radioactive contamination in the CEZ, and particularly those facilities that are flooded and represent higher risks.

For the less known and less studied waste facilities it will be necessary to reduce the uncertainties associated with the waste inventories and facility characteristics, assess their long term safety, monitor the dynamics of radionuclide migration into the environment and, where necessary, implement remediation measures. This is important for the successful implementation of waste management activities in the CEZ and the conversion of the zone into a safe environmental system.

7.4.2. Recommendations

Recognizing the ongoing effort on improving safety and addressing the aforementioned uncertainties in the existing input data, the following main recommendations are made regarding the dismantling of the shelter and the management of the radioactive waste generated as a result of the accident.

(a) Since individual safety and environmental assessments have been performed only for individual facilities at and around the Chernobyl nuclear power plant, a comprehensive safety and environmental impact assessment, in accordance with international standards and recommendations, that encompasses all activities inside the entire CEZ, should be performed.

- (b) During the preparation and construction of the NSC and soil removal, special monitoring wells are expected to be destroyed. Therefore, it is important to maintain and improve the environmental monitoring strategies, methods, equipment and staff qualification needed for the adequate performance of monitoring of the conditions at the Chernobyl nuclear power plant site and the CEZ.
- (c) The dismantling of the shelter after a delay of about 50 years does not seem to be a viable option, due to the need for long term maintenance of structure stability and integrity, resources and knowledge. This long term strategy raises concerns related to the potential loss of the most experienced personnel at the Chernobyl nuclear power plant and the maintenance of a stable workforce necessary for the safe operation of the NSC. It is reasonable, therefore, to begin retrieving FCM soon after dismantling the unstable structures of the shelter rather than waiting for the availability of a geological disposal facility.
- (d) Development of an integrated radioactive waste management programme for the shelter, the Chernobyl nuclear power plant site and the CEZ is needed to ensure application of consistent management approaches and sufficient facility capacity for all waste types. Specific emphasis needs to be given to the characterization and classification of waste (in particular waste with transuranic elements) from all remediation and decommissioning activities, as well as to the establishment of sufficient infrastructure for the safe long term management of long lived and high level waste. Therefore, development of an appropriate waste management infrastructure is needed in order to ensure sufficient waste storage capacity; at present, the rate and continuity of remediation activities at the Chernobyl nuclear power plant site and in the CEZ are being limited.
- (e) A coherent and comprehensive strategy for the rehabilitation of the CEZ is needed, with particular focus on improving the safety of the existing waste storage and disposal facilities. This will require development of a prioritization approach for remediation of the sites, based on safety assessment results, aimed at making decisions about those sites at which waste will be retrieved and disposed of and

those sites at which the waste will be allowed to decay in situ.

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The explosion on 26 April 1986 at the Chernobyl nuclear power plant and the consequent reactor fire resulted in an unprecedented release of radioactive material from a nuclear reactor and adverse consequences for the public and the environment. Although the accident occurred nearly two decades ago, controversy still surrounds the real impact of the disaster. Therefore the IAEA, in cooperation with the Food and Agriculture Organization of the United Nations, the United Nations Development Programme, the United Nations Environment Programme, the United Nations Office for the Coordination of Humanitarian Affairs, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Health Organization and the World Bank, as well as the competent authorities of Belarus, the Russian Federation and Ukraine, established the Chernobyl Forum in 2003. The mission of the Forum was to generate “authoritative consensual statements” on the environmental consequences and health effects attributable to radiation exposure arising from the accident as well as to provide advice on environmental remediation and special health care programmes, and to suggest areas in which further research is required. This report presents the findings and recommendations of the Chernobyl Forum concerning the environmental effects of the Chernobyl accident.