IAEA-TECDOC-1240

Present and future environmental impact of the Chernobyl accident

Study monitored by an International Advisory Committee under the project management of the Institut de protection et de sûreté nucléaire (IPSN), France

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

August 2001

The originating Section of this publication in the IAEA was:

Waste Safety Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

PRESENT AND FUTURE ENVIRONMENTAL IMPACT OF THE
CHERNOBYL ACCIDENT
IAEA, VIENNA, 2001
IAEA-TECDOC-1240
ISSN 1011–4289

Printed by the IAEA in Austria
August 2001

FOREWORD

The environmental impact of the Chernobyl nuclear power plant accident has been extensively investigated by scientists in the countries affected and by international organizations. Assessment of the environmental contamination and the resulting radiation exposure of the population was an important part of the International Chernobyl Project in 1990–1991. This project was designed to assess the measures that the then USSR Government had taken to enable people to live safely in contaminated areas, and to evaluate the measures taken to safeguard human health there. It was organized by the IAEA under the auspices of an International Advisory Committee with the participation of the Commission of the European Communities (CEC), the Food and Agriculture Organization of the United Nations (FAO), the International Labour Organisation (ILO), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO) and the World Meteorological Organization (WMO). The IAEA has also been engaged in further studies in this area through projects such as the one on validation of environmental model predictions (VAMP) and through its technical co-operation programme.

The project described in this report was initiated after a proposal by Belarus to the 38th regular session of the IAEA General Conference in September 1994 to convene an international group of high level experts to review the information drawn from the long term studies of the Chernobyl accident and its consequences*. After other relevant international organizations had been consulted, it was agreed that the IAEA would formulate a project focusing on the environmental impact of the Chernobyl accident. France responded favourably to the IAEA's invitation to help finance this study, supporting it through the Institut de protection et de sûreté nucléaire (IPSN).

The IPSN provided the head of the project, D. Robeau, assisted by a group of technical advisers. The technical investigation of the material reviewed and the drafting of the working document necessary for the compilation of the final report were carried out by specialists in fields including radioecology, radiation protection, rehabilitation and recovery, economics and sociology from Belarus, the Russian Federation and Ukraine. The work was based on the national reports and additional material including experimental data obtained and analysed by experts from these three States by 1996.

The work was supervised by a project supervisory committee made up of senior experts nominated by the Governments of Belarus, the Russian Federation and Ukraine, one expert from France and a chairman, P. Hedemann Jensen, from Denmark. This committee approved the final report after considering comments from five renowned experts who formed an international peer review committee.

---

* *"We propose that the IAEA, UNESCO, the World Health Organization and other interested organizations together with the scientists and specialists from Russia, Ukraine and Belarus will analyze and generalize the results of ten years study of the Chernobyl accident. For this reason it seems advisable to form an international group of high-level experts. There is no such necessity at all for this group, as a rule, to go to the contaminated areas and carry out the investigations there. Its task is to study and generalize the material having been already accumulated. In this case the Republic of Belarus is ready to present all the necessary materials. The result of such a work could be the publication of a special final report."* (Taken from the Statement of the Head of the Delegation of the Republic of Belarus Mr. A. Mikhalevich at the XXXVIII Session of the IAEA General Conference, 1994).

The project had to be completed within a very short time. Its successful completion was only possible with a substantial contribution from the IPSN and the commitment shown in Belarus, the Russian Federation and Ukraine. These and other contributors, listed at the end of the report, are gratefully acknowledged.

A draft of this report was originally during the EC/IAEA/WHO International Conference, "One Decade after Chernobyl: Summing up the Consequences of the Accident", held in Vienna, 8–12 April 1996. Comments of the Peer Review Committee and of others have been taken into account in the final version of the report. The efforts of P.J. Waight in unifying the terminology and ensuring clarity of expression are gratefully acknowledged. The IAEA officers responsible for this publication were M. Balonov and M. Gustafsson of the Division of Radiation and Waste Safety.

EDITORIAL NOTE

CONTENTS

SUMMARY

This report presents the results of studies of the radiological and social consequences of the Chernobyl accident. The studies, carried out by experts from Belarus, the Russian Federation and Ukraine during the period 1986–1995, covered the current and likely radiological situation; the effects of the accident on human life in the contaminated regions; radiobiological consequences of the irradiation of flora and fauna in the exclusion zone; and remedial actions to reduce long term human exposure.

The radiological data include recent estimates of the radionuclide releases in April–May 1986 from the damaged reactor and of soil contamination levels in Belarus, the Russian Federation and Ukraine. It is shown that most of the long lived radionuclide activity is still concentrated in the upper (0–10 cm) soil layer. The report describes the dynamics of radionuclide concentration in surface water, in agricultural produce of vegetable and animal origin, in forest litter/soil and trees, and in mushrooms consumed by the local population. The results of reconstructions of the external and internal doses received by inhabitants of contaminated areas during the period 1986–1995 and dose forecasts for 1996–2056 are presented. For most of the population, external irradiation due to ^{137}Cs will be the main contributor to the total future dose.

The report discusses the social and economic impact of the Chernobyl accident on the well-being of the people in the affected countries caused by reduced collective and private production and by trade restrictions due to the radioactive contamination of produce. Increased morbidity has been reported, attributable especially to thyroid cancer in children. The psychological state of people is characterized by high anxiety; the demographic situation is worsening because of the departure of young families. Radiation protection, medical services and economic aid are being provided and the affected areas are being rehabilitated through State programmes.

The conditions of exposure of and the radiobiological effects on flora and fauna in the near exclusion zone are described. Here, the doses reached 100 Gy, killing and damaging conifers, suppressing the reproductive ability of plants and animals, and causing molecular and cellular abnormalities in wild and domestic animals. A forecast of ecological changes in the exclusion zone is given for the next decade.

The report pays special attention to the experience of applying radiation protection measures in the post-accident period. Also, it presents the history of implementation of countermeasures at different stages: evacuation and resettlement; decontamination of land and buildings; restriction of access to severely contaminated areas; limitation of the consumption of contaminated food; and agricultural countermeasures. For some countermeasures, estimates of their cost-effectiveness are given.

The prospects for the economic and social rehabilitation of contaminated areas are considered. Since the need for agricultural countermeasures will continue for a long time and economic rehabilitation will require considerable investment, it is crucial to inform the population about current and likely future radiological conditions.

1. INTRODUCTION

1.1. Background

Over one decade after the Chernobyl accident, the levels of radioactive contamination[1] of the affected territories are generally well known. At the instigation of national and international organizations, pertinent scientific and technical studies have been undertaken in order to reach a better understanding of the circumstances of the accident, the behaviour of radioactive materials in different environmental media and the most efficient methods of decontamination. Radiation doses to the population have been, and continue to be, assessed.

In 1995, taking into account the completed and ongoing studies by other organizations as well as the results of the International Chernobyl Project completed in 1991, the IAEA formulated, in co-operation with the Institut de protection et de sûreté nucléaire (IPSN) in France, a project focusing on the environmental impact of the Chernobyl accident in the Russian Federation, Belarus and Ukraine.

1.2. Objective and scope

The project aimed to make the findings of the scientific studies comprehensible to and relevant for the decision makers who would form the target audience. Thus, the study focused on future environmental impact and was complementary to the other studies performed. It was a synthesis of available material and reports.

The questions to be addressed within the scope of the project were, for example, whether or not people could live safely in the areas studied, whether or not agriculture could be resumed and, if not, how and when safe living conditions could be restored in those areas. The effects of the remedial actions taken and the development of criteria for these actions internationally and in the three republics were described. Issues related to the preservation of the natural environment were also addressed.

The project concentrated on chronic exposure of the population, at the same time looking at particular areas, such as the exclusion zone, the Gomel region and part of the Bryansk region.

1.3. Structure

The project addressed four different but interrelated issues. The four main sections of the report (Sections 2–5) describe the issues.

Section 1 describes the situation as of 1996, and includes the mapping of deposited radioactive materials and quantification of the contamination, a prognosis of how and at what rate these levels will change in the future, and numerical estimates of the resulting exposure of the inhabitants, with and without countermeasures.

Section 2 describes living conditions in selected areas, where high unemployment and a lack of capital investment, and also the actions taken to manage the situation, have been obstacles to industrial and agricultural development.

---

[1] The word 'contamination' is used here to describe any level of artificially produced radionuclides, not associated necessarily with a 'hazard' to health. Any estimate of the potential detriment must be based on the actual level of contamination.

Section 3 reviews the effects on the natural environment in the more contaminated areas. Section 6 discusses possible remedial actions. The development, effects, cost and efficacy of such remedial actions as the resettlement of exposed people, the decontamination of urban sites, and the modification of forestry and agricultural practices are described in some detail.

The general conclusions drawn from each section complete the report.

Annex I defines the areas and zones discussed in the report.

Annex II reviews the international criteria for long term countermeasures.

2. CURRENT RADIOLOGICAL SITUATION AND PROGNOSIS FOR THE FUTURE

2.1. Soil contamination with radionuclides

2.1.1. Release of radionuclides and contamination of territories

As a result of the accident to Unit 4 of the Chernobyl nuclear power plant (NPP), the environment was contaminated with radioactive materials whose total activity amounted to approximately 12.5 EBq (1 EBq = 10^{18} Bq), including 6.5 EBq of noble gases. This is the sum, as of 26 April 1986, of all the radionuclides with a half-life of more than one day. Table I presents the assessment by different authors of the release of specific radionuclides [1–4]. It should be noted that the most recent estimates (columns [3] and [4] of Table I) give significantly different figures from the initial ones (column [1] of Table I), especially for iodine and caesium releases. The quantities of iodine and caesium radioisotopes released represent 50–60% and 30–35% respectively of the core inventory of these nuclides at the time of the accident.

Owing to the specific features of the accident (i.e. the long duration of the release of radioactive products into the atmosphere, the complex changes in physical and chemical makeup) and to the change in meteorological conditions, the local and distant contamination was non-uniform, not only in fallout density and radionuclide composition, but also in its physicochemical characteristics.

An analysis of meteorological conditions during the period of the most intense release of radioactive products (26 April–5 May 1986) has made it possible to establish that the radionuclide contamination on the territory of the Ukrainian and Belarus Polessye (the 'western trace') was mainly due to the release which took place on 26 and 27 April. The contamination of the eastern regions of Belarus and of the European part of the Russian Federation (the 'northeastern trace') was due to the release which occurred between 27 and 29 April. Air mass transfer towards the south, which began on 30 April, was responsible for contamination in Ukraine, through both the release of radioactive products which took place between 30 April and 5 May, and the return of air masses from Belarus and the Russian Federation contaminated by earlier releases [5–7].

The radioactive fallout in the Russian Federation, in much of Belarus and in the Ukrainian Polessye contained a larger proportion of volatile nuclides such as $^{103/106}$Ru, ^{131}I and $^{134/137}$Cs and for these territories, the ^{90}Sr/^{137}Cs ratio varied within the range 0.01–0.05. The contamination of the area of Ukraine south of the Chernobyl NPP contained non-volatile elements such as ^{95}Zr, ^{95}Nb, ^{141,144}Ce, and ^{140}La. The ^{90}Sr/^{137}Cs ratio varied in that area within the range 0.08–0.5. The pattern of contamination was mosaic-like, with high gradients of radionuclide concentration, usually due to rainfall coincident with the passage of the plume.

During the months immediately after the accident, the short-lived radionuclides were present mostly in soil deposition, among which ^{131}I had the greatest radiological significance. Figs 1 [5] and 2 [8] show the maps of ^{131}I deposition in Belarus and in part of the Russian Federation; these maps are deduced from comparison with ^{137}Cs deposition in the soil. The highest soil contamination by radioiodine has been estimated to exceed 18 500 kBq m^{-2} [9].

TABLE I. ASSESSMENT OF ACTIVITY OF RADIONUCLIDES RELEASED AS A RESULT OF THE CHERNOBYL ACCIDENT

Nuclide	Activity (PBq)		
	[1]*	[3]*	[4]*
^{85}Kr	$3.33.\ 10^{1}$	$3.33\ 10^{1}$	$3.3\ 10^{1}$
^{89}Sr	$9.25\ 10^{1}$	$8.14\ 10^{1}$	$8.1\ 10^{1}$
^{90}Sr	8.14	8.14	8.0
^{95}Zr	$1.55\ 10^{2}$	$1.67\ 10^{2}$	$1.7\ 10^{2}$
^{99}Mo	$1.37\ 10^{2}$	–	$2.1\ 10^{2}$
^{103}Ru	$1.41\ 10^{2}$	$1.7\ 10^{2}$	$1.7\ 10^{2}$
^{106}Ru	$5.92\ 10^{1}$	$2.96\ 10^{1}$	$3.0\ 10^{1}$
^{129m}Te	–	–	$2.4\ 10^{2}$
^{132}Te	$4.07\ 10^{2}$	$4.07\ 10^{2}$	$1.0\ 10^{3}$
^{131}I	$6.29\ 10^{2}$	$1.67\ 10^{3}$	$1.7\ 10^{3}$
^{133}Xe	$6.29.10^{3}$	$6.29\ 10^{3}$	$6.5\ 10^{3}$
^{134}Cs	$1.85\ 10^{1}$	$4.44\ 10^{1}$	$4.4\ 10^{1}$
^{137}Cs	$3.7\ 10^{1}$	$8.51\ 10^{1}$	$8.5\ 10^{1}$
^{140}Ba	$2.7\ 10^{2}$	$1.7\ 10^{2}$	$1.7\ 10^{2}$
^{141}Ce	$1.3\ 10^{2}$	$1.96\ 10^{2}$	$2.0\ 10^{2}$
^{144}Ce	$8.88\ 10^{1}$	$1.37\ 10^{2}$	$1.4\ 10^{2}$
^{239}Np	$8.51\ 10^{2}$	$1.67\ 10^{2}$	$1.7\ 10^{3}$
^{238}Pu	$2.96\ 10^{-2}$	$2.96\ 10^{-2}$	$3.0\ 10^{-2}$
^{239}Pu	$2.59\ 10^{-2}$	$2.96\ 10^{-2}$	$3.0\ 10^{-2}$
^{240}Pu	$3.7\ 10^{-2}$	$4.44\ 10^{-2}$	$4.4\ 10^{-2}$
^{241}Pu	$5.18\ 10^{0}$	5.96	5.9
^{242}Pu	$7.4\ 10^{-5}$	$8.51\ 10^{-5}$	$9.0\ 10^{-5}$
^{242}Cm	$7.77\ 10^{-1}$	$9.25\ 10^{-1}$	$9.3\ 10^{-1}$
Total	$9.35\ 10^{3}$	$9.66\ 10^{3}$	$1.25\ 10^{4}$

* The numbers in square brackets refer to references.

In the Russian Federation, the reconstruction of ^{131}I maps has been carried out by the statistical analysis of the results of gamma spectrometry of soil samples. Statistically significant regression relations between activities of ^{131}I and ^{137}Cs, depending on the distance between the point of the sample collection and the power plant, have been obtained for the northeastern trace [8]. In order to draw the ^{131}I deposition map in Belarus, the following data were used [5, 9]:

- direct gamma-spectrometry measurements of the ^{131}I content in soil samples for May–July 1986;
- gamma-spectrometry data of the ^{131}I content in samples of daily depositions;
- correlation between the ^{131}I and ^{137}Cs content in soil;
- assessment of the ^{131}I contribution to the gamma radiation dose rate in May 1986.

At a later stage, the radiological impact was mostly due to ^{134}Cs and ^{137}Cs deposited on land. Maps of the ^{137}Cs contamination of the three republics are shown in Figs 3, 4 [7], and 5 [6]. Table II shows the areas of land within the different radioactive contamination zones defined in the legislation of these countries.

TABLE II. AREA OF ^{137}CS CONTAMINATION OF THE TERRITORIES OF BELARUS, THE RUSSIAN FEDERATION AND UKRAINE AS OF 1 JANUARY 1995 (thousand km²)

Country	^{137}Cs soil deposition, kBq.m^{-2} (Ci.km^{-2})			
	37–185 (1–5)	185–55 (5–15)	555–1480 (15–40)	> 1480 (> 40)
Belarus	29.92	10.17	4.21	2.15
Russian Federation	48.8	5.72	2.1	0.31
Ukraine	37.21	3.18	0.88	0.57
Total	115.93	19.07	7.19	3.03

By way of illustration, Fig. 6 and Fig. 7 show estimates of the levels of contamination in Belarus by ^{90}Sr and $^{238-240}Pu$ respectively. On a large part of the State Polessye Radiological and Ecological Reserve, $^{238-240}Pu$ surface activity exceeded 3.7 kBq.m^{-2}. In the most contaminated regions of Russia, ^{90}Sr soil deposition varied from 0.4 to 70 kBq.m^{-2}, corresponding to 1–5% of the ^{137}Cs fallout. Compared with the exclusion zone, lower levels of soil contamination with $^{238-240}Pu$ were measured in southwestern parts of the Bryansk region (less than 0.7 kBq.m^{-2}) and in the Tula and Kaluga regions (less than 0.3 kBq.m^{-2}). In the Ukrainian exclusion zone, the level of soil deposition of ^{90}Sr in some areas exceeded 5000 kBq.m^{-2} and the soil deposition by $^{238-240}Pu$ exceeded 100 kBq.m^{-2}. In Ukraine, on about 27 600 km^2 ^{90}Sr contamination now exceeds 5 kBq.m^{-2} and on about 1000 km^2 it exceeds 111 kBq.m^{-2}.

After the evacuation of the population within the 30 km zone in April and early May 1986, the area closest to the reactor site (over 4000 km²) was excluded from cultivation. At present, this exclusion zone includes 2100 km² in Belarus (the Polessye Radiological and Ecological Reserve), 2040 km² in Ukraine (the Ukrainian exclusion zone) and 170 km² in the Russian Federation, which have the highest contamination levels. The deposition is largely characterized by ^{137}Cs, ^{90}Sr and the transuranium elements. About 95% of the radioactive contamination remains in the top 5–8 cm of the soil.

The principal physicochemical forms of the fallout are dispersed fuel particles, “condensation-generated” particles and mixed-type particles, including “adsorption-generated” ones. The narrow, clearly outlined, fork-shaped western trace of radioactive contamination, whose width at a distance of 13 km from the damaged reactor does not exceed 1.5 km, is characterized by the predominance of “fuel particles” over the “condensation-generated” ones, and by high contamination levels; along the axis of the western trace, the levels of ^{137}Cs activity exceed 75 000 kBq.m^{-2} [10]. The northern pattern of fallout is characterized by the fact that the contribution of the “condensation-generated” particles increases with distance from the reactor, until they become dominant at great distances from it.

Text cont. on page 11.

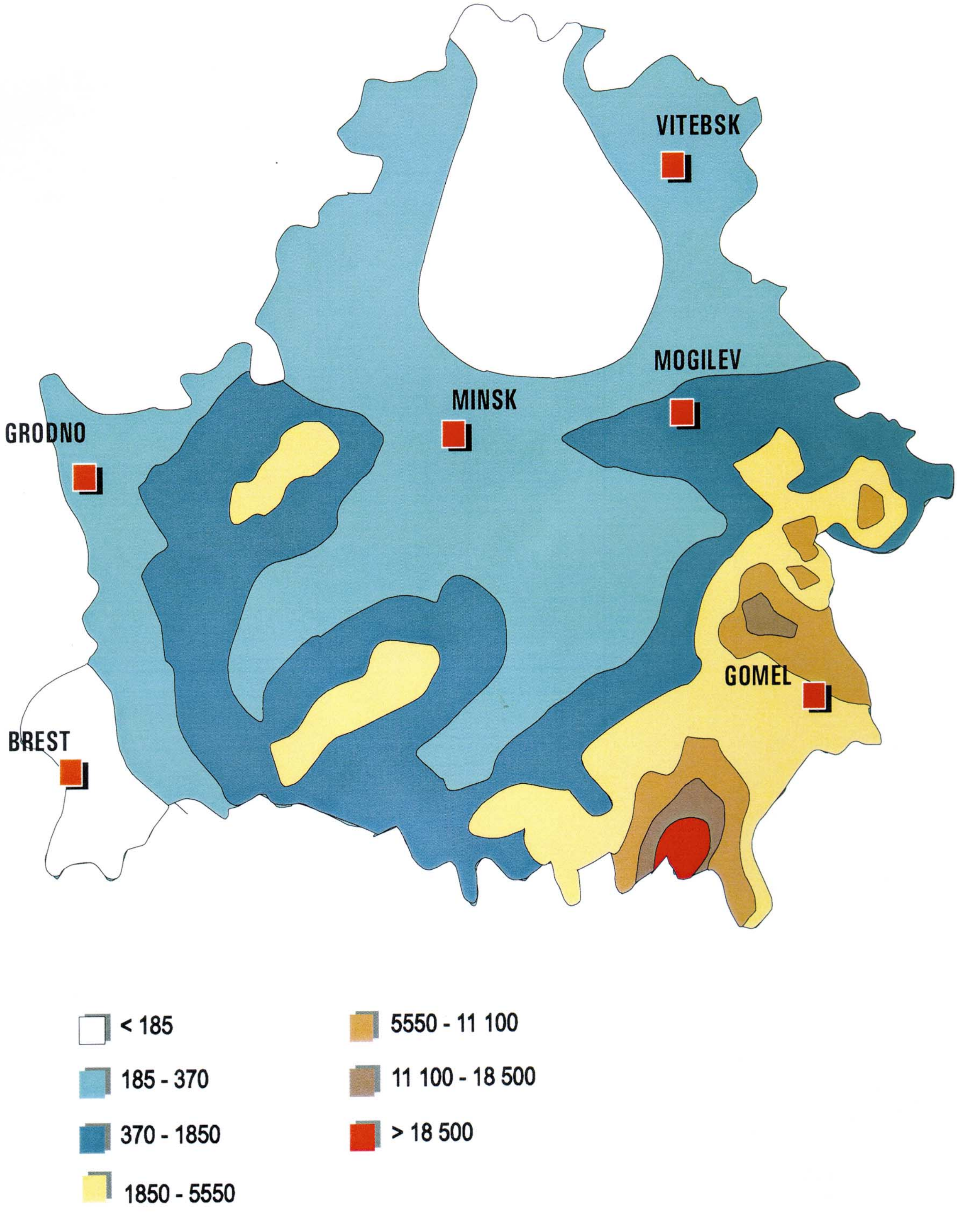


Fig. 1. Map of ^{131}I soil deposition in Belarus, as restored for May 10, 1986 (kBq.m^{-2}).

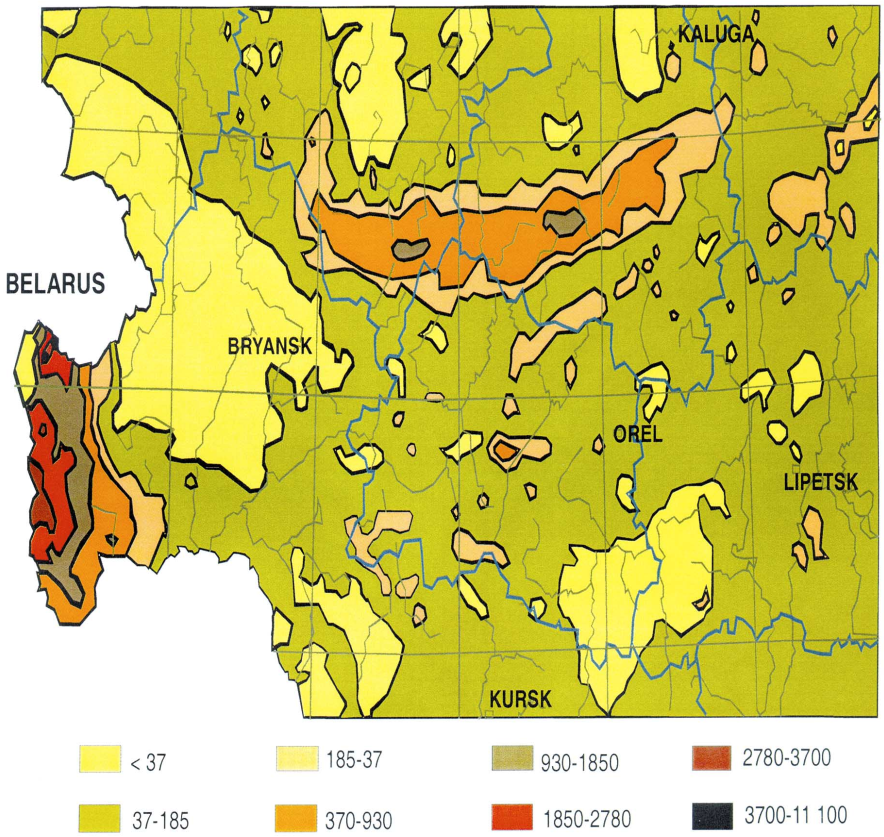


Fig. 2. Map of ^{131}I soil deposition in the West of the Russian Federation as restored for May 10, 1986 (kBq.m^{-2}).

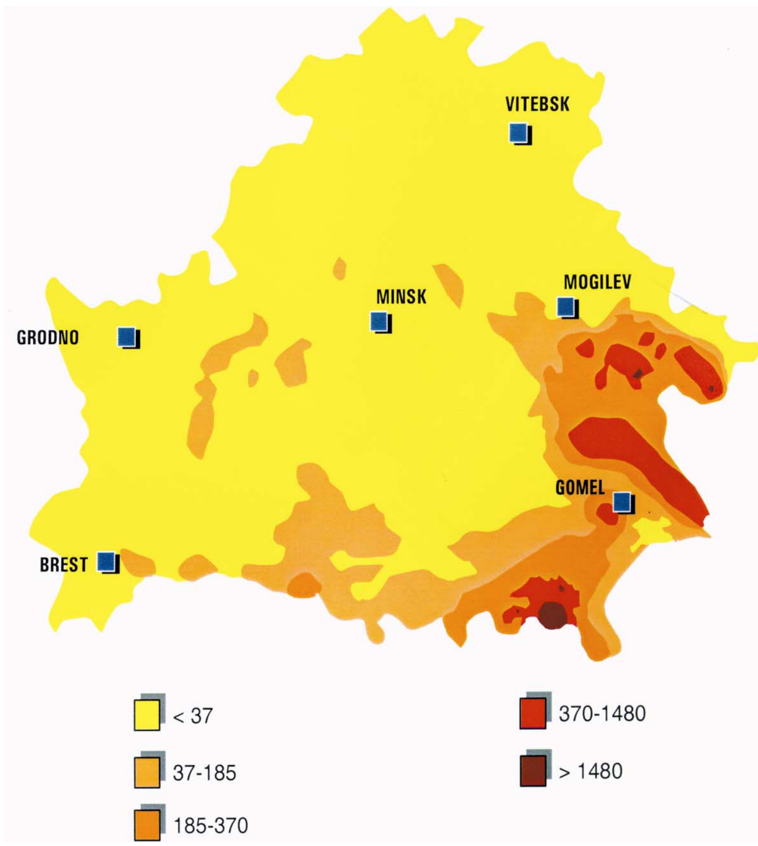


Fig. 3. Map of ^{137}Cs soil deposition in Belarus, as restored for January 1st, 1995 (kBq.m^{-2}).

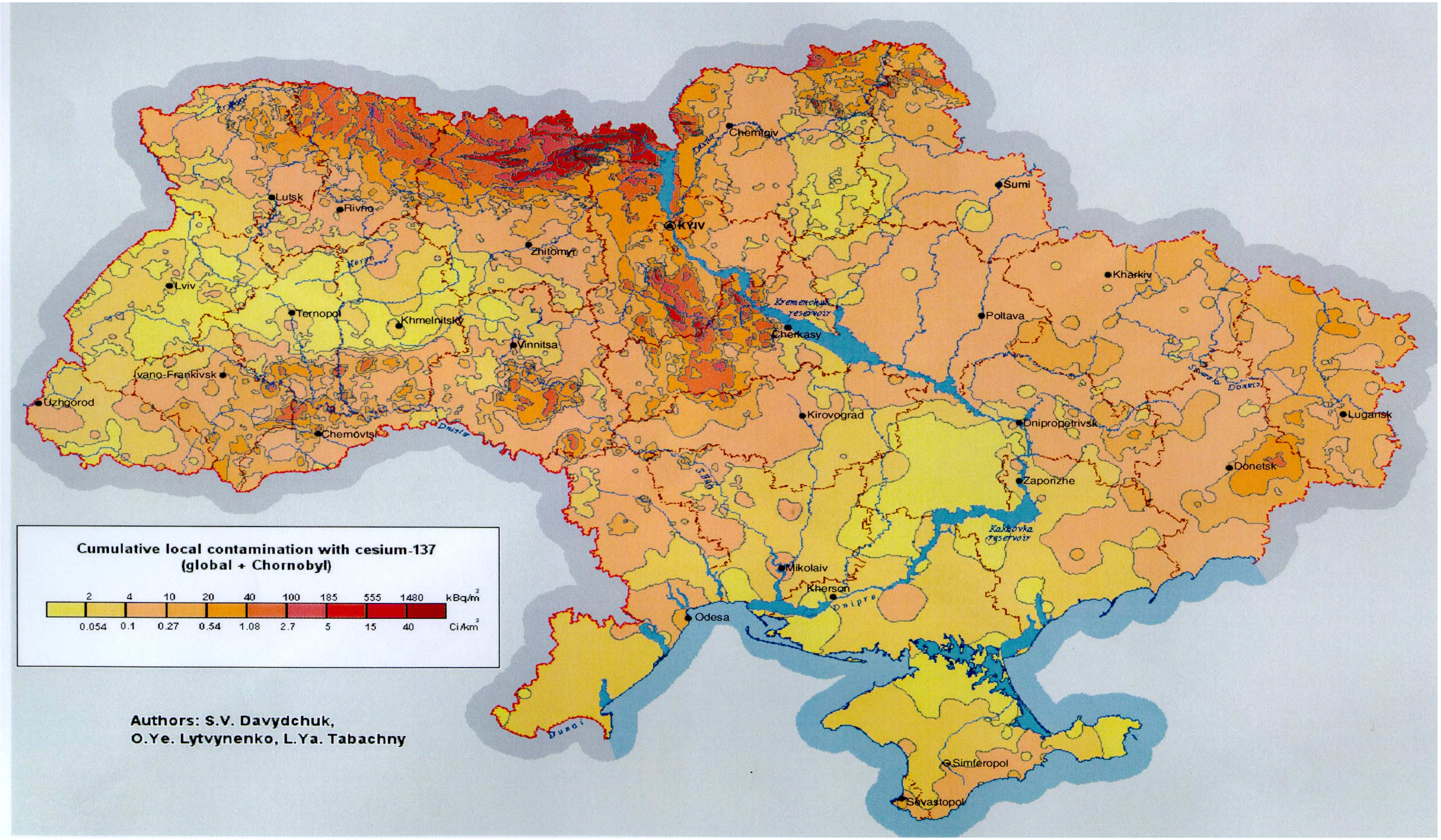


Fig. 4. Map of ^{137}*Cs soil deposition in Ukraine (kBq.m*$^{-2}$*) [7].*

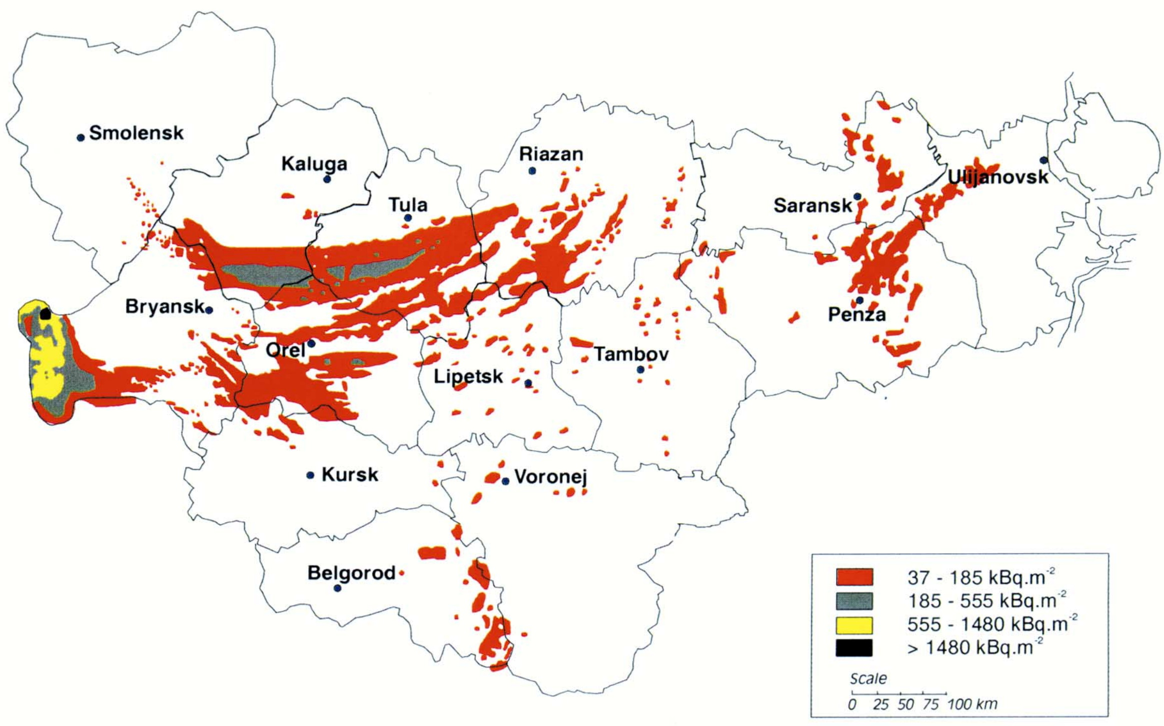


Fig. 5. Map of ^{137}Cs soil deposition in the west of the Russian Federation [6].

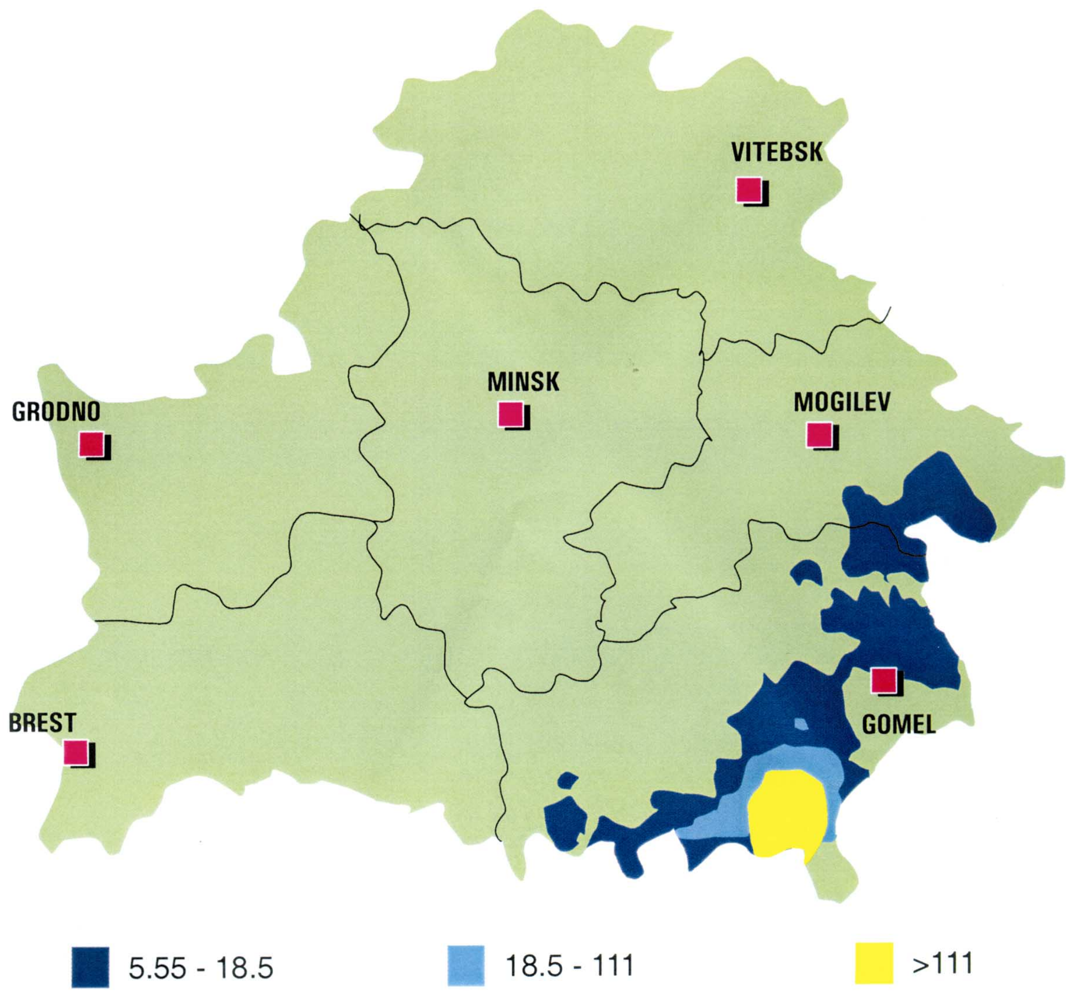


Fig. 6. Map of ^{90}Sr soil deposition in Belarus, as restored for January 1st, 1995 (kBq.m^{-2}).

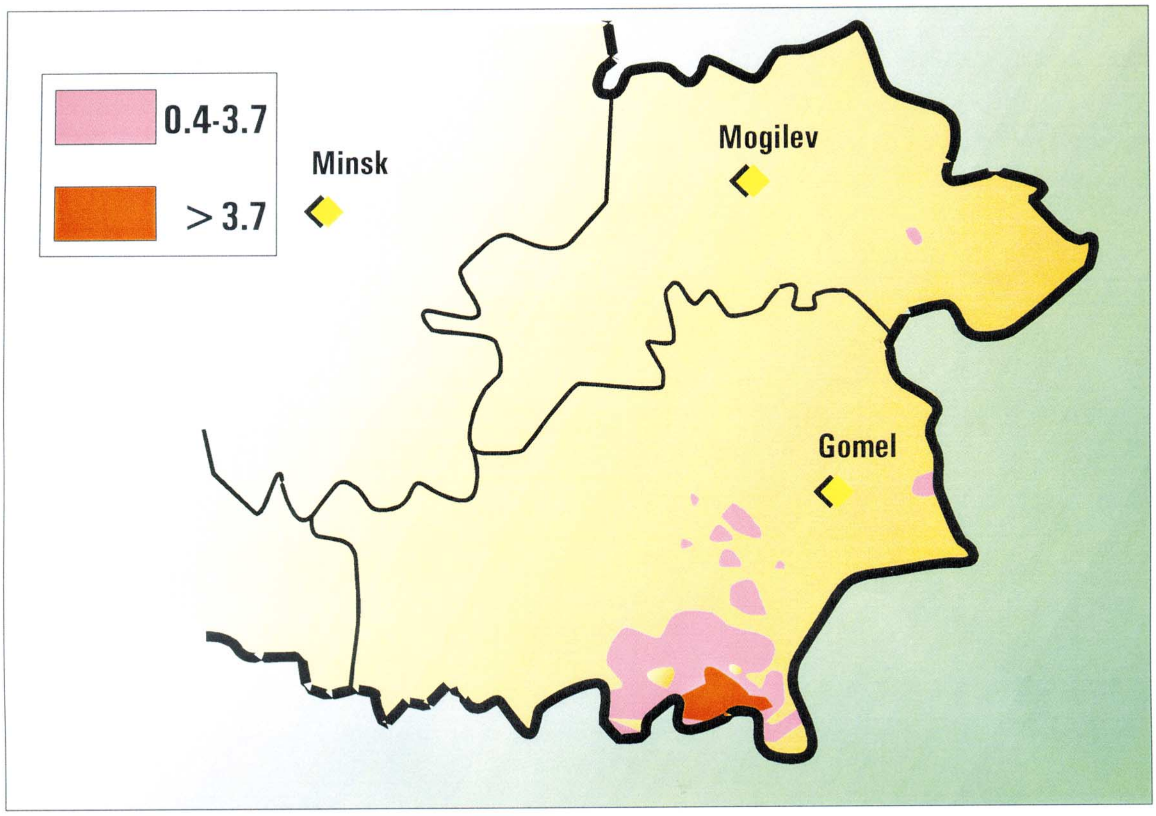


Fig. 7. Map of $^{238-240}$Pu soil deposition in Belarus, as restored for January 1st, 1995 (kBq.m^{-2}).

More than 70% of the exclusion zone is contaminated with over 500 kBq.m^{-2} of ^{137}Cs, over 100 kBq.m^{-2} of ^{90}Sr, and over 3 kBq.m^{-2} of $^{239/240}$Pu. The deposition of radioactive material was most widespread in Belarus, where 23% of the land, populated by 2.2 million people (over one fifth of the total population of Belarus), has sustained radioactive contamination of over 37 kBq m^{-2} of ^{137}Cs. In Ukraine, the areas classified as radioactive contamination zones are inhabited by over 2.4 million people, and in the Russian Federation by 2.6 million people.

Waste sites are mostly located in Ukrainian exclusion zone. According to recent assessments, the shelter contains about 180 tonnes of nuclear fuel with radioactivity exceeding 740 PBq (20 MCi) [11]. The 1996 National Report of Ukraine [12] states that this radioactivity includes 229 PBq (6.2 MCi) of $^{134+137}$Cs, 122 PBq (3.3 MCi) of Pu, 7.4 PBq (0.2 MCi) of ^{241}Am, 52 TBq (1.4 kCi) of ^{14}C and 7.4 PBq (0.2 MCi) of ^{60}Co. The shelter also serves to store large quantities of radioactive products comprising the remains of the damaged reactor, such as graphite and other contaminated material. The radioactive waste burial sites, created during emergency and decontamination activities, and other temporary waste burial sites, contain radioactive products whose total activity amounts to 15 PBq and whose volume is approximately 1 000 000 m^3 [12]. Eight hundred temporary radioactive waste burial sites for contaminated structures are distributed in the vicinity of the damaged reactor.

2.1.2. Vertical migration of radionuclides in the soil

The rate of radionuclide migration in the soil-plant system is determined by a number of natural phenomena, including relief features, type of vegetation, structure and properties of the soil, hydrological and weather conditions, and physical and chemical characteristics of the radionuclides and their isotope carriers in the soil [13–16]. Agricultural practices and other factors have an 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. The system of soil improvement measures which has been implemented also has an impact on the physicochemical state and on the mobility of radionuclides [14, 17–19].

The vertical migration of ^{90}Sr and ^{137}Cs in the soil of different types of natural meadows has been rather slow, and most of the radionuclides are still contained in its upper layer (0–10 cm). However, the type of vertical radionuclide migration depends on the type of meadow, its drainage and soil features. The ^{90}Sr and ^{137}Cs migration rates are significantly slower in dry meadows than in wetlands. In peaty soils, radionuclide migration is faster: eight years after the accident, the maximum radionuclide concentration was measured at a depth of 3–5 cm. In such soils, the characteristic radionuclide distribution is determined not only by their migration into deeper soil layers but also by the increasing amount of dead vegetable biomass in the upper layer of the soil. “Chernobyl-originated” ^{90}Sr and ^{137}Cs in peaty soils may be detected even at a depth of 20 cm. On average, in the case of peat soils, 40–70% of the ^{90}Sr and ^{137}Cs is found in the 0–5 cm layer; in the case of mineral soils, up to 90% of the ^{90}Sr and ^{137}Cs is found in this layer. Fig. 8 shows profiles of ^{90}Sr and ^{137}Cs vertical distribution in the Chernigov region which are typical for the soddy-podzolic soils prevailing in the contaminated territories of the polessye. The most important characteristics of soil which influence the migration of radionuclides are the mineral and physical composition of the soil, its organic composition, its cation exchange capacity and its acidity [13, 15, 16, 20].

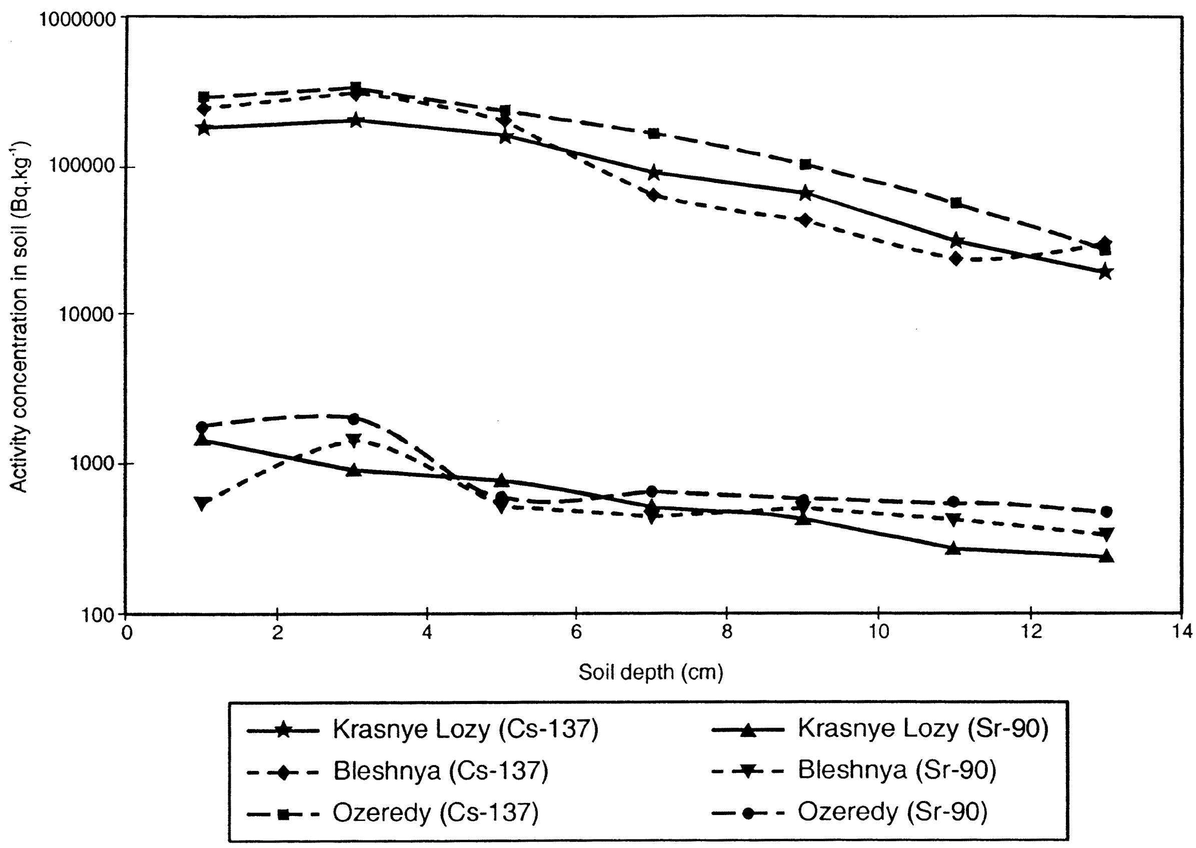


Fig. 8. Depth distribution of ^{137}Cs and ^{90}Sr in undisturbed soddy-podzolic soils in the Chernigov region, Ukraine, 1994.

Calculations carried out with a two-component convection-diffusion model [14] show that in dry meadows, the migration velocity of ^{137}Cs for the “slow” component varies from 0.015 to 0.62 cm, and for the “fast” component, from 0.09 to 1.39 cm per year. These velocities for wetlands and low-lying meadows range from 0.014 to 0.108 cm for the “slow” component and from 0.15 to 0.71 cm per year for the “fast” one. The highest migration velocities have been found in peaty soils, from 0.097 to 0.46 cm for the "slow" component and from 0.40 to 1.28 cm per year for the “fast” component.

It has also been established that migration velocity decreases with time. Thus, for the “fast” component, diffusion coefficients have decreased between 1986 and 1994 by a factor of 1.5–6.0. The same behaviour has been demonstrated for ^{90}Sr, but the quantitative parameters for ^{90}Sr migration are 1.5–5.0 times higher than the corresponding parameters for ^{137}Cs migration.

This can be summarized in terms of the root-layer effective clearance half-life. The effective clearance half-life for ^{137}Cs varies from 10 to 25 years for the 0–10 cm mineral soil layer [13, 14]. Generally, the processes of soil ^{90}Sr clearance are 1.2–3.0 times faster than those of ^{137}Cs. Hence, the effective clearance half-life for ^{90}Sr is estimated to be 7 to 12 years [13, 14].

2.1.3. Radioactive contamination of water bodies

The initial contamination of water systems was due to primary aerosol fallout during the passage of contaminated air masses. During the first post-accident days, the maximum concentrations in the Pripyat river estuary amounted to 3000 $Bq.L^{-1}$ of β-emitters [21]. During May and June, the radionuclide content of surface water decreased markedly and by July 1986, it amounted to 4–7 $Bq.L^{-1}$ in the Dnieper river near Kiev [21]. Regular monitoring data show a steady time-dependent decrease in the radionuclide content of water bodies. During the spring run-off and rainstorm floods, the radionuclide activity increases by up to four times in the rivers whose main drainage basins are situated within the most contaminated areas. Table III shows the dynamics of radioactive water contamination (average annual concentration) in the Pripyat river and the Chernobyl cooling pond, which are the principal water bodies in the exclusion zone.

In 1990–1994, the annual releases into the Kiev water reservoir amounted to 6–9 TBq for ^{137}Cs and 15–20 TBq (1TBq = 10^{12} Bq) for ^{90}Sr, with an equal contribution from the Dnieper and Pripyat rivers for ^{137}Cs, and a greater contribution from the Pripyat river for ^{90}Sr. Over 60% of the Pripyat ^{90}Sr outflow and 20% of the Pripyat ^{137}Cs outflow were formed in the exclusion zones of Belarus and Ukraine. Data on the average annual water flow of the river Pripyat and on the average annual release of ^{90}Sr and ^{137}Cs in the Kiev reservoir during 1986–1994 are shown in Table IV.

Between 10% and 40% of the total ^{137}Cs activity in water was transported on suspended solids. During a flood period, not only was there an increase in the total ^{137}Cs transport, but the suspended solid fraction of ^{137}Cs increased as well by as much as 80%. Radionuclide activity was most frequently associated with a suspended grain size of less than 0.2 μm of clay minerals. However, occasionally up to 60–70% of the activity was related to more coarse fractions. Unlike ^{137}Cs, the majority of ^{90}Sr (50–99%) migrated in solution, mainly as cations, but also as soluble complex compounds with organic matter.

TABLE III. AVERAGE ANNUAL CONCENTRATION (kBq.m^{-3}) IN THE RIVER PRIPYAT AND THE COOLING POND OF THE CHERNOBYL NUCLEAR POWER PLANT [21]

Year	Pripyat river (city of Chernobyl)		Cooling pond of the Chernobyl nuclear power plant	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
1986	22	1.9		
1987	3	2.2	70	7.4
1988	0.9	0.7	32	16
1989	0.4	0.8	21	16
1990	0.3	1.0	12	8.5
1991	0.4	1.3	8.9	7.0
1992	0.2	0.6	7.0	5.6
1993	0.2	0.8	6.3	4.4
1994	0.2	0.9	5.2	3.5
1995	0.1	0.3	5.3	3.7

TABLE IV. ^{90}Sr AND ^{137}Cs RELEASE FROM THE RIVER PRIPYAT INTO THE KIEV RESERVOIR DURING 1986–1994 [21]

Year	Average annual flow rate (m^3.s^{-1})	Annual release (TBq)		Radionuclide concentration (kBq.m^{-3})	
		^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
1986	302	66	27.6	6.9	2.9
1987	247	12.7	10.4	1.6	1.3
1988	411	9.5	18.7	0.7	1.4
1989	392	6.4	8.9	0.5	0.7
1990	409	4.6	10.1	0.4	0.8
1991	442	2.9	14.4	0.2	1.0
1992	295	1.9	4.1	0.2	0.4
1993	598	3.9	15.7	0.2	0.8
1994	478	3.0	14.1	0.2	0.9

As release of radionuclides from the upper soil layer by washout from thawing snow, rain and flood water decreased, the contribution of radioactive release with the groundwater into the rivers had a tendency to increase. The contribution of drainage water coming from the cooling pond into the Pripyat river accounted for up to 20% of ^{90}Sr contamination from within the exclusion zone.

As a general rule, bottom deposits and bank deposition in the Sozh, Dnieper and Pripyat rivers contained $^{134,137}Cs$, ^{90}Sr, $^{238,239,240}Pu$, and ^{241}Am. ^{137}Cs contributed most (up to 80%) of the current total activity of bottom deposits.

The activity concentrations in river sediment deposits were highest in the sludgy deposits and lowest in the coarse-grained and medium-grained deposits on the river bed. The ^{137}Cs content in deposits in the Pripyat river amounted to 400–20 000 $Bq.kg^{-1}$ in suspended sediments, 20–550 $Bq.kg^{-1}$ in river banks and 12–250 $Bq.kg^{-1}$ in bed sediments. The ^{90}Sr activity in river deposits varied from 2–66 $Bq.kg^{-1}$ (bank and river bed deposits) to 400–4200 $Bq.kg^{-1}$ (sludgy deposits). The activity of α-emitters in river bottom deposits was lower than in the drainage area soil cover but higher than in river waters (^{238}Pu 0.05–9.0 $Bq.kg^{-1}$; $^{239–240}Pu$ 0.1–28 $Bq.kg^{-1}$, ^{241}Am 0.07–16 $Bq.kg^{-1}$).

The activity concentration of radionuclides was higher in the bottom deposits than in water organisms, and concentrations in water (including suspensions and dissolved forms) were lower than those in deposits and in organisms.

2.2. Radioactive contamination affecting agriculture

Restoration of agricultural production in the contaminated areas forms an essential part of the process of reclaiming them and ensuring safe living conditions. The development of systems of management of agricultural and food production in these areas must be based on the analysis of the radiological status and the assessment of its future possible changes. Such an assessment may be derived from generalized data on levels of contamination, on the scope of protective measures and the impact of their implementation, on the dynamics of agricultural product contamination, and on the influence of natural biochemical processes in reducing the movement of radionuclides into the food chain [14, 15, 22].

2.2.1. Soil-to-plant transfer

When implementing measures for mitigating the accident consequences and for rehabilitating the contaminated territories, it is important to take into account the availability of radionuclides to plants and their interaction with soil constituents. These factors determine the transfer rate of radionuclides into food chains [15].

The available fraction of radionuclides in the soil for root uptake is determined by two parameters: the radionuclide content in exchangeable form and in mobile form on the one hand, and the value of the soil-to-plant transfer coefficient of ^{137}Cs on the other. These parameters make it possible to correlate the radionuclide concentration in plants with the soil contamination per unit area. As a result of alteration in its non-exchangeable state, the quantity of ^{137}Cs desorbed from samples of the soil into 1M KCl solution decreased by a factor of three between 1987 and 1992. The availability of ^{137}Cs for plants is not high: in 1994, it was responsible for 5–29% of the total ^{137}Cs activity in the soil [23]. The availability of ^{90}Sr for plants is characterized by the prevalence of easily mobile forms (exchangeable and water-soluble substances) which account for 50–90% of the total ^{90}Sr content. From 1996, the plant uptake of ^{90}Sr continued to increase [20, 23, 24].

On the territory of the Russian Federation, the “condensation-generated” type of fallout predominated. In 1986, the content of ^{137}Cs exchangeable forms in the soil was higher than in subsequent years, and varied from 15 to 55%. Due to sorption processes in soil particles since

1986, the current content of ^{137}Cs exchangeable forms is 3–5 times lower than immediately after the accident, and the content of its mobile forms (i.e. that displaced by 1N HCl) 1–4 times lower. The dynamics of ^{137}Cs forms depends on soil properties. The sorption of this radionuclide has a higher rate in automorphic soils normally moisturized by atmospheric condensation: the content of ^{137}Cs exchangeable forms in automorphic soils was 1–10 times lower than in constantly overmoisturized hydromorphic soils [14]. Generally, the content of ^{137}Cs acid-soluble forms is higher in hydromorphic soils [16].

During the first post-accident year, the ^{137}Cs content in plants was determined by aerial contamination and reached its maximum value. During the second post-accident year (1987), the ^{137}Cs content in the plants dropped by a factor of 3–6 as a result of the prevalence of root uptake over other routes of ^{137}Cs uptake by plants. Since 1987, the transfer rate of ^{137}Cs to plants has continued to decrease, although the rate of decrease has slowed: within the past eight years, the transfer coefficients of ^{137}Cs decreased on average by a factor of 1.5–7.0.

Beginning in 1989, the soil-to-plant transfer coefficients of ^{137}Cs showed a tendency to stabilize. The differences in radionuclide accumulation in the plants were mainly determined by different soil properties. The accumulation in herbiage of ^{137}Cs from soddy-podzolic and sod soils was 1.2–3.2 times lower than from the soddy-gley and soddy-gley peat ones (Gley is water-logged grey clay soil). The maximum values of the transfer coefficient for ^{137}Cs were found in peat-boggy soils. These values were 1.5–6.0 times higher than in automorphic soils [24, 25].

In order to predict future radioecological conditions, it is necessary to determine the duration of the period after which a relative stabilization may be expected in the soil-to-plant transfer of ^{137}Cs. Both for automorphic and hydromorphic soils, two periods may be distinguished, 1986–1989 and 1989–1994, when the change in the concentration of ^{137}Cs in exchangeable and mobile forms proceeded with different intensities. Despite the significant variability of experimental data, the integral parameters characteristic for the ^{137}Cs sorption in the soil during these periods could be approximately evaluated [19].

The first effective clearance half-life (1986–1989) related to exchangeable ^{137}Cs was approximately three years; the second one (1989–1994) approximately 12 years. These estimates are based upon the following observations [26]:

(a) For natural herbage of dry meadows in areas of soluble aerosol fallout, the first clearance half-life (1986–1989) of exchangeable ^{137}Cs was determined to be approximately two years, and the second one (1989–1994) approximately 4–12 years; and

(b) The effective clearance half-life also depends on the type of meadow and the soil properties. For dry meadows on soils with heavy physical composition and for lowland meadows on peat soils, the first clearance half-life (1986–1989) of the exchangeable ^{137}Cs was shorter and the second one (1989–1994) two to three times longer than for dry meadows on soils with lighter physical composition.

The higher caesium uptake from peaty soil is important because such soils underlie natural unmanaged grassland used for cattle grazing and hay production. The radical improvement of such lands has been a major factor in the reduction of radiocaesium concentration in milk [25, 26].

The level of radioactive contamination of agricultural products also depends on soil properties. The transfer coefficients of radionuclides into plants growing on soddy-podzolic loamy soils are one to three times lower than the same coefficients for soddy-podzolic sandstone soils. The agrochemical properties of soils, which determine their level of fertility, also have an important influence on radionuclide accumulation in agricultural crops. For instance, an increase in the content of humus in the soddy-podzolic soils of Belarus from 1% to 3% has resulted in a decrease in the level of ^{137}Cs contamination of perennial grasses by a factor of 1.7, and of ^{90}Sr contamination by a factor of 1.9 (Fig. 9). The use of organic fertilizers has increased the agricultural crop harvest and slightly reduced the soil-to-plant transfer of radionuclides (by 15–20%) [20, 25].

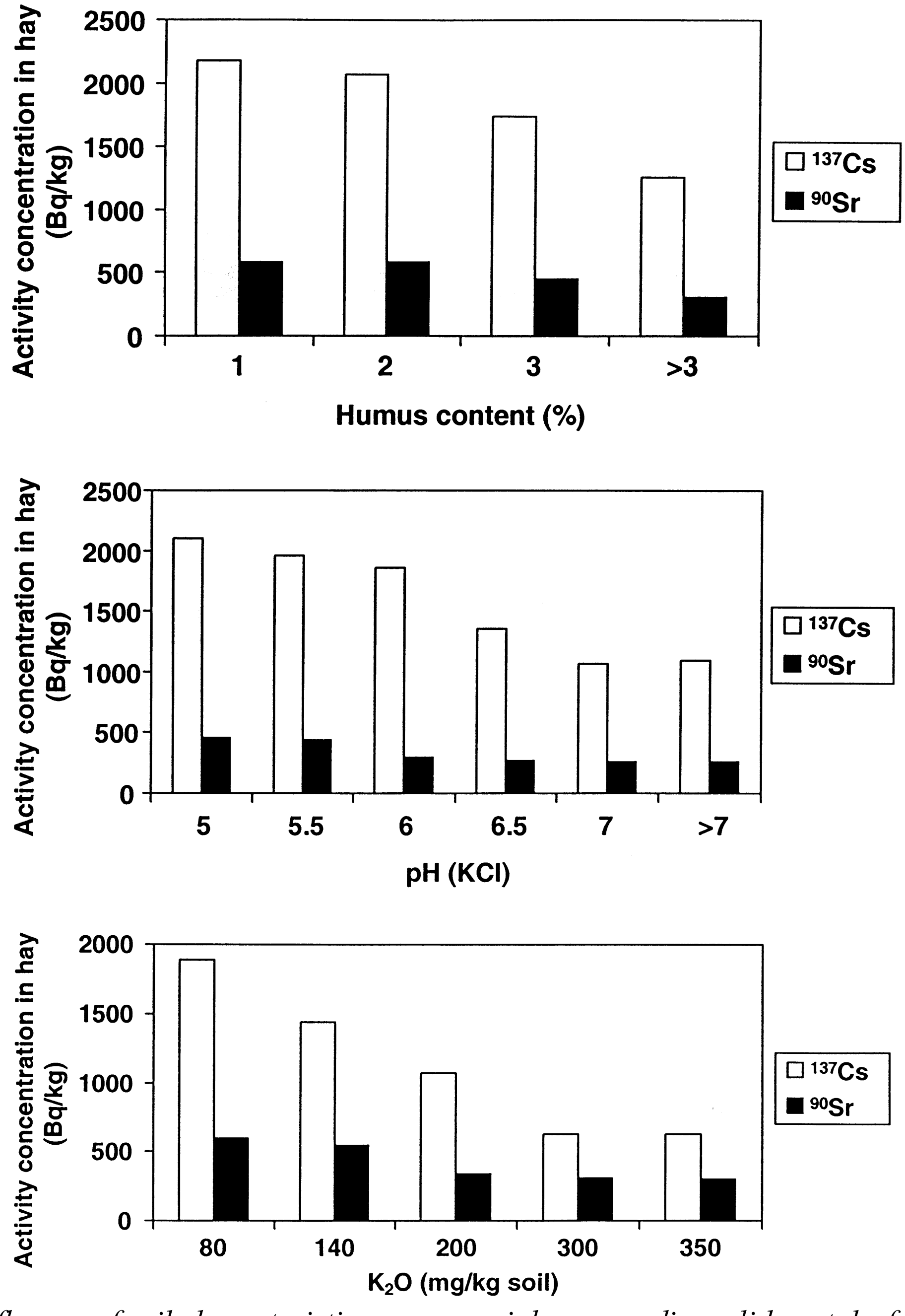


Fig. 9. Influence of soil characteristics on perennial grass radionuclide uptake from soddy-podzolic loamy sand soil related to a deposition of 370 kBq/m² ^{137}Cs and of 37 kBq/m² ^{90}Sr.

By increasing the content of exchangeable potassium in the soil to optimal values, (200–300 mg of K_2O per kg for sandy and loamy soddy-podzolic soils), a drop in the ^{137}Cs transfer into perennial grasses by a factor of three can be achieved, and in the ^{90}Sr transfer, by a factor of up to 1.5–1.8 (Fig. 9). The increased use of potassium fertilizers on soils with low and medium content of exchangeable potassium leads to a drop in the ^{137}Cs transfer from the soil into agricultural crops by a factor of 1.3–2 [27]. The influence of phosphorous fertilizers is lower, but they also reduce radionuclide contamination of plants. The traditional approach of soil liming makes it possible to reduce the acidity of soddy-podzolic soils from pH5.0 to pH6.0–6.5, and to reduce the ^{137}Cs and ^{90}Sr contamination in crops by a factor of two (Fig. 9).

In the case of highly-acidic soils (pH4.0–4.5), liming may reduce radionuclide transfer by a factor of up to three. The soil humidity has an even more important influence on these processes. The ^{137}Cs contamination of perennial grasses on soddy-podzolic and sod automorphic soils with a normal degree of humidity is some 10–27 times lower than on gley soils with a permanently increased degree of humidity. The transfer coefficients for ^{90}Sr are also up to two times lower in normally humid soils than in excessively humid ones, although the difference is less significant [20, 27].

Therefore, the improvement of soddy-podzolic soils through the complex use of organic fertilizers, liming and high doses of potassium and phosphorous fertilizers makes it possible to reduce the ^{137}Cs contamination of agricultural crops by a factor of 4–6 and, when accompanied by irrigation control, by a factor of up to 10.

The results obtained make it possible to conclude that, five years after the Chernobyl accident, the ^{137}Cs soil-to-plant transfer had become stable, and marked the completion of the period of quasi-non-equilibrium increase in the stability of ^{137}Cs sorption in the soil solid phase. The process of radionuclide trapping in the soil slows down with time. The main mechanism of durable radionuclide trapping in the soil is its inclusion into the crystal lattice of clay minerals. The subsequent decrease in the ^{137}Cs transfer into plants will occur at a slower rate [22].

2.2.2. Levels of contamination in agricultural products

Radionuclide concentrations in both vegetable and animal agricultural food products presented below are compared with national standards. National regulations for temporary permissible levels in drinking water and food products are indicated in Table V for the former USSR (1986–1991), in Tables VI and VII for Belarus (adopted in 1992), and in Table VIII for the Russian Federation (adopted in 1993).

It should be noted that, due to the extensive implementation of protective measures in animal production, only a small quantity of milk was produced with ^{137}Cs content above the permissible levels. The distribution of settlements according to mean ^{137}Cs activity concentration in milk in Ukraine is shown in Fig. 10 and the changes with time in ^{137}Cs content in milk from contaminated regions of the Russian Federation are shown in Fig. 11.

TABLE V. TEMPORARY PERMISSIBLE LEVELS (TPLs) IN DRINKING WATER AND FOOD PRODUCTS ($Bq.L^{-1}$ or $Bq.kg^{-1}$). USSR REGULATIONS

Product	06/05/86*	30/05/86**	15/12/87***	22/01/91
Drinking water	3700	370	20	20
Milk	3700	370	370	370
Condensed milk	–	18500	1110	1110
Dried milk	–	3700	1850	1850
Curds	37000	370	370	370
Sour cream	18500	3700	370	370
Vegetable oil	–	7400	370	185
Margarine	–	7400	370	185
Animal fat	–	–	370	185
Cheese	74000	7400	370	370
Butter	74000	7400	1110	370
Meat, meat products	–	3700	1850	740
Meat (beef)	–	–	2960	740
Meat (pork, mutton)	–	–	1850	740
Poultry	–	3700	1850	740
Egg	–	1850	1850	740
Fish	37000	3700	1850	740
Vegetables	–	3700	740	600
Leafy vegetables	37000	3700	740	600
Root vegetables	–	–	740	600
Potatoes	–	3700	740	600
Fruits berries (fresh)	–	3700	740	600
Fruit, berries (dried)	–	3700	1110	2900
Juice	–	3700	740	–
Jam	–	–	740	–
Grain, flour, cereals	–	370	370	370
Bread, bread products	–	370	370	370
Sugar	–	1850	370	370
Mushrooms	–	18500	1850	1480
Mushrooms (dried)	–	–	11100	7400
Wild growing berries	–	–	1850	1480
Tinned food (vegetables, fruit)	–	–	740	600
Honey	–	–	740	600
Herbs	–	18500	–	7400
Baby food	–	–	370	185

* The TPL dated 6 May 1986 limited ^{131}I concentration in food (based on a permissible thyroid dose in children of 0.3 Gy).

** The TPL dated 30 May 1986 limited the total beta activity in food (based on a permissible annual internal dose of 50 mS or 5 rem).

*** The TPL dated 15 December 1987 and later limited the content of caesium radionuclides in food.

TABLE VI. TEMPORARY PERMISSIBLE LEVELS (TPLs) FOR CAESIUM RADIONUCLIDES IN DRINKING WATER AND FOOD PRODUCTS ($Bq.L^{-1}$ or $Bq.kg^{-1}$). BELARUS REGULATIONS, 1992

Product	TPL ($Bq.L^{-1}$ or $Bq.kg^{-1}$)
Drinking water	18,5
Milk and other dairy products	111
Dried milk	740
Meat and meat products	600
Potatoes and tubers	370
Bread and bread products	185
Flour, cereals, sugar and honey	370
Vegetable oil, animal fat, margarine	185
Vegetable, garden fruit and berries, wild berries	185
Tinned garden vegetables, fruit and berries	185
Dried mushrooms	3700
Baby food	37
Other food	370

TABLE VII. TEMPORARY PERMISSIBLE LEVELS (TPLs) IN RAW PRODUCTS AND FOOD FOR CAESIUM RADIONUCLIDES AND ^{90}Sr. BELARUS REPUBLIC, 1992

Products	TPL	
	^{137}Cs ($Bq.kg^{-1}$)	^{90}Sr ($Bq.kg^{-1}$)
Milk	370	18
Meat	600	–
Vegetable raw products (fruit, vegetables)	370	–
Grain	600	11
Grain for baby food	55	3.7
Other raw products	370	–

TABLE VIII. TEMPORARY PERMISSIBLE LEVELS (TPLs) FOR CAESIUM RADIONUCLIDES AND ^{90}Sr IN FOODSTUFFS ($Bq.L^{-1}$ or $Bq.kg^{-1}$). RUSSIAN REGULATIONS, 1993

Products	TPL ($Bq.L^{-1}$ or $Bq.kg^{-1}$)	
	^{137}Cs	^{90}Sr
Milk, curd, sour cream, vegetable oil, margarine, animal fat, cheese, butter, grain, flour, cereals, bread, bread products, sugar	370	37
Baby food	185	3.7
Other	600	100

TABLE IX. THE RADIONUCLIDE CONCENTRATION IN SOME FRESH AGRICULTURAL PRODUCTS ON THE TERRITORY OF THE VILLAGE OF STAROYE SELO, ROVNO REGION, UKRAINE (1994) [12]

Product	^{137}Cs Concentration (Bq.kg^{-1})			^{90}Sr Concentration (Bq.kg^{-1})			^{137}Cs Transfer coefficient (Bq.kg^{-1})/(kBq.m^{-2})			^{90}Sr Transfer coefficient (Bq.kg^{-1})/(kBq.m^{-2})		
	min.	avg.	max.	min.	avg.	max.	min.	avg.	max.	min.	avg.	max.
Potato	92	128	188	5	7	9	0.3	0.8	1.1	1.0	1.8	3.9
Garden beet	24	47	72	0.7	1	1.5	0.09	0.32	0.71	0.12	0.33	0.80
Beetroot	8	25	48	0.4	1	1.5	0.05	0.15	0.28	0.13	0.22	0.28
Hay	4033	8391	15910	15	18	26	17	57	156	2.7	5.1	13.4

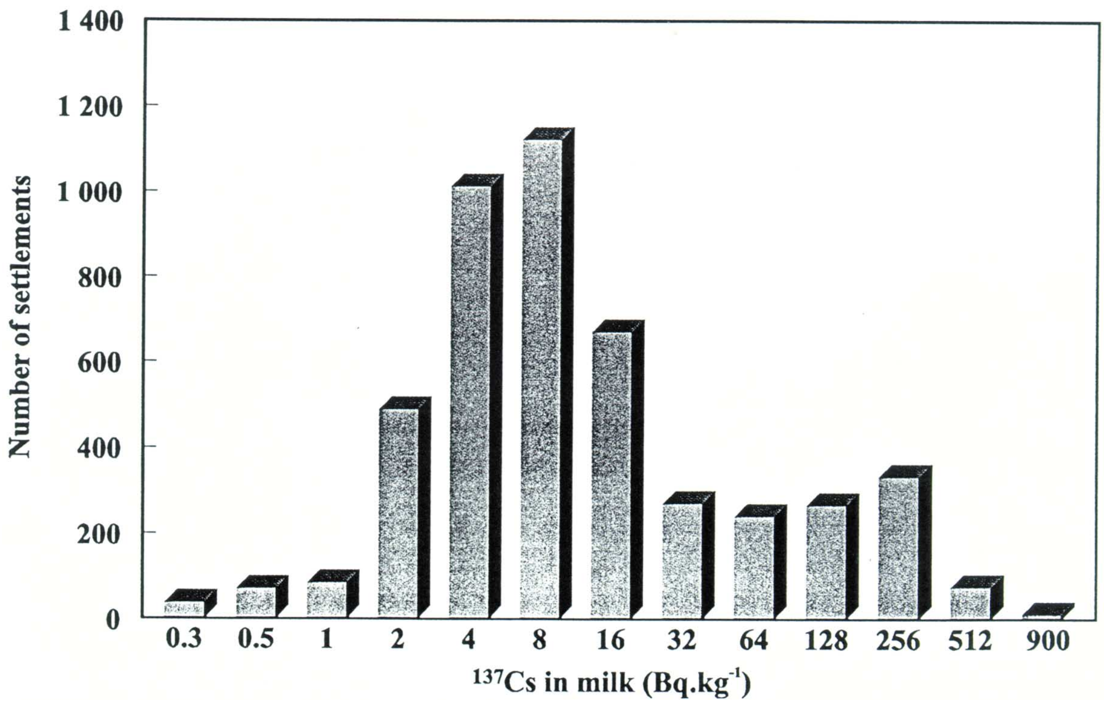
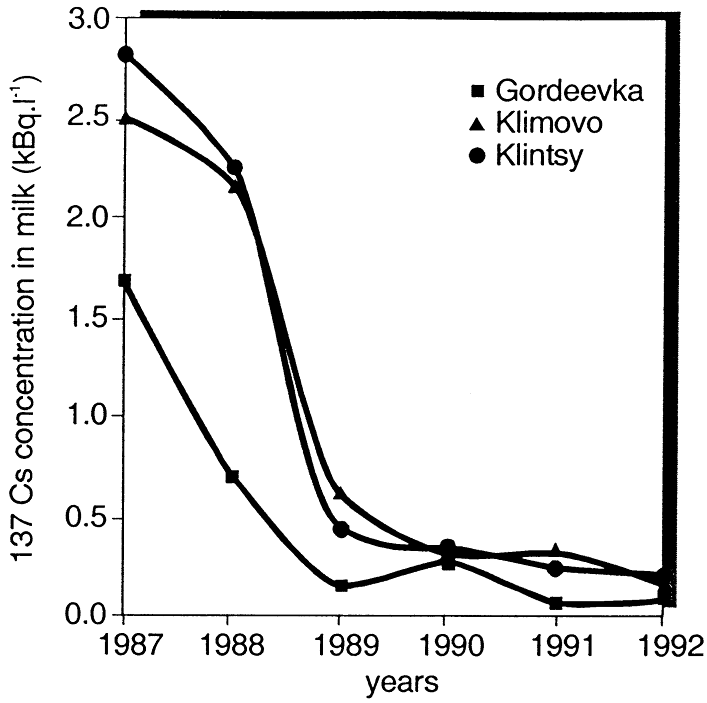
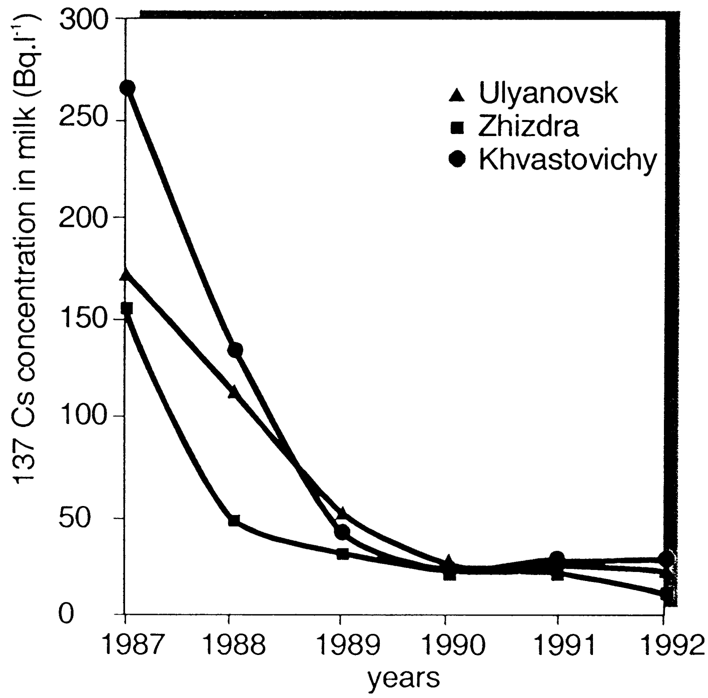


Fig. 10. Distribution of Ukrainian settlements according to mean ^{137}Cs concentration in locally produced milk in 1992–1994.

A study of the dynamics of the change in ^{137}Cs content in agricultural products has been carried out in the Russian Federation on the basis of 1987–1992 data from the five most severely affected districts in the Bryansk region (Gordeevo, Klimovo, Klintsy, Krasnaya Gora, and Novozybkov) and from three districts in the Kaluga region (Khvastovichy, Ulyanovo and Zhizdra) (Fig. 12). As the districts in question are quite different in their levels of agricultural product contamination, soil characteristics, the types of agricultural countermeasure applied and the extent of their implementation, such an analysis makes it possible to evaluate not only the parameters involved in changes in the ^{137}Cs content in agricultural products, but also the influence of factors determining the changes in the biological availability of radionuclides to enter into food chains.



Bryansk Region



Kaluga Region

Fig. 11. Dynamics of mean ^{137}Cs concentration in milk in contaminated districts of the Russian Federation.

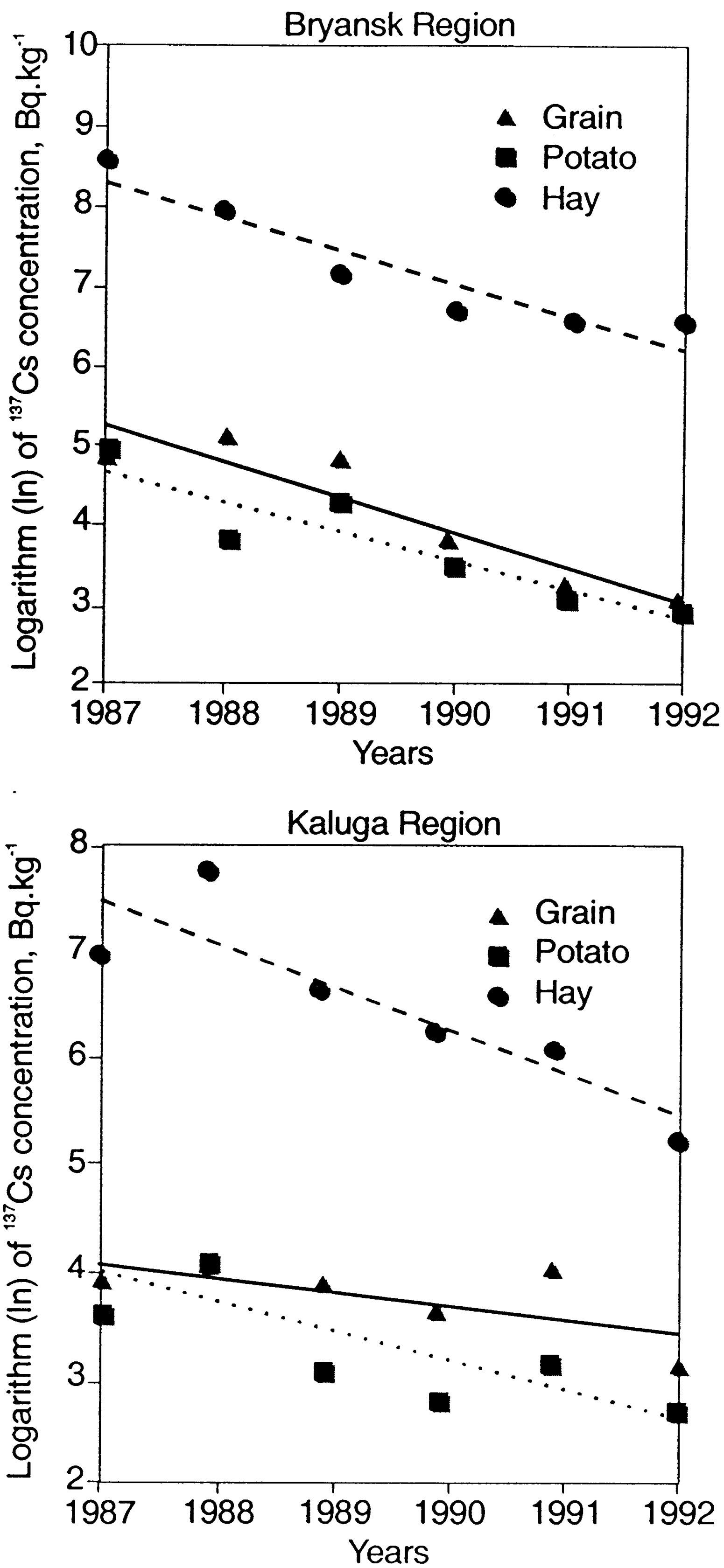


Fig. 12. Dynamics of mean ^{137}Cs concentration in vegetable products.

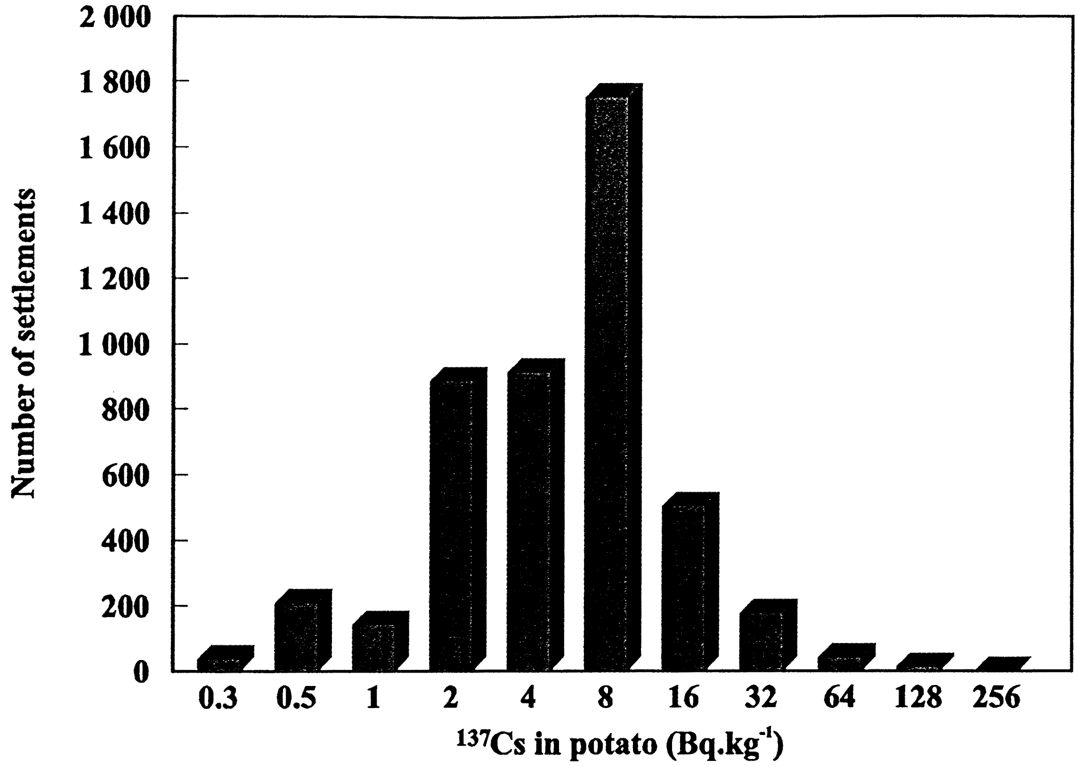


Fig. 13. Distribution of Ukrainian settlements according to mean ^{137}Cs concentration in locally produced potato in 1992–1994.

Fig. 13 shows the distribution of Ukrainian settlements according to mean ^{137}Cs activity concentration in locally produced potato between 1992 and 1994 and Table IX shows the transfer coefficients and levels of contamination of agricultural products in the Rovno region, which is characterized by unusually high transfer coefficients.

The results obtained show that the dynamics of ^{137}Cs and other radionuclides in agricultural products following an accident with radioactive release into the environment depend on natural biochemical processes and on weather-related and climatic conditions as well as on the scope of protective measures. The significance of these factors in different periods of post-accident contamination of the environment may be quite different, depending on the types of agricultural countermeasure applied and the extent of their implementation. In those regions where countermeasures have been extensively implemented, the decrease in radionuclide concentration in agricultural products was mainly determined by the efficacy of the countermeasures. Their implementation was responsible for up to 60% of the overall decrease in the contamination levels during the period under consideration. In those regions where the implementation of countermeasures was limited, approximately 70% of the decrease in the contamination levels of agricultural products was due to natural biochemical processes determining the radionuclide sorption on the absorbing soil complex, rather than to the countermeasures [17, 22].

2.3. Radioactive contamination of forest

2.3.1. Tree contamination

Woodlands with a ^{137}Cs surface contamination exceeding 37 kBq.m^{-2} cover a total area of over 40 000 km²: about 17 000 km² in Belarus, 13 000 km² in Ukraine and 10 000 km² in the Russian Federation. The surface contamination of woodland does not significantly differ from contamination of the adjacent meadows. However, in windward forest perimeters, the radionuclide content in the soil layer is 20–30% higher than in the forests themselves.

The radionuclide fallout during the accident occurred in the season when tree crowns were already covered with leaves, and resulted in a significant radionuclide concentration in the upper part of the forest, which is the centre of new tree growth. Immediately after the fallout, 60–90% of the radionuclides were trapped in the aerial part of the trees. The initial effective half-life of tree crown clearance, excluding radioactive decay, was approximately one month. By the end of the summer of 1986, 13–15% of the total deposition of radionuclides remained in the aerial phytomass, and by August 1987, 6–7% still remained there.

Beginning in 1988, along with the continuing reduction in contamination of tree crowns, an increased soil-to-plant transfer of ^{137}Cs and ^{90}Sr could be detected. Ten years after the Chernobyl accident, the greater part of the ^{137}Cs was concentrated in ground litter and the 5 cm soil layer. This accounts for 95% of the fallout in automorphic (dry) soils and 40–80% in hydromorphic (wet) soils. Most of the ^{137}Cs (50–95%), depending on the type of soil and its humidity level, remains in the fixed form. Fixed forms of radionuclides, i.e. those absorbed inside a crystal lattice of loamy minerals, cannot be transferred to plants. The fixed forms are released only when soil is treated with a 6M solution of HCl.

On the whole, the radionuclide content in wood and in other parts of the trees during the first three to four years after the accident was the result of two processes operating in different directions: clearance of directly deposited radionuclides, and uptake of radionuclides through tree roots. On hydromorphic soils, the radionuclide transfer is more intensive: since ^{137}Cs is more available for plants, the rate of increase in the aerial phytomass is quite high. At the same time, on automorphic soils, the self-clearance of the wood stand was the dominant process during the first five–eight years after the accident. The radionuclide pathways in new forest growth in the contaminated zones (both the radionuclide inflow through ^{137}Cs uptake by roots, and the outflow through rainfall, water erosion, etc.) do not account for more than a few tenths of a per cent of the total ^{137}Cs inventory in the aerial phytomass on automorphic soils, and do not exceed 1–2% on hydromorphic soils.

In 1994, depending on the age and the density of forest stands, the wood species and local conditions of the vegetation, 6–7% of radionuclides present in forests were accumulated in the aerial part of the trees (Table X). Radionuclides will continue to be accumulated in the main wood species for several years. Wood contamination, therefore, continues to increase and root uptake is the main mechanism of radionuclide transfer into the trees. Within the next 10 years, the aerial phytomass of 30-year old pine forests will accumulate up to 10% of the ^{137}Cs concentration in the soil. Then the clearance process will dominate, with a clearance half-life of approximately 30 years.

The ^{137}Cs content in wood for various tree species varies. The ^{137}Cs accumulation in birch, oak and aspen is 2.3–2.4 times higher than in common pine; in black alder it is almost the same as in pine.

The industrial and domestic use of pine wood is permitted if the ^{137}Cs surface contamination does not exceed the 1500 $kBq.m^{-2}$ agreed on by the three States. The ^{137}Cs stock in the aerial phytomass of pine stands accounts for 2.9% of its total content in the soil. In foliage stands the value of this parameter is 2–3 times higher than in pine stands.

TABLE X. ^{137}Cs DISTRIBUTION IN VARIOUS ELEMENTS OF THE PHYTOMASS OF A 30-YEAR OLD MOSSY PINE FOREST (%)

Year	Phytocenocytic elements						Total		
	Stem wood	Bark faggot-wood	Stem bark	One-year old sprouts	Present year needles	Previous year needles	Aerial part	Litter	Mineral soil
^{137}Cs soil deposition, 2,590 kBq.m^{-2}									
1991	1.3	0.6	0.6	0.3	1.1	0.6	4.5	44.7	50.8
1992	1.5	0.8	0.5	0.3	1.4	0.5	5.1	43.0	51.9
1993	1.8	0.9	0.5	0.4	1.6	0.6	5.8	40.9	53.3
1994	1.9	1.0	0.6	0.4	1.6	0.7	6.2	37.5	56.3
^{137}Cs soil deposition, 13,870 kBq.m^{-2}									
1991	1.5	0.7	0.6	0.3	1.1	0.4	4.6	39.3	56.1
1992	1.8	0.8	0.5	0.3	1.2	0.5	5.1	37.4	57.5
1993	2.0	0.8	0.5	0.3	1.4	0.6	5.7	35.1	59.2
1994	2.2	0.9	0.5	0.3	1.6	0.6	6.2	34.1	59.7

The ^{90}Sr accumulation is 2–5 times higher than that for ^{137}Cs, depending on tree species. However, the ^{90}Sr activity concentration is 2–3 times lower than that of ^{137}Cs. At the same time, the flux of ^{90}Sr to wood phytocenoses for the last 10 years is almost equal to the decrease in its content due to natural decay.

On most of the territory in the three republics affected by the Chernobyl accident, the ^{137}Cs concentration in disbarked wood has not exceeded the national TPLs which, depending on the use of the wood, vary from 740 to 11 000 Bq.kg^{-1}. In the exclusion zone, up to 30% of wood is contaminated by ^{137}Cs exceeding the national TPLs. The by-products of wood processing, such as turpentine, resin, tar or alcohol, for all practical purposes do not contain any radionuclides.

As in the case of grass plants, the root uptake of ^{137}Cs by other plants has gradually decreased during the post-accident period. The effective ^{137}Cs clearance half-life in wood plants on soddy-podzolic sandy soils (for the period from 1991) is 10–11 years, in bushy plants 7–15 years and in grass plants 6–12 years. Therefore, even the most conservative assessments make it possible to conclude that, within the next 15 years, the ^{137}Cs concentration in most forest products will decrease by a factor of at least two.

There is thought to be some risk of radionuclide dispersion onto the adjacent territories as a result of forest fires. However, the available data on radionuclide transfer during forest fires are contradictory. In 1992, thousands of hectares of woodlands in the area around Chernobyl NPP were affected by fires. The main problem produced by forest fires is the resuspension of contaminated ash in the atmosphere.

2.3.2. Contamination of mushrooms and berries

Mushrooms and berries from forests are an important part of the diet of the residents of rural regions in Belarus, the Russian Federation and Ukraine. The decrease in the concentration of the radionuclides they contain has been extremely slow, with variations from one year to another depending on weather conditions. According to some assessments, the effective clearance half-life is 14–26 years [28] but, according to other authors, because of yearly variations it is impossible to obtain statistically reliable data on the specific activity decrease over long periods [29]. It has also been impossible to find statistically reliable differences between the transfer coefficients of ^{137}Cs of the Chernobyl and global fallout origin. Table XI lists the assessment [28, 29] of the ^{137}Cs concentration in mushrooms and berries gathered on Russian territories with different contamination densities and Table XII shows similar data for the Rovno region of Ukraine, where the soil has a high transfer factor [12].

TABLE XI. ^{137}Cs IN MUSHROOMS AND BERRIES (WET WEIGHT) WITH DIFFERENT LEVELS OF FOREST CONTAMINATION IN THE RUSSIAN FEDERATION [28, 29]

Species	^{137}Cs concentration range (kBq.kg^{-1}) in areas with the following soil deposition:			^{137}Cs transfer coefficient (Bq.kg^{1})/(Bq.m^{-2})
	37 kBq.m^{-2}	185 kBq.m^{-2}	555kBq.m^{-2}	
Mushrooms				
Orange Cap Boletus	0.037–0.085	0.18–0.41	0.056–1.22	–
Edible Boletus (Boletus edulis)	0.037–0.26	0.18–1.3	0.56–4.07	0.0073
Honey-coloured Agaric (Armillaria mellea)	0.044–0.34	0.22–1.74	0.67–5.18	0.0016
Blue and yellow Russula (Russula cyanoxantha)	0.059–0.15	0.30–0.74	0.89–1.85	0.01
Rough-stalked Boletus (Leccinium scabrum)	0.18–0.26	0.93–1.3	2.78–4.07	0.015
Chanterelle (Cantharellus cibarius)	0.26–0.74	1.30–3.7	7.07–11.1	0.062
Black Lactarius (Lactarius necator)	0.11–1.85	0.56–9.25	1.67–27.8	0.012
Brown-yellow Boletus (Suillus luteus)	0.67–0.85	3.33–4.44	10.–13.3	0.032
Boletus	1.85–6.67	9.25–33.3	27.8–100	–
Agaric	0.15–0.26	0.74–1.3	2.22–4.44	–
Berries				
Myrtle Whortleberry (Vaccinium myrtillus)	0.074–0.19	0.37–0.93	1.11–2.81	0.0065
Mountain Cranberry (Vaccinium vitis-idaea)	0.11–0.26	0.56–1.3	1.67–4.07	0.01
Raspberry	0.037–0.15	0.18–0.74	0.56–3.7	0.0026

TABLE XII. ASSESSMENT OF THE ACTIVITY CONCENTRATION AND TRANSFER COEFFICIENTS OF ^{137}Cs IN MUSHROOMS AND BERRIES GATHERED ON THE TERRITORY OF ROKITNO AND STAROYE SELO FORESTS IN ROVNO REGION, UKRAINE, (1994) [12]

Product	^{137}Cs concentration, (kBq.kg^{-1})			^{137}Cs transfer coefficient, (Bq.kg^{-1})/(Bq.m^{-2})		
	min.	avg.	max.	min.	avg.	max.
Mushrooms	4.6	7.2	9.4	0.057	0.083	0.109
Berries	0.4	0.9	1.6	0.004	0.01	0.018

Depending on the specific characteristics of the species, average ^{137}Cs transfer coefficients vary by a factor of 20 in mushroom species and a factor of seven in berries. The ^{90}Sr contribution to the radioactive contamination of mushrooms accounts for approximately 1% of the total. On chernozem and grey forest soils, the ^{137}Cs uptake by mushrooms is 30–50 times lower than on soddy-podzolic sandy soils.

2.4. Individual annual doses and lifetime doses to the population

In analysing the radiation dose to the population, three periods may be distinguished:

- The first year following the accident is the most significant from the point of view of the radiological impact. The dose in this first year is complex to assess because of the duration and the non-uniform character of the release and fallout, fast changes in isotopic and radiation composition because of radionuclide decay, and the need to take into account the effectiveness of protective measures.
- During the period 1987–1991, the radiation impact was largely determined by the ^{137}Cs and ^{134}Cs external and internal exposures, by the official limitation and self-limitation of the population's activities, and by extensive countermeasures, including resettlement and decontamination, especially as they affected agricultural and forest production.
- The period 1992–1995 is essentially similar to the second period but the extent of protective action was reduced.

2.4.1. Doses to the thyroid

Until June 1986, ^{131}I was one of the major radionuclides contributing to the irradiation of the population. A large number of measurements of ^{131}I activity in the thyroid have shown wide variations (about two orders of magnitude) between individual doses, even within the same settlement. The highest dose values were found in children. Fig. 14 is a map showing mean thyroid doses to children in Ukraine [12]. Radioiodine contamination of milk was the most common cause of thyroid exposure. According to a 1993 publication [30], the coefficient of ^{131}I interception in pasture grass, due to various weather conditions during the fallout period, seemed higher in the less contaminated territories than in the more contaminated ones. This observation has been confirmed by further studies.

The average dose to the thyroid in young children from the most contaminated rural settlements was 3 Gy, and in children evacuated from some settlements in Belarus the dose even exceeded 10 Gy.

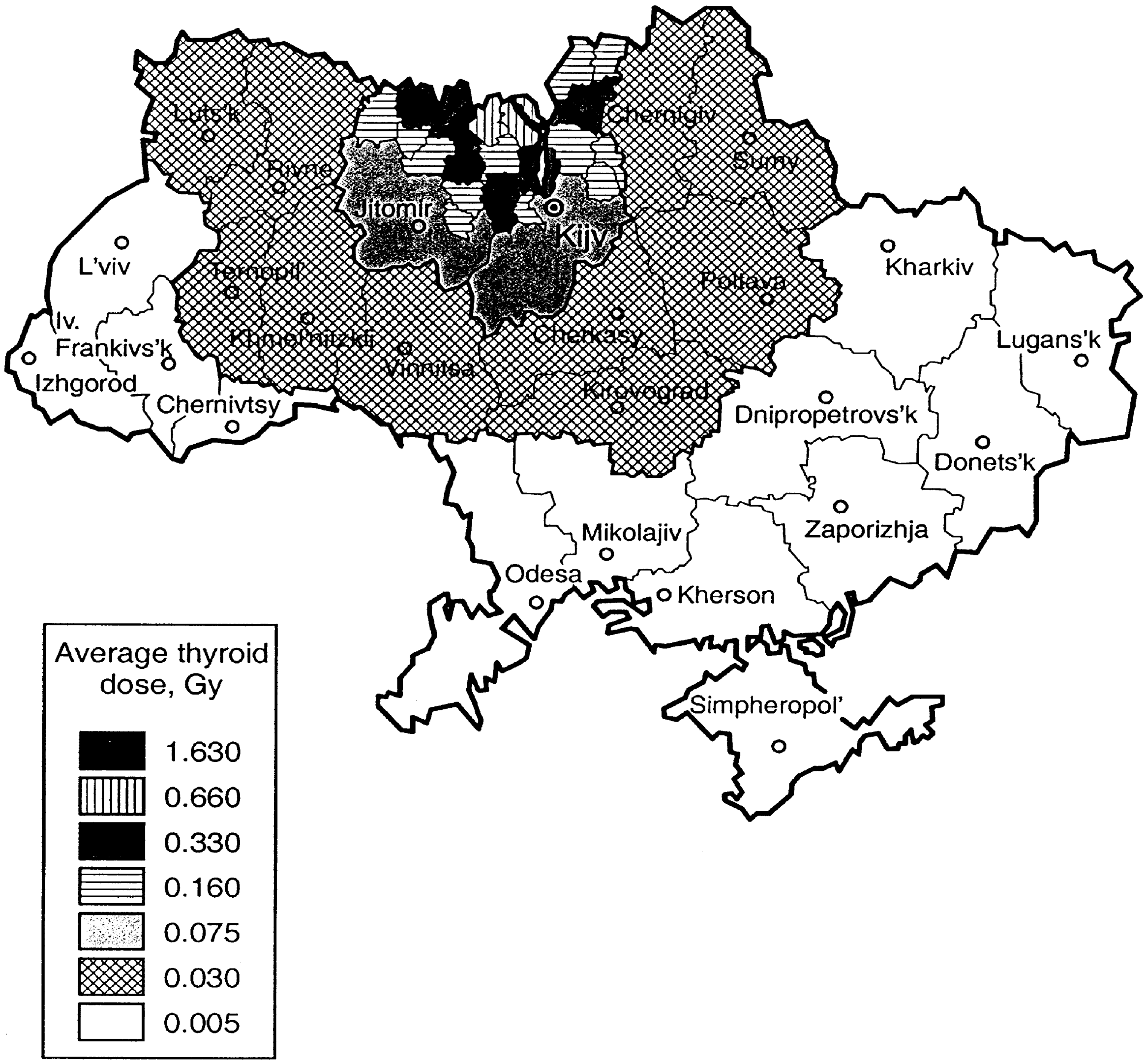


Fig. 14. Geographical distribution of the mean thyroid dose in Ukraine for people exposed in childhood due to radiological release.

2.4.2. External dose

During the first post-accident year, two main sources were responsible for the external exposure of population: the radioactive cloud and radioactive fallout onto ground litter, vegetation and buildings. The assessment, carried out in several countries, of the external dose due to the γ-emitters in passing radioactive cloud indicates the small contribution of the cloud to external exposure. According to the highest estimates, it accounted for approximately 3% of the external dose during the first year. The external dose was evaluated using three types of data:

- characteristics of the γ-radiation field;
- characteristics of human behaviour in this field;
- coefficients of conversion from the γ-radiation field to the dose to individuals.

Models for dose assessment took account of such factors as the radioactive deposition on soil, the radioactive decay of the radionuclides, the vertical migration of long lived radionuclides in the upper soil layer, the presence of snow, and the modification of these factors in an inhabited environment [31–33].

In addition, reconstruction of external exposure was carried out from 1986 to 1995 in settlements with varying ^{137}Cs deposition (40–4000 kBq.m^{-2}). This external dose reconstruction included the measurement of individual doses by thermoluminescent dosimeters, and the measurement of local dose rates in streets, courtyards, gardens, and houses, and on fallow land. The results obtained with these two methods are quite similar, but the second approach makes it possible to determine radiation doses to subgroups of the population more accurately, and also the influence of people's life-style on dose. Table XIII shows some results of measurements of external radiation dose to the population of contaminated settlements in the Bryansk region of the Russian Federation. The analysis of these data shows a good correlation with ^{137}Cs surface contamination [34].

The critical group were people working in the forests and in agriculture. For urban population, a marked variability in individual dose estimates could be observed, depending on living conditions. The effective external dose to the residents of multi-storey buildings was less than half of that to the residents of single-storey houses located in city suburbs.

On the basis of the analysis of all the data available, a model was created to reconstruct annual radiation doses to the population during the first post-accident decade, and to arrive at reliable assessments. The external doses per unit of ^{137}Cs surface contamination are presented in Table XIV [31, 35].

2.4.3. Internal dose from long lived radionuclides

Since the summer of 1986, the internal dose has been mainly caused by ingesting foodstuffs contaminated by ^{134}Cs and ^{137}Cs and ^{90}Sr, and also by inhaling plutonium and ^{241}Am with dust particles.

The retrospective assessment of internal doses received by inhabitants of contaminated areas of the Russian Federation in 1986–1995 [31] has been carried out using:

- ^{137}Cs and ^{134}Cs whole-body counting data (about 1 000 000 measurements);
- the results of ^{137}Cs, ^{134}Cs and ^{90}Sr activity concentration measurements in local food products;
- the results of calculations based on the transfer coefficients of radionuclides in different types of soils prevailing in agricultural land;
- the results of measurements of internal contamination, by radiochemical analyses of urine.

In 1986, the internal dose (E_{int}) to individuals consisted of two components:

- E_s — the dose to individuals due to surface contamination of vegetation with radionuclides and subsequent consumption of foodstuffs contaminated directly (leafy vegetables) or indirectly (milk, meat); and
- E_r — the dose to individuals due to root uptake of radionuclides deposited in the soil by vegetation and consumption of contaminated foodstuffs. Since the autumn of 1986, the root uptake pathway has been prevalent.

TABLE XIII. MEAN EFFECTIVE EXTERNAL DOSES RECEIVED BY ADULT INHABITANTS OF SOME CONTAMINATED LOCALITIES OF THE BRYANSK REGION, RUSSIAN FEDERATION, 1993–1995

Locality	^{137}Cs soil deposition ($kBq.m^{-2}$)	Monthly effective external dose (μSv)		
		1993	1994	1995
v. Novye Bobovichi	1030	–	160/140	–
v. StaryeBobovichi	980	–	190/160	–
v. Dobrodeevka	1020	–	220/190	–
v. StaryVyshkov	1250	300/260	–	–
v. Kuznets	850	170/160	–	–
v. Makarichi	660	150/140	–	–
v. Yalovka	2600	390/370	–	–
t. Novozybkov	680	–	–	69/64/57

Note: In this table, the first figure is data for inhabitants living in single-storey wooden houses, the second figure, in single-storey stone houses and the third figure (when provided) in a multistorey stone building.

TABLE XIV. STANDARDIZED EFFECTIVE EXTERNAL DOSES TO RURAL AND URBAN POPULATIONS IN VARIOUS POST-ACCIDENT PERIODS (μSv per $kBq.m^{-2}$ of ^{137}Cs)

Country	Years							
	1986		1987–1995		1996–2056		1986–2056	
	rural	urban	rural	urban	rural	urban	rural	urban
Belarus	32*	–	36*	–	33*	–	100*	–
Russian Federation	15	11	21	13	31	16	67	40
Ukraine	16	6	26	11	32**	13**	74**	32**

*) Effective external average doses in the Bragin, Khojniki and Narovlya districts.
**) Preliminary assessments.

It should be noted that in many areas the surface component (E_s), formed during the first post-accident months, was the major source of the internal dose to the population in the ten years from 1986 to 1995. The root component (E_r) in this period and the dose forecast for the future show significant variations depending on the type of soil prevailing in a given region. For example, in the Ukrainian Polessye and Bryansk region, characterized mainly by poor soddy-podzolic sandy and sandstone soils with high soil-to-plant transfer coefficients, doses are the highest, while in chernozem areas (Tula and Orel regions) they are significantly lower (Tables XV, XVI and XVII).

The contribution of ^{90}Sr to the internal dose caused mainly by ingestion of ^{137}Cs with food is currently negligible but it is predicted to increase in the future, and could reach tens of a per cent on chernozem soils. The internal radiation dose due to ^{90}Sr was evaluated by its concentration in major diet components and by the results of measurement of its specific activity in urine samples.

TABLE XV. MEAN EFFECTIVE INTERNAL DOSE TO THE RURAL POPULATION IN VARIOUS POST-ACCIDENT PERIODS IN BELARUS AND THE RUSSIAN FEDERATION (μSv per $kBq.m^{-2}$ of ^{137}Cs)

Country	Region or district	^{137}Cs soil deposition ($kBq.m^{-2}$)	Years			
			1986	1987–1995	1996–2056	1986–2056
Belarus	Bragin	>555	8	13	7	28
		<555	10	18	9	37
	Khojniki	>555	8	13	7	28
		<555	9	16	8	33
	Narovlya	>555	9	16	8	33
		<555	8	15	8	31
Russian Federation*	Bryansk	>555	10 (0.6%)	11 (1.0%)	9 (7.1%)	30 (2.9%)
		<555	36 (0.5%)	48 (1.2%)	9 (7.1%)	93 (1.5%)
	Tula	<555	15 (1.3%)	6 (3.6%)	1.8 (35%)	23 (4.6%)
	Orel	<555	15 (2.0%)	8 (4.1%)	2.4 (3.3%)	25 (5.6%)

* In brackets — the assessment of the ^{90}Sr contribution to the internal dose.

TABLE XVI. EFFECTIVE ACCUMULATED INTERNAL DOSE TO THE RURAL POPULATION IN VARIOUS POST-ACCIDENT PERIODS IN UKRAINE (μSv per $kBq.m^{-2}$ of ^{137}Cs) [37]

Soil–milk transfer coefficient in 1991 ($Bq.L^{-1}/kBq.m^{-2}$)	Year									
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
<1	8	15	21	25	29	31	34	35	37	38
1–5	42	76	103	124	141	154	165	173	180	185
5–10	94	170	230	277	315	345	369	387	402	414
>10	175	315	425	513	583	638	682	717	744	766

TABLE XVII. ANNUAL INTERNAL AND EXTERNAL EFFECTIVE DOSES TO INHABITANTS OF SOME UKRAINIAN SETTLEMENTS WITH VARIOUS SOIL–MILK TRANSFER COEFFICIENTS

Settlements	^{137}Cs soil deposition (kBq.m^{-2})	Soil–milk transfer coefficient (Bq.kg^{-1})/(kBq.m^{-2})	Annual effective doses (mSv**)									
			1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Denissovichi, Polessye district,	555	0.94	7.93	1.96	1.88	1.83	1.78	1.75	1.65	1.52	1.40	1.34
Kiev region			4.5*	2.5*	2.3	1.1*	1.15	1.0	0.8	0.78	0.70	0.64
Narodichi,	350	0.24	3.5	0.87	0.83	0.81	0.79	0.77	0.73	0.67	0.62	0.59
Zhitomir region			6.11	1.0*	1.85*	0.46*	0.12*	0.12*	0.12*	0.42*	0.27*	0.64*
Deleta, Ovrouch district,	174	9,2	2.49	0.61	0.59	0.57	0.56	0.55	0.52	0.48	0.44	0.42
Zhitomir region			2.6	2.3	2.5	2.34	2.2*	0.71*	1.54	2.01	1.56*	2.03*
Rokitno	75	8.3	0.75	0.19	0.18	0.17	0.17	0.17	0.16	0.14	0.13	0.13
Rovno region			0.6*	1.51*	0.7*	0.62	0.31*	0.62	0.54	0.52	0.73	0.62
Staroye Rokitno,	40	25.3	0.57	0.14	0.14	0.13	0.13	0.13	0.12	0.11	0.1	0.1
Rovno region			1.65	2.03	2.36*	1.58*	2.01*	2.67*	2.5*	2.39*	2.59*	1.8*

* Dose estimations based on whole body counting data.

** For each settlement, the upper line presents annual effective external dose and the lower line presents annual effective internal dose.

An assessment of annual effective internal dose levels from plutonium in the population of the contaminated regions of the Russian Federation between 1986 and 1992 [36], shows that this component amounted to 25 μSv. The levels of effective dose in the critical group (machine operators) are approximately 5–6 times higher. For the inhabitants of Kiev, the upper estimate of lifetime dose from plutonium isotopes and ^{241}Am is 18 μSv [12].

2.5. Dose rate reduction with time

Figs 15–17 show the changes in average whole body content of ^{137}Cs, the annual effective external and internal doses of the residents of settlements in the controlled and non-controlled contaminated areas of the Russian Federation (controlled areas are all those with ^{137}Cs contamination greater than 555 kBq.m^{-2}). The average whole body content of ^{137}Cs (kBq) has been standardized to the ^{137}Cs deposition on soil (kBq.m^{-2}). These results are presented in units (kBq)/(kBq.m^{-2}) equal to m^2. The figures show the important influence of the type of soil (see Fig. 16 and 17), the effects of countermeasures in controlled areas (see Figs 15 and 17) and the decrease in the internal dose until 1993 (Figs 15, 16 and 17). It should be noted that in the Bryansk region poor soddy-podsolic soils with high soil-to-plant transfer of caesium radionuclides dominate and in the Tula and Orel regions, rich black soils with low transfer of radionuclides prevail in agricultural areas [38, 39].

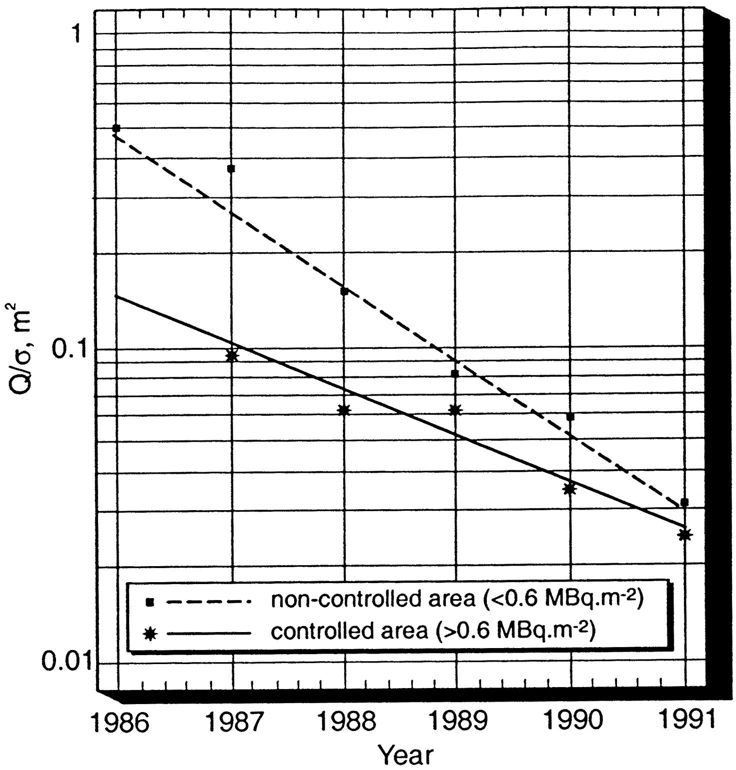


Fig. 15. Average content of [137]Cs (Q/σ, m²) in adults residing in the villages of the Bryansk region, Russian Federation, standardized to the soil deposition of [137]Cs (σ) [38, 39].

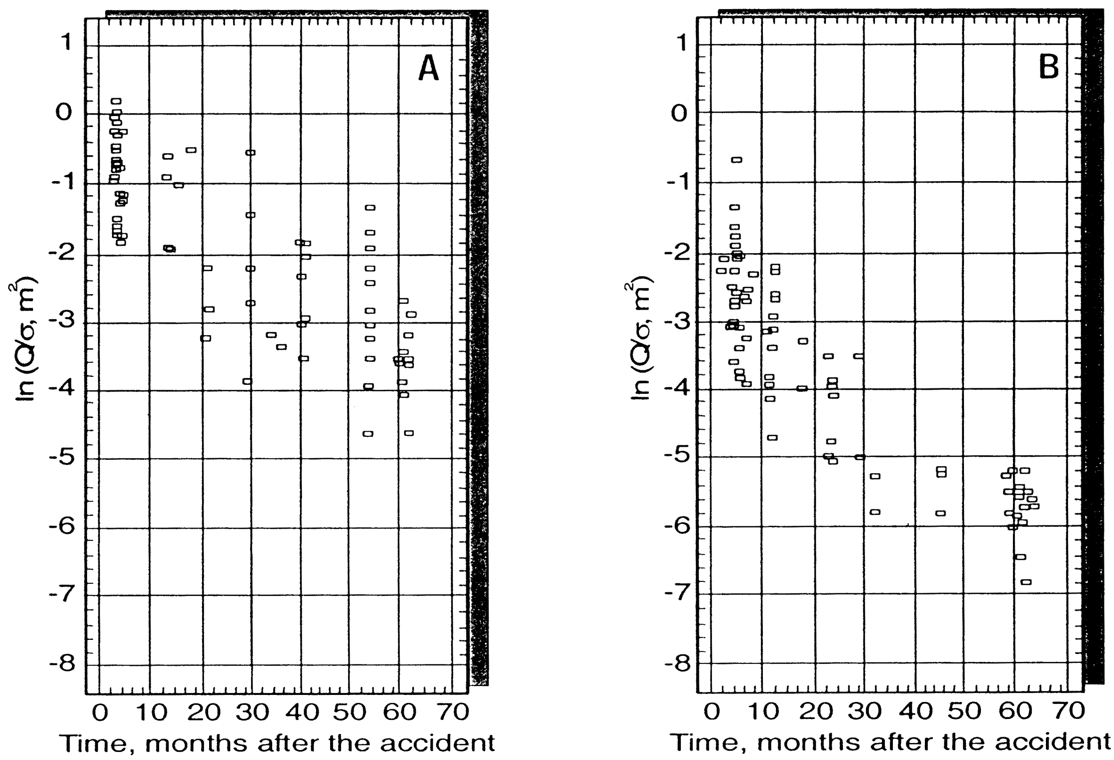


Fig. 16. Dynamics of the average content of [137]Cs (Q/σ, m²) in adults residing in the villages of the Bryansk(A) and Tula (B) regions, Russian Federation, standardized to the soil deposition of [137]Cs (σ) [38].

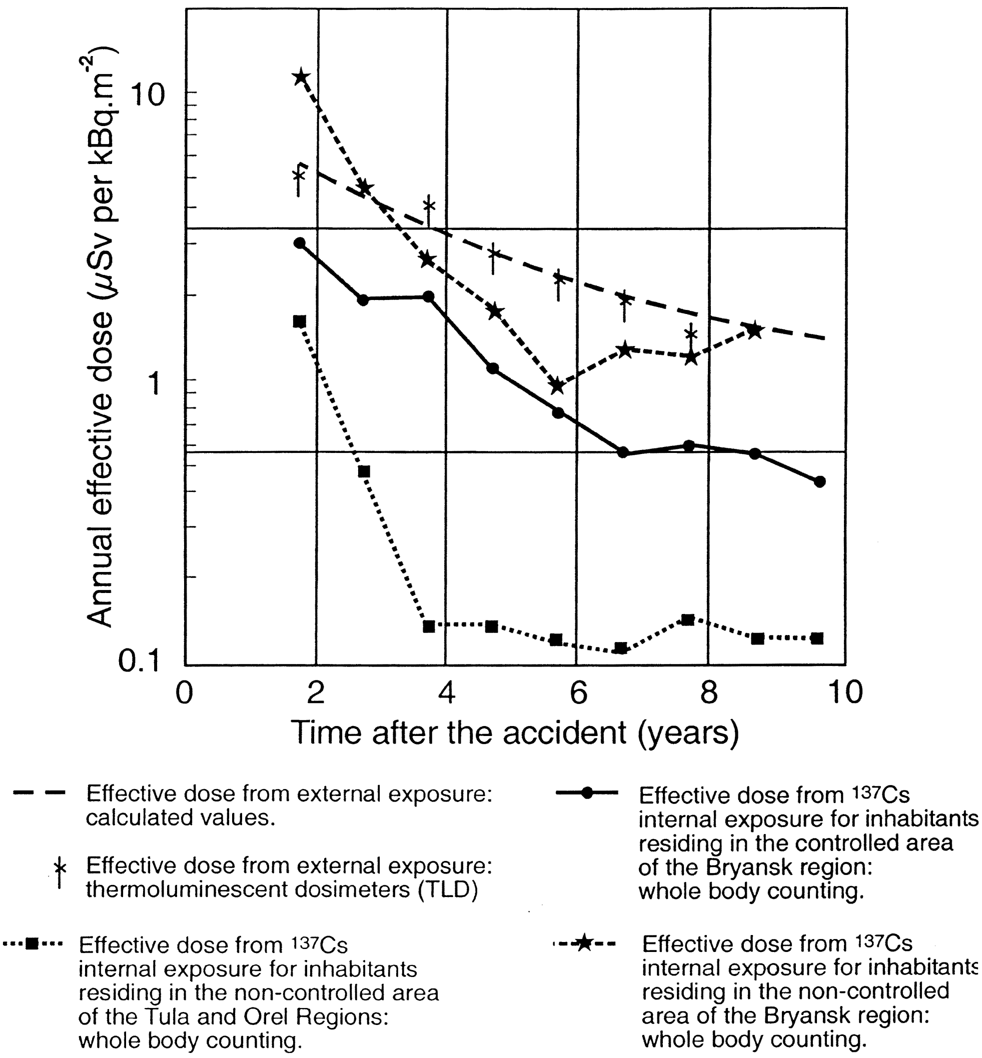


Fig. 17. Dynamics of annual external and internal effective doses of adults, standardized to the ^{137}Cs soil deposition, Russian data.

The important point here is the change in balance between internal and external doses (see Table XVII) as a result of changing soil-to-plant transfer factors. Evidence of this is demonstrated by the aggregated transfer coefficient to milk. The ^{137}Cs clearance in the human body is typical of the natural rate of clearance of the environment and the ecosystem in regions where no complementary agrotechnical and agrochemical measures are implemented (non-controlled areas) [37, 40].

As presented in Table XVIII, the effective dose forecast for 1996–2056 is two to three times lower than the effective dose already received 1986–1995, about half of which — it should be noted — was received in 1986. In addition, the internal dose already accumulated 1986–1995 accounts for about 90–95% of the 70-year committed internal dose (1986–2056). In contrast, the external dose already accumulated 1986–1995 accounts for only 60% of the 70-year external dose. However, the forecast external and internal doses for 1996–2056 account respectively for 70–95% and 5–30% of the total effective dose for this period, depending on dominating soil type and assuming termination of countermeasures from 1996. Table XVIII gives numerical values of the accumulated and forecast effective doses to the rural population of some contaminated regions of Belarus and the Russian Federation.

TABLE XVIII. TOTAL EFFECTIVE DOSE TO THE RURAL POPULATION IN VARIOUS POST-ACCIDENT PERIODS IN BELARUS AND THE RUSSIAN FEDERATION (μSv per kBq.m^{-2} of ^{137}Cs)

Country	Region or district	^{137}Cs soil deposition (kBq.m^{-2})	Year			
			1986	1987–1995	1996–2056	1986–2056
Belarus	Bragin	n.a	48	52	42	142
	Khojniki	n.a	42	50	41	133
	Narovlya	n.a	34	49	41	124
Russian Federation	Bryansk	>555	25	31	40	96
		<555	51	57	40	148
	Tula	<555	30	27	33	90
	Orel	<555	30	29	33	92

An increase in the annual internal dose of the residents has been observed during the past few years. This is due mainly to the increase in the consumption of natural food products (mushrooms and berries) whose ^{137}Cs contamination often exceeds the national TPLs. Also, the contribution of natural food products to the internal dose increases with time after the accident. This is due to their very low natural clearance rate in comparison with agricultural products. Since it is impossible to determine the rate of this process accurately at present, it has been assumed that the radionuclide clearance of ^{137}Cs from natural food products occurs only by radioactive decay. Thus, in the case of people ingesting large quantities of mushrooms, berries and game, ^{137}Cs incorporation will decrease by 2–3% per year, and the internal dose accumulated between 1996 and 2056 will reach a value equal to 30–40 times the doses accumulated in 1995.

On the other hand, the ^{137}Cs incorporation in the residents of the contaminated regions who do not ingest forest products will decrease by 3–7% per year (effective clearance half-life 10–15 years), and the internal dose accumulated between 1996 and 2056 will amount to 15–30 times the doses accumulated in 1995.

REFERENCES TO SECTION 2

[1] USSR STATE COMMITTEE ON THE UTILIZATION OF ATOMIC ENERGY, The Accident at the Chernobyl NPP and its Consequences. Summary Report of the Post-accident Review Meeting of the Chernobyl Accident, Safety Series N 75-INSAG-1, International Atomic Energy Agency (1986).

[2] Sources, effects and risks of ionizing radiation. Annex D. Exposures from the Chernobyl accident, UNSCEAR, 1988 Report, United Nations, New York (1988).

[3] BUZULUKOV, Yu.P., DOBRYNIN, Y.L., "Release of radionuclides during the Chernobyl accident", The Chernobyl Papers: Dose to the Soviet Population and Early Health Effects Studies (S. Merwin, M. Balonov, Eds), Research Enterprises, Richland (1993) 3–21.
[4] SICH, A., BOROVOY, RASMUSSEN, The Chernobyl Accident Revisited: Source Term Analysis and Reconstruction of Events During the Active Phase, Department of Nuclear Engineering — Massachusetts Institute of Technology, Cambridge (1994).
[5] GERMENCHUK, M.G., MATVIENKO, I.I., ZHUKOVA, O.M., International Conference on Geoinformation Systems, Ottawa (1994) 1269–1280.
[6] IZRAEL, YU., DE CORT, M., JONES, A.R., et al., “The atlas of ^{137}Cs contamination of europe after the Chernobyl accident”, The Radiological Consequences of the Chernobyl Accident (A. Karaoglou, G. Desmet, G.N. Kelly, H.G. Menzel, Eds), Rep. EUR 16544 EN (1996) 1–10.
[7] PRISTER, B.S., TABACHNYI, L.J., CHABANYUK, V.S., “Liquidation of the Chernobyl after-effects and GI”, Proc. Canadian Conf. on GIS, Ottawa, Canada, June 6–10, 1994 2 (1025–1035).
[8] PITKEVICH, V.A., DUBA V.V., IVANOV V.K., et al., Reconstruction of the composition of the Chernobyl radionuclide fallout and external radiation absorbed doses to the population of areas in Russia, Radiation Protection Dosimetry **64** (1996) 69–92.
[9] MINISTRY OF EMERGENCIES AND POPULATION PROTECTION FROM THE CHERNOBYL NPP CATASTROPHE CONSEQUENCES, The Chernobyl Catastrophe Consequences in the Republic of Belarus — National Report (1996).
[10] Comprehensive Radioecological Monitoring of Contamination Territory on Different Landscape — Geochemical Zone. Report, Kiev (1995).
[11] ACADEMY OF SCIENCES OF UKRAINE, Description of the Ukraine Encasement and Requirement for its Conservation. Minchernobyl of Ukraine, Kiev, Naukova Dumka (1992).
[12] Ten Years After the Accident of Chernobyl NPP, National Report of Ukraine 1996 — Minchernobyl, Kiev (1996).
[13] AGEYESTS, V.Yu., SHUGLYA, N.N., SHMIGELSKIY, A.A., "Migration of caesium and strontium radionuclides in the various types of soils in Belarus". Fourth Conf. on Geochemical Pathways of Migration of Artificial Radionuclides in Biosphere, Pushino (1991) 26.
[14] ALEXAKHIN R.M., KORNEEV, N.A. (Eds), Agricultural Radioecology, Ecology, Moscow (1991) 397 (in Russian).
[15] LOSHCHILOV, N.A., et. al., “A vertical migration in the Poliesje soils of the Chernobyl origin radionuclides in different physico-chemical forms”, Problems of Agricultural Radiology (Loshchilov N.A., Ed.), Kiev (1991) 36–44 (in Russian).
[16] SANZHAROVA, N.I., et al., Quantitative parameters of vertical migration of radionuclides in soils on different types of meadows, Radiatsionnaya Biologia, Radioekologia **36** 4 (1996), 488–497 (in Russian).
[17] PRISTER, B.S., Countermeasures used in the Ukraine to produce forage and animal food products with radionuclide levels below intervention limits after the Chernobyl accident, Sci Total Environ. (1993) **137**, 183–198.
[18] PRISTER, B.S., et al., Behaviour of radionuclides in meadows including countermeasures application, The radiological consequences of the Chernobyl accident, Reps. ISSN 1018–5593, EUR 16544 EN. ECSC-EC-EAEC, Brussels–Luxembourg (1996) 59–68.

[19] SANZHAROVA, N.I., FESENKO, S.V., KOTIK, V.A., SPIRIDONOV, S.I., Behaviour of radionuclides in meadows and efficiency of countermeasures, Radiation Protection Dosim. (1996) **64** 1 1/2, 43–48.
[20] BOGDEVITCH, I., AGEYETS, V., “Migration of radionuclides in the soil-crop-food product system and assessment of agricultural countermeasures”, The Radiological Consequences of the Chernobyl Accident (Proc. 1st Int. Conf. Minsk, 1996) 487–490.
[21] VOITCEKHOVICH, O., et al, Radioactive Contamination of the Ecological Systems in the Exclusion Zone, Report, Minchernobyl of Ukraine, Kiev (1996) 30.
[22] ALEXAKHIN, R.M., Radioecological lessons of Chernobyl, Radiobiologia **33** 1, 3–14 (In Russian).
[23] BOGDEVITCH, I.M., AGEYETS, B.Y., SHIGELSKAYA, I.D., Accumulation of radionuclides of ^{137}Cs and ^{90}Sr by farm crops depending on soil properties, Proc. of the Belarus–Japan Symposium, Minsk, 1994, 20.
[24] FESENKO, S.V., SPIRIDONOV, S.I., SANZHAROVA, N.I., ALEXAKHIN, R.M., Changes in ^{137}Cs bioavailability in meadow ecosystems after the ChNPP accident, Doklady Akademii Nauk **347** 6 (1996) 847–849 (In Russian).
[25] ALEXAKHIN, R., et al., “Fluxes of radionuclides in agricultural environment — main results and still unsolved problems”, The radiological consequences of the Chernobyl accident, Reps. ISSN 1018–5593, EUR 16544 EN. ECSC-EC-EAEC, Brussels–Luxembourg (1996) 39–47.
[26] FESENKO, S.V.,et al., The dynamics of the transfer of caesium–137 to animal fodder in areas of Russia affected by the Chernobyl accident and doses resulting from the consumption of milk and milk products, Radiation Protection Dosim. **69** 4 (1997) 289–299.
[27] Guide for Agricultural Practice on Lands Contaminated by Radionuclides in the Republic of Belarus for 1997–2000 (Bogdevitch, I.M., Ed.), Minsk, (1997) 76 (in Russian).
[28] SHUTOV, V.N., et al., The role of mushrooms and berries in the formation of internal exposure doses to the population of Russia after the Chernobyl accident, Radiation Protection Dosim. **67** 1 (1996) 55–64.
[29] Recommendations on Agricultural Activity in 1991–1995 for the Areas Contaminated After the Accident at the Chernobyl NPP, Ministry of Agriculture and Provision of the Russian Federation, Moscow (1991) (in Russian).
[30] GAVRILIN, Yu.I., KHRUSCH, V.T., SHINKAREV, S.M., Internal thyroid dose to the residents of contaminated regions in Belarus, Medical Radiol. **6** (1993) 15–20 (in Russian).
[31] Reconstruction of the Mean Effective Dose Accumulated in 1986–1995 by Inhabitants of Localities of the Russian Federation Subjected to Radioactive Contamination due to the Chernobyl Accident in 1986, Methodic Instruction of the Russian Ministry of Public Health Nr. MU-2.6.1.579–96 (1996).
[32] LIKHTARIOV, I., KOVGAN, L., NOVAK, D., JACOB, P., PARETZKE, H.G., Effective doses due to external irradiation from the Chernobyl accident for different population groups of Ukraine, Health Physics **70** 1 (1996) 87–98.
[33] GOLIKOV, V.Yu, BALONOV, M., PONOMAREV, A.V., “Estimation of external radiation doses to the population after the Chernobyl accident”, The Chernobyl Papers, v. 1, Doses to the Soviet Population and Early Health Effects Studies (Merwin, S.E, Balonov, M.I., Eds), Richland, Research Enterprises (1993) 247–288.

[34] ERKIN, V.G.; LEBEDEV, O.V., “Thermoluminescent dosimeter measurements of external doses to the population of the Bryansk region after the Chernobyl accident”, The Chernobyl Papers., v. 1. Research Enterprises; Publishing Segment (Balonov M.I., Merwin S.E., Eds), Richland, Washington (1993) 289–311.

[35] BALONOV, M., JACOB, P., LIKHTAREV, I., MINENKO, V., “Pathways, levels and trends of population exposure after the Chernobyl accident”, The Radiological Consequences of the Chernobyl Accident (Karaoglou, A., Desmet G., Kelly, G.N., Menzel, H.G., Eds), Rep. EUR 16544 EN (1996) 235–250.

[36] IVANOVA, N.P., SHVYDKO, N.S., ERSHOV, E.B., BALONOV, M., Doses to the population of Russia from plutonium fallout following the Chernobyl accident, Rad. Protection Dosim. **58** 4 (1995) 255–260.

[37] LIKHTAREV, I., PARETZKE, H., “Exposure of different population groups of Ukraine after the Chernobyl accident and main health-risk assessments”, Zehn Jahre nach Tschernobyl, eine Bilanz (Bayer, A., Kaul, A., Reiners, C., Eds.), Gustav Fisher Verlag, Stuttgart (1996).

[38] SHUTOV, V.N., et al., “Cesium and strontium radionuclide migration in the agricultural ecosystem and estimation doses to the population”, The Chernobyl Papers 1 (S.E.Merwin, M.I.Balonov, Eds), Richland, Research Enterprises (1993) 167–218.

[39] BALONOV, M.I., TRAVNIKOVA, I.G., “Importance of diet and protective actions on internal dose from Cs radionuclides in inhabitants of the Chernobyl region”, The Chernobyl Papers (Merwin, S.E, Balonov, M.I., Eds), Richland, Research Enterprises (1993) 1127–166.

[40] SAVKIN, M., TITOV, A., LEBEDEV, A., Distributions of individual and collective doses on Belarus population during the first year after the Chernobyl accident", Radiation & Risk/Bulletin of the All-Russian Medical and Dosimetric State Registry **7** (1996) 87–113.

3. FACTORS AFFECTING LIFE IN THE CONTAMINATED REGIONS

3.1. Features common to the Commonwealth of Independent States (CIS)

3.1.1. Effects on the well-being of the population

The past years have been distinguished by major changes in all spheres of life, first in the former USSR and now carried over to Belarus, Russia and Ukraine. Therefore, any analysis of the consequences of the Chernobyl accident must take the general trends seen in the social and economic situation into account. In the economy, these trends may be summarized as a decline in production in the early '80s, some improvement in the late '80s, and a crisis in the '90s brought about by the reorganization of the economy. In fact, starting from 1991–1992, the economy has been adversely affected by the present restructuring, causing a sharp fall in production. Since 1988, the move towards an economy with multiple forms of property has caused a consistent and uncontrolled decline in the standard of living. This decline has had an impact on demography: notably, the birth rate has decreased, life expectancy has been reduced and the mortality rate has begun to rise. Even greater changes in the social sphere were caused initially by 'perestroika' and 'glasnost' ('restructuring' and 'openness'), and then by the dissolution of the USSR and the transition in the three republics towards a market economy.

In all the areas that were extensively contaminated following the accident, the environmental measures taken in conjunction with the general disruption of the economy and social network had severe effects on the health of the people in these areas. Special laws were adopted in the former USSR, and later in Belarus, the Russian Federation and Ukraine, which aimed at the social protection of citizens exposed to radiation as a result of the Chernobyl accident. According to these laws, such citizens are entitled to compensation for potential health damage, to preferential medical care and to compensation and privileges for living and working in the contaminated territories under difficult conditions.

Since 1986, medical examinations of the population have been undertaken in the contaminated areas, together with the development of health care facilities. Increased incidence has been recorded of diseases of the endocrine and the haematopoietic systems, of ischaemic disease and peptic ulcers, and of depressed functioning of the immune system. For most of the diseases, the highest incidences were found in the disaster 'liquidators' (cleaning up workers and others). In children, rises in general and primary morbidity have been recorded with regard to haematological diseases, congenital development anomalies, and digestive tract diseases. Along with somatic morbidity, a steady rise has been observed in mental disorders. Many of these diseases are not known to be caused by radiation and their reported increased incidence may well be the result of increased surveillance combined with the deterioration in living standards.

3.1.2. Effects on industrial and agricultural production

The Chernobyl accident, in addition to having ecological and potential health consequences, has greatly hindered social and economic development in the affected republics. This is due to: first, the radioactive contamination of vast tracts of land containing industrial zones, agricultural lands, forest areas, and major water basins; second, the large funds drained from State budgets to mitigate the consequences; and third, the significant material and human resources used in the mitigation process. The disaster has caused a change in people's awareness, and has resulted in the re-evaluation of many firmly-held attitudes. It has produced novel approaches towards the problem of ensuring safety in the nuclear power industry and at radioactive material production sites. One result is that the construction of nuclear power plants and other nuclear industrial facilities has been suspended [1–3].

The largest decline in production output has been observed in the contaminated areas. In these areas, not only has there been a general decline in the economy common to all the CIS, but additional factors associated with the remedial measures have exacerbated this impact. These factors include:

- the withdrawal of contaminated agricultural lands, forests and water resources from economic development;
- the necessity for special reclamation measures on agricultural lands;
- the withdrawal of some facilities from trade operation;
- the need to continue decontamination actions, store radioactive waste, and maintain radioecological and radiation control of manufactured goods and agricultural products;
- the absence of local recreation conditions for the population.

3.1.3. Changes in agricultural practices in the contaminated areas

The main objective of agricultural production in the contaminated territories is to obtain products which satisfy the relevant national permissible levels for radionuclide concentrations. In order to do so, measures have had to be implemented which have modified the usual agricultural practices in those areas.

It has been observed that special agronomic, agrochemical and reclamation measures can decrease the caesium transfer to crop production by a factor of 1.5–4. For example: the liming of acidic soils decreases the caesium soil-to-plant transfer by a factor of 1.4–1.7; applying more potassium fertilizers decreases it by a factor of 1.7–2.5, and deep ploughing with digging combined with liming and potassium fertilizers decreases it by a factor of 3–4.

The contamination level in animal produce depends on the type of feeding, the composition of the fodder, the type of animal husbandry and the contamination levels of fodder crops and soils. Feeding animals with clean fodder at the final stage before slaughter has proven to be very efficient. The prolongation of such a feeding period from two to seven months, depending on the animal age and the caesium content in muscles, makes it possible to obtain practically clean meat [2]. Feeding with concentrated fodder leads to a decrease in the radionuclide content in animal produce by a factor of 2–4, while administering ferrocenes, in the form of boluses, to cattle decreases the radionuclide content in milk by a factor of 4–5.

3.1.4. Conditions for safe living

The time for the implementation of countermeasures after the Chernobyl accident can be divided into separate periods: the emergency phase (1986); the intermediate phase (1987–1989); and the rehabilitation phase (1990 onwards). During the emergency phase, action was taken primarily to minimize the effects of radiation on human health and the environment, and to reduce social, ecological and economic damage. During the intermediate and rehabilitation phases, a wide range of specific measures aimed at reducing the additional dose to the local population. This was achieved by undertaking the decontamination of the area and by implementing various other protective and prohibitive measures. To ensure the social protection of the affected population and provide for the social, economic and ecological rehabilitation of the territories, State programmes of protective measures were adopted first in the former USSR and later by Belarus, the Russian Federation and Ukraine.

The overall rehabilitation programme has three major components: the strengthening of the national economies, the ecological rehabilitation of the contaminated territories combined with social protection, and rehabilitation of the population living and working in the contaminated areas.

The life of the rural population in contaminated areas has been severely affected by various restrictions. Restrictions on the consumption and free trade of foodstuffs produced on local farms and personal plots were established in May 1986 and are still in force, though less severe than in 1986. In the areas under "strict control" (^{137}Cs soil deposition exceeding 555 kBq.m^{-2}) the inhabitants were forced to give up their dairy cattle and were advised not to eat foodstuffs grown on personal plots, or mushrooms and wild plants. To compensate for the losses, a monthly allowance of 30 rubles (approximately US $50 in 1986) was given to each family member. The delivery of "clean" products, including milk, was organized. Such substitutions had a number of drawbacks: the quality of the milk brought in from the outside was markedly inferior to that of local fresh milk. During those early post-accident years, the food supply system could not provide fresh fruit and vegetables, especially not wild mushrooms and berries, to the rural population. These restrictions produced the desired effect of reducing internal doses, but in subsequent years they were less effective. Therefore, recommendations on the cultivation of private plots were developed for the rural population. However, many of the recommended measures, such as the restrictions on the use of manure and firewood from local forests, were inconsistent with the established way of life.

Many major restrictions to people’s activities are still in effect. Radiation control in the contaminated areas and the attitude of the population towards products from these areas make it practically impossible for the rural population to sell produce privately, even in other regions. Restrictive and prohibitive measures have aggravated the burden caused by the consequences of the accident, all the more so because the measures are long term. Early on, the allowance granted to compensate for loss was nicknamed "coffin money", which clearly illustrates the attitude of the local population towards the authorities' action. In the current economic situation, the people living in contaminated areas cannot afford to purchase goods brought in from other regions, and they have no other choice but to consume the foodstuffs which they produce themselves.

3.2. Situation in Belarus

3.2.1. Effects on the well-being of the population

In Belarus, the areas with a ^{137}Cs soil deposition greater than 37 kBq.m^{-2} (46 450 km^2) were populated by 2.2 million people. In 1986, these areas represented 23% of Belarusian territory, which indicates the extent to which contamination has affected all sectors of social and economic life. The projected total cost incurred through possible deterioration in human health, losses suffered by the industry, agriculture, construction, transportation and communication sectors, the social cost, and the damage to land, water, forests and mineral resources is estimated at 235 billion US dollars for 1986–2015 [3]. The annual expenditure of 15–20% of the State budget on overcoming the consequences of Chernobyl has contributed considerably to the decline in the economic well-being of the whole population. Moreover, the State budget has decreased as a result of the economic crisis caused by the consequences of the mitigation of the disaster. The greatest detriment has arisen from the deteriorated demographic situation and the decreased competitiveness of agricultural products.

The total number of people engaged in agriculture in the contaminated territory continues to decrease. An uneven distribution of labour resources has resulted from the State-funded resettlement of over 130 000 people from the most contaminated areas to relatively "clean" areas, and from the self-initiated movement of about 50 000 people. As a result, the zone where the ^{137}Cs contamination is over 555 kBq.m^{-2} (the obligatory resettlement zone) has practically no labour resources left. As for the zone of 185–555 kBq.m^{-2} contamination (the voluntary resettlement zone), its labour resources can only partially meet the demands of the economy. The bulk of labour resources, often an oversupply, is concentrated in a zone of less than 185 kBq.m^{-2} (the radiological control zone) which has attracted the main migrant flow. Predictions of the demographic situation suggest a further rise in mortality rate and decrease in birth rate. The lowest birth rates are expected in the Gomel and Mogilev regions, especially in contaminated rural areas. In Belarus as a whole, the mortality rate currently exceeds the birth rate.

A psychological barrier has radically reduced the export of Belarusian agricultural produce, particularly from the contaminated areas to other countries in the CIS. This factor, combined with others, has led to a decline in the total agricultural production by one third; prior to the accident, this sector accounted for about 40% of the gross national product. Correspondingly, personal income has decreased, and latent unemployment in rural areas has increased. In the most severely contaminated areas, the average wage level in agriculture is 36% lower than in less contaminated areas with similar environmental conditions. For example, the average monthly salary, expressed in US dollars, during the first nine months of 1995 in contaminated districts was: Bragin — $29.80; Chechersk — $29.40; Khojniki — $32.50; and Narovlya — $25.00. In the non-contaminated districts of the Grodno and Minsk regions, the average wage was: Grodno — $54.40; Kopyl — $38.00; Korelich — $53.40; and Nesvizh — $38.30. On average, arrears in wage payments in Belarus agriculture amount to 15% of the total wage fund, while in contaminated districts they rise to 22%.

3.2.2. Effects on industrial and agricultural production

In Belarus, the largest drop in production output, 20–25%, was registered in 1994. The decline in output in the fuel and light industrial sectors was even more dramatic: 50–55% and 30% respectively. The production decline in light industry was determined by price increases for raw materials and energy, and a decrease in consumer demand [1].The prospects of industrial development in contaminated areas will depend on attracting investment in the modernization of technical equipment, on restructuring and on attracting the younger workforce, especially engineers and skilled workers. In 1994–1996, not a single university graduate wished to take a position in the Bragin, Chechersk Khojniki and Narovlya districts. In the areas with ^{137}Cs contamination below 185 kBq.m^{-2}, there are prospects for developing forest, woodwork, and cellulose and paper industries. Priority should be given to the furniture industry, and to the processing of wood, potatoes, beet and rape. This would require substantial investment, including funds from abroad.

In the countryside, more than 18 000 km^2 of cultivated land was contaminated to over 37 kBq.m^{-2} of ^{137}Cs. Of this, 2650 were excluded from cultivation, mainly in those areas where the contamination exceeded 1480 kBq.m^{-2} for ^{137}Cs, 111 kBq.m^{-2} for ^{90}Sr, or 3.7 kBq. m^{-2} for plutonium. Moreover, considerable areas of less contaminated land adjoining evacuated settlements were also excluded from commercial exploitation. In 1996, 14 000 km^2

of the 18 000 km^2 contaminated countryside were being used for agricultural production. Annual direct losses of agricultural produce from abandoned lands are about $69 million (at 1995 prices), while the value of the abandoned means of production is many times more [4, 5].

By 1990, agricultural production in Belarus as a whole and in the Gomel region was no longer falling compared with 1985. The drop in cereal and potato production in the most affected districts was, until 1990, caused only by land abandonment, while the productivity of arable fields and meadows even increased to some extent (Table XIX). However, from 1991 to 1994, the crop yield from all cultivation fell sharply. Especially notable is the decrease in grain, potato and green fodder production from meadows in these districts compared with the average national figures. The decline in meat and milk production in the affected districts was even more significant, e.g. in 1990–1994 in the Narovlya district, the decline was twice as great as the corresponding figure for Belarus as a whole (Table XX). The main reasons for this are an ever increasing drain of younger workers and diminishing State subsidies to the farms in the contaminated areas. The difficult economic situation has compelled many farmers to slaughter their cattle prematurely in order to reduce livestock numbers (Table XXI). This action was prompted by low prices which made animal production unprofitable. In the Chechersk, Khojniki and Narovlya districts, the cattle herd in the private sector decreased by 26–36%, while in Belarus as a whole it rose [3, 6].

People were evacuated from a total area of 4310 km^2 of the Chernobyl NPP exclusion zone, which included 2100 km^2 in Belarus (the Polyesse Radiological and Ecological Reserve). Most of the exclusion zone cannot be reclaimed for agriculture in the foreseeable future, due to high contamination by long lived radionuclides.

The highly contaminated areas of the resettlement zone (outside the 30 km exclusion zone) comprise separate territories in the Brest, Gomel and Mogilev regions where economic activity stopped after the relocation of 415 settlements. The soil contamination generally ranges from 37 to 1480 kBq.m^{-2}, but even up to 5400 kBq.m^{-2} in some places, for ^{137}Cs and from 11 to 222 kBq.m^{-2} for ^{90}Sr. The plutonium content is relatively low and largely concentrated in the area adjoining the Chernobyl NPP. Three categories of agricultural land can be distinguished within the resettlement zone [6].

The first category of land in the resettlement zone consists of about 670 km^2 of cultivated land with contamination density below 555 kBq.m^{-2} for ^{137}Cs and below 74 kBq.m^{-2} for ^{90}Sr. Some areas with largely loamy and sandy soils have already been reclaimed for agriculture. The second category of land comprises about 500 km^2 with a contamination density of 555 to 1480 kBq.m^{-2} for ^{137}Cs or of 74 to 111 kBq.m^{-2} for ^{90}Sr. This land can also be used for agriculture but will require relatively expensive soil reclamation; it could be partially reclaimed and used for cereals, rape and fodder crops for cattle, but complete agricultural use of these lands would only be possible after rehabilitation.

For all practical purposes, only that land in the resettlement zone where the living quarters and production infrastructure have been at least partly preserved can be reclaimed. The rehabilitation of resettled territories will require State subsidies because, during the first years, the cost of agricultural production from the recultivated lands will significantly exceed the sale prices even for produce cultivated on highly fertile soils. Sandy soils with low fertility and land requiring afforestation to protect it against water and wind erosion cannot be reclaimed [7]. The third category of land contaminated above 1480 kBq.m^{-2} for ^{137}Cs or 111 kBq.m^{-2} for ^{90}Sr cannot be reclaimed.

TABLE XIX. AGRICULTURAL PRODUCTION IN THE PUBLIC SECTOR

Area	1985 (kilotonnes)	1990 as % of 1985	1994 as % of 1985
Grain			
Belarus	5719	122	100
Gomel region	987	107	89
Bragin district	57	85	52
Narovlya district	21	91	48
Khojniki district	41	99	78
Cherchersk district	41	84	72
Potato			
Gomel region	1170	104	114
Bragin district	78	36	14
Narovlya district	28	24	12
Khojniki district	50	42	21
Cherchersk district	46	63	21
Productivity of arable land, in 100 kg per hectare			
Belarus	37.4	122	85
Gomel region	40	110	77
Bragin district	41.4	116	72
Narovlya district	36.4	122	58
Khojniki district	42.6	115	86
Cherchersk district	41.1	103	71
Productivity of meadows, in 100 kg per hectare			
Belarus	18.7	108	88
Gomel region	19.5	109	80
Bragin district	23.4	97	68
Narovlya district	14.5	120	59
Khojniki district	21.6	111	75
Cherchersk district	20.6	110	59

TABLE XX. MILK AND MEAT PRODUCTION (LIVE WEIGHT) IN THE PUBLIC SECTOR

Area	Milk		Meat	
	1990 (kilotonnes)	1994 as % of 1990	1990 (kilotonnes)	1994 as % of 1990
Belarus	7457	74	1758	64
Gomel region	4213	64	282	57
Bragin district	38.4	52	8.2	48
Narovlya district	16.2	30	5	38
Khojniki district	33.9	52	8.1	40
Chechersk district	28.7	43	5.3	43

TABLE XXI. CHANGES IN LIVESTOCK

Area	Public Sector		Private Sector	
	1990 (thousand head)	1994 as % of 1990	1990 (thousand head)	1994 as % of 1990
Cattle				
Belarus	1749	84	681	106
Gomel region	312	76	99	97
Bragin district	12.1	70	2.4	96
Narovlya district	5	46	1.1	64
Khojniki district	10.3	57	1.2	67
Chechersk district	10.8	54	2.7	74
Pigs				
Belarus	3569	72	1521	100
Gomel region	498	92	243	98
Bragin district	15.2	34	8.2	100
Narovlya district	12.5	74	4.2	93
Khojniki district	7	44	13.1	66
Chechersk district	14.8	30	7	86

3.2.3. Changes in agricultural practices in the contaminated areas

In Belarus, 14 000 km^2 of land used for agricultural production is contaminated with ^{137}Cs at deposition densities of 37 to 1480 kBq.m^{-2}, including almost 5000 km^2 contaminated with ^{90}Sr at densities of 11 to 111 kBq.m^{-2}. The land contamination status is updated once in five years by regional fertilization stations together with an agrochemical survey of soils under the guidance of the Belarus Research Institute for Soil Science and Agrochemistry.

In 1994, the area contaminated at more than 37 kBq.m^{-2} ^{137}Cs represented 62% of the total agricultural lands in the Gomel region. All the agricultural land in the Chechersk, Khojniki, and Narovlya districts and 75% of the agricultural land in the Bragin district was contaminated with more than 37 kBq.m^{-2}. The cultivated areas have decreased here by 17%–43% compared with the pre-accident period.

As a result of the extensive monitoring introduced by the Ministry of Agricultural Production, the production of contaminated milk with an excessive content of caesium radionuclides produced in the public sector decreased from 524 600 tonnes (13.8% of total production) in 1986 to 22 100 tonnes (0.7%) in 1991, and has been at that level (0.3%–0.6%) since then. The amount of contaminated meat decreased correspondingly from 21 100 tonnes (4.3%) to a few tonnes in 1993–1994. Practically all grain and potato production satisfies the national permissible levels (Table XXII).

In the most affected areas, a considerable proportion of the locally produced fodder given to milk cattle contains ^{137}Cs. On soils with ^{137}Cs contamination over 555 kBq.m^{-2}, up to 80% of fodder crops are significantly contaminated. In 1994, a significant part of the milk produced had a ^{137}Cs content above the permissible level. This averaged 11% of the milk production in the four districts (Table XXIII). The ^{90}Sr content in agricultural products is monitored selectively; its concentration in food products has decreased by approximately half since 1986. However, the ^{90}Sr transfer to plants remains high and is tending to increase in some areas [8, 9].

TABLE XXII. CHANGE IN AGRICULTURAL PRODUCE WITH CONCENTRATION OF CAESIUM RADIONUCLIDES EXCEEDING APPROPRIATE PERMISSIBLE LEVELS*, BELARUS

Product	Thousand tonnes % of total production								
	1986	1987	1988	1989	1990	1991	1992	1993	1994
Grain	312 4.4%	340 3.7%	122 1.8%	92 1.1%	25 0.3%	6 0.09%	0.8 0.01%	0 0%	0 0%
Potato	86 1.2%	27 0.4%	0.4 0.01%	0 0%	0.6 0.01%	0.2 0.01%	0 0%	0 0%	0 0%
Milk	524 13.8%	308 8.3%	193 5%	68 2%	7.2 0.2%	22.1 0.7%	9.4 0.3%	14.5 0.6%	12.4 0.5%
Meat	21.1 4.3%	6.9 1.6%	1.5 0.45%	0.6 0.15%	0.08 0.01%	0.03 0.01%	0.3 0.07%	0.007 0.002%	.003 0.003%

* The Temporary Permissible Levels in drinking water and food products are presented in Tables V (for USSR) and VI, VII (for Belarus) from 1986 to 1996.

TABLE XXIII. PRODUCTION OF MILK WITH ^{137}Cs CONCENTRATION EXCEEDING THE RPL–92 PERMISSIBLE LEVELS IN THE PUBLIC SECTOR OF SOME DISTRICTS OF THE GOMEL REGION, BELARUS

District	Produced, tonnes of contaminated milk		% of the total amount of milk	
	1993	1994	1993	1994
Bragin	2167	1491	8.8	9.7
Narovlya	915	730	19.3	20.8
Khojniki	104	416	0.7	2.8
Chechersk	511	815	5.8	8.6
Total	3697	3452	10.7	11

Long term protective measures have been implemented in two stages: the first in 1987–1991, and the second since 1992. In the first stage, severely contaminated land was taken out of use. Crops, such as lupine, peas, buckwheat, and, on ^{90}Sr contaminated lands, clover, which accumulate high levels of radionuclides, were completely excluded. The acid soil was chalked, increased amounts of phosphorus and potassium fertilizers were introduced, and some marshy plots were drained, deep sown and meadowed. Overall, the radiocaesium penetration into agricultural products decreased by a factor of 3.5. About a half of this reduction is due to sorption of ^{137}Cs in soils [10].

In spite of the considerable progress already made, more work is needed to reduce the excessive acidity of the soil and to improve the potassium content of 50% of the meadows and 20% of the arable land. Other measures required include irrigation control, and improvement of marshy and low-production pastures and of the hay meadows used mainly by cattle in the private sector [7]. In the meantime, the samples of milk and meat above the permissible levels produced in the private sector from 1993 to 1995 accounted for about 10% of all the samples (see Table XXIII for milk). During 1991–1995, up to 10–25% of the samples of locally produced food submitted for testing by residents contained levels of ^{137}Cs above the permissible level of 111 Bq L^{-1}.

Since 1992, the second stage of detailed countermeasures has been under way, taking into account the characteristics of every individual field or cattle farm. Methods are being developed to reduce vegetable product contamination by means of controlled mineral nutrition, by using bacterial preparations and new types of fertilizers. In animal farming, such approaches as selection of fodder depending on its contamination level, nutritional value and additives are suggested [7]. Programmes have been developed for the farms of the 11 most contaminated districts which provide for a 1.8–2.0 fold decrease in the radionuclide transfer to the food chain. The analysis of such programmes for the four districts of Bragin, Chechersk, Khojniki and Narovlya has shown that fodder for milk cattle and whole milk satisfying the permissible levels can be produced on 54% of the arable land and on 33% of the improved hay meadows and pastures. The rest of the cultivated land can currently be used only for producing fodder intended for meat and raw milk production [11].

Owing to the economic crisis, no more than 30% of the required agricultural protective measures could be financed in 1993–1995. A sharp decline occurred in the implementation of such countermeasures as liming, fertilizing, and irrigation control and in the establishment of cultivated pastures. The decrease in soil fertility has led to considerable reduction in crop production, which may have the effect of increasing the radionuclide transfer to produce. The need for further research and economic justification of the choice of protective measures is essential in view of the current budgetary constraints. Economic and technical aspects of ways to reduce population exposure and improve the competitiveness of agriculture are being studied. These include: 1) using the contaminated land for growing industrial crops, such as rape, sunflower and sugar beet, and 2) modernizing and upgrading the present facilities which process oleaginous crops for industrial purposes, and also potato and grain processing into starch and alcohol. The solution to these problems requires international co-operation and large scale investment [7, 9].

3.2.4. Conditions for safe living

The production of food in the contaminated areas of the republic is of primary concern. A thorough plan of action with compulsory measures must be implemented in all areas where foodstuffs may contain radionuclide concentrations above the permissible levels. Particular attention is being paid to the production of foodstuffs below the permissible levels by the private farms of 485 settlements where both stable and periodic increases in levels of ^{137}Cs and ^{90}Sr in milk are monitored. Here it is necessary for the local authority and the agricultural enterprises to allot 0.5 ha for crops and the same area of pasture per cow, and to provide for 0.5 kg of combined fodder with caesium-binding additives per cow and per day [12]. It would be worthwhile to start broad, systematic monitoring of ^{90}Sr in farm produce (especially milk, potatoes and vegetables) grown on soil with contamination exceeding 18 kBq.m^{-2}.

Most of the effort of rehabilitation must be directed to those contaminated areas where people are living. It is then necessary to introduce measures which enable the local population, especially land workers, to live and work safely on the land, such as providing them with additional sets of work clothes and other means of individual protection and supplying all settlements with gas in order to reduce the use of contaminated firewood.

Evacuated areas can be rehabilitated only as the general economic situation in the republic stabilizes and improves.

3.2.5. Perspectives for the future

It is vital to inform the population of the current radiation situation, of the radionuclide concentrations measured in foodstuffs, of scientific data concerning radiation related health hazards, and of any other indispensable facts and figures. Research undertaken by the Institute of Sociology of the Belarus Academy of Medical Sciences indicates that social and psychological stress is increasing in the contaminated areas.

One of the main reasons for stress among the affected people is fear for the future of their children and themselves related to what they expect of the potentially hazardous consequences of living in a contaminated area [13]. In 1989, 55.5% of the interviewed people expressed worry about their health, a figure which rose to 89.1% in 1993. In order to improve the psychological situation and morale, strict medical control and efficient medical aid must be provided; clinics, care centres and teaching and educational facilities must be set up, and State subsidies must be distributed more effectively. To solve these problems, priorities must be periodically reconsidered and the resources provided by the State optimally used.

3.3. Situation in the Russian Federation

3.3.1. Effects on the well-being of the population

Following the Chernobyl accident, about 50 000 people in the Russian Federation were resettled, or moved on their own initiative from the contaminated areas. They were for the most part (47 800 people), residents of the south western districts of the Bryansk region. The population in the contaminated areas of the Bryansk region includes 90 800 in the obligatory resettlement zone, 147 100 in the voluntary resettlement zone, and 236 400 in the radiological control zone [14]. From these areas, the inhabitants of 36 settlements were completely resettled in an organized manner by 1992. In 1994 in the most contaminated southwestern districts of the Bryansk region, the population decreased by 8 per 1000 residents, compared with 5.1 per 1000 for the Russian Federation as a whole. The overall mortality rate in 1994 in the same areas was 18.7 per 1000 residents — the highest rate in the period 1986–1996 — compared with 14.5 per 1000 for the Russian Federation.

Since 1986, medical examinations of the population have been undertaken together with the development of health care facilities in the contaminated areas. Later on, legislation provided for increased medical assistance, which included free pharmaceuticals. These measures had two opposing effects. On the one hand, they contributed to improvement in the welfare of the population, but on the other, they convinced the residents that their health had been definitely damaged as a result of radiation exposure, all the more so as the examinations were sometimes excessive. Increased incidences were recorded as described briefly in Section 1.1.1. The health situation was exacerbated by the fact that more physicians, as well as other professionals (teachers, agronomists, etc.), than other sectors of the population had left the contaminated areas.

How does the population evaluate its status of health? In the contaminated areas, the percentage of residents who rate their health as bad is four times that of those who rate it as good. In clean areas, the two percentages are approximately equal. Women view their health more pessimistically than men do, and this pessimism increases with age. Such perceptions influence the evaluation of environmental change in the residence area, which is also pessimistic [15].

The standard of living in all parts of the Russian Federation has been declining in recent years. This decline is even more pronounced in the most contaminated regions of Bryansk, Kaluga, Orel, and Tula. Until 1992, the deterioration of the standard of living due to the transition processes in the economy was offset to some degree by the State programme which provided compensation and privileges. But in 1993, over 90% of the residents in contaminated areas estimated their situation was unchanged or had deteriorated. Since then, the situation has worsened. The change in retail sales volume is an important indicator of the well-being in a particular region. While in the Russian Federation this volume, recalculated to stable 1995 prices, decreased compared with 1994 by 8%, the decrease was 30% in the Bryansk region, 21% in the Orel region, and 14% in the Tula region.

The housing space per resident in the contaminated areas has risen during recent years, although it is still slightly lower (17.9 m^2 per resident) than in the Bryansk region as a whole (18.8 m^2 per resident). Nevertheless, this figure exceeds the Russian average (17.4 m^2). This is a result of the State programme to overcome the accident consequences. Indicators of hospital care availability in the contaminated areas are quite close to those for the region and for the Russian Federation (129 beds per 10 000 residents against 127 and 130, respectively) [16].

Unemployment is steadily rising in the affected regions. By the end of September 1995, 30 500 people in the Bryansk region were unemployed (a 13.5% rise compared with the beginning of the year), 13 600 in the Kaluga region (a 27.8% rise), and 13 200 in the Tula region (a 50.9% rise) [17].

3.3.2. Effects on industrial and agricultural production

Since the beginning of economic reforms in the Russian Federation, industrial and agricultural production have declined year after year. This negative trend was not reversed in 1995. The worst situation has emerged in those Russian regions whose territories were extensively contaminated following the Chernobyl accident: the Bryansk, Kaluga, Orel, and Tula regions. While the overall production decline in the Russian Federation in 1994 was 23% compared to 1993, it was 38% the in Bryansk region, 30% in the Kaluga region, 32% in the Orel region, and 41% in the Tula region.

The areas in the Russian Federation most severely affected by radioactive contamination were agricultural. In those areas, annual yields of cereals, potatoes, milk and meat decreased during 1981–1985, followed by notable yield rises during 1986–1990. This trend is typical for the most contaminated areas of the Bryansk, Kaluga, Orel, and Tula regions, and for other contaminated regions of Central Russia. In the Bryansk region, the grain yield increased during 1986–1990 by a factor of 1.44, potato production by a factor of 1.17, and milk production by a factor of 1.06. These increases took place under significant limitations in agricultural production caused by radioactive contamination. An increase in productivity in the affected areas in the Bryansk region was due to the successful implementation of countermeasures such as fertilizer application, and to the radical improvement of natural grassland. Since 1991–1992 however, agricultural production has sharply decreased because of the national economic crisis. Moreover, due to the spring and summer drought, crop production in 1995 significantly decreased in comparison with 1994.

Economic activities in the contaminated territories of the Russian Federation are regulated by law and by the State decree "On the Status of the Territories Affected by Radioactive Contamination as a Result of the Chernobyl Disaster". The principal objective of the decree is the gradual return of the contaminated production facilities and environment into the economic cycle. The following modes of economic exploitation have been introduced in these territories, depending on their contamination level:

(a) **The (Russian) exclusion zone**. Special conditions for use of natural resources have been established: all kinds of forest activities, agricultural production, mining and processing of mineral resources are prohibited. Any commercial activity or transit of goods by any transportation mode is also forbidden. In this zone, provisions are being made for the conservation of the most valuable productive facilities, the prevention of the more valuable and potentially reclaimable agricultural land from turning wild, the afforestation of the less valuable agricultural land, the demolition of highly contaminated and fire-hazardous commercial and residential properties, and the conservation of historical, cultural and religious monuments of special national value.

(b) **The obligatory resettlement zone** (^{137}Cs soil deposition above 555 $kBq.m^{-2}$). All kinds of forest activities, cattle and other animal pasturing, and mineral mining are allowed only with special permission. Economic activities are carried out in accordance with recommendations contingent on the results of radioecological monitoring; the use of agricultural land is also subject to scientific recommendations. The restrictions established within this zone on the use of natural resources are aimed at the eventual recovery of the contaminated areas along with their gradual rehabilitation, making them suitable for economic exploitation and human habitation and activities.

(c) **The voluntary resettlement zone** (^{137}Cs soil deposition between 185 and 555 $kBq.m^{-2}$). Economic activities are allowed with practically no restrictions, and environmental monitoring has been improved. Providing that radiological monitoring is being conducted, and the results show radionuclide concentrations below the permissible levels, agricultural production, house building and other construction are permitted. Depending on the territory's contamination level, freedom of choice is offered to all economic sectors and to all types of business activity, and the development of private enterprise is encouraged.

(d) **The radiological control zone** (^{137}Cs soil deposition between 37 and 185 $kBq.m^{-2}$). All economic activities are allowed.

3.3.3. Changes in agricultural practices in the contaminated areas

The measures implemented to improve agricultural production, such as the cultivation of pastures, increased use of mineral fertilizers, soil liming, deep ploughing, supply of clean fodder, and special stabling and feeding of animals, have produced clean crops and almost completely clean animal products that satisfy the relevant permissible levels. Only in isolated places in the Bryansk region have milk and meat been found to contain radionuclides in concentrations above the permissible levels. This has involved less than 1% of milk samples and less than 0.1% of meat samples in the most contaminated southwestern districts of the region. Such instances occurred at private farms where the animal stabling and feeding recommendations might not have been observed. However, reduced funding and the resulting decrease in mineral fertilization and other reclamation measures on contaminated agricultural lands may well lead again to increased radionuclide concentrations in agricultural products.

The data from the Novozybkov district of the Bryansk region illustrate both negative and positive trends in the agricultural countermeasures. In this district, the average contamination density of agricultural land was 740 kBq.m^{-2} ^{137}Cs, ploughed land in 1986 — 703 kBq.m^{-2}, meadows — 851 kBq.m^{-2}, excluding 57 km^2 of agricultural land withdrawn from use. From 1986 to 1993, the soil-to-plant transfer factors, notably of caesium radionuclides, decreased by a factor of 2.4–7 depending on the soil type. The radiation situation led to changes in arable land use. The area sown with leguminous crops decreased by a factor of 2.9, that with fodder by a factor of 4.6, and that with potatoes by a factor of 1.9. During 1986–1994, measures to improve contaminated land were carried out. Radical improvement occurred in 175 km^2 of meadow and pasture. Between 1991 and 1994, 306 km^2 of land were limed; phosphorous fertilizers were applied to 196 km^2, and increased amounts of potassium fertilizers were also introduced. These measures improved the agrochemical and radiological characteristics of the soil and, by 1992, assured the compliance of almost all produce with the permissible levels in force. The contamination of different kinds of fodder decreased by a factor of 4–12 and, as a result, 98.6% of milk and 100% of meat produced in the public sector in 1993 complied with the permissible levels.

However, from 1993 to 1995, the deterioration in the economic situation of farming enterprises and cuts in budget subsidies reduced the application of special measures in the contaminated territories by a factor of 4–10. For example, the radical improvement of meadows and pastures in 1994 involved only 7.6 km^2, about 11.9% of the 1989 level; liming was done on 11.7 km^2 and only 16 kg per hectare of potassium fertilizers and 26 kg per hectare of phosphorus fertilizers were applied. This represented just 13.0%, 9.8%, and 37.0% respectively of the 1991 level. The application of nitrogenous fertilizers decreased by a factor of 2.9. The diminished application of special agrochemical and reclamation measures negatively affected the agrochemical characteristics of the soil. The soil acidity rose, while the soil content of potassium, nitrogen and humus decreased. This process developed especially rapidly in light soils. The arable land use changed, crop yields decreased, and the caesium contamination of the produce increased. The grain yield dropped from 2.4 to 2.2 tonnes/hectare, potatoes from 17.5 to 12.5 tonnes/hectare, and fodder corn from 26.1 to 16.3 tons/hectare. In 1994, the area producing potatoes decreased from 43.4 to 27.1 km^2, i.e. by a factor of 1.6. The area devoted to fodder corn, which is extensively used in animal diets, decreased from 39.5 to 13.1 km^2, i.e. by a factor of three. The caesium content increased in all crops, most of all in fodder crops. In 1994, compared with 1992, caesium contamination increased: in hay by a factor of 1.5, in green produce by a factor of 1.4 and in root crops by a factor of 1.5. This has resulted in an elevated caesium radionuclide content in human and animal diets.

3.3.4. Conditions for safe living

The Russian State programmes provided for a broad plan of action in the contaminated territories: protection of human health, specific measures for the exclusion and the obligatory resettlement zones, reduction of doses including measures in agriculture, food processing and forestry, economic rehabilitation of the territories, and restoration of the social and socio-psychological status of the population. These measures involved creating a system of health protection and a radiation monitoring network. In parallel, it was necessary to elaborate and implement a whole series of measures designed to create conditions of physical, psychological and social well-being for the inhabitants of the contaminated areas.

Unfortunately, the programmes have not been fully implemented, having received only partial financial support, due to the difficult economic situation in the Russian

Federation. Nevertheless, it has been possible to solve many social and economic problems experienced in the contaminated regions. Two million square metres of housing, hundreds of schools, hospitals, outpatients clinics, and structures for municipal services and production have been built for the inhabitants of these regions, allowing the population to restart activity. In Bryansk, the most severely contaminated region, more than 800 000 square metres of housing, 1000 km of gas pipeline, schools with an enrolment capacity of 6000, and hospitals and clinics have been constructed.

To achieve these objectives it was necessary to change, reorganize and modernize the means of production, and to elaborate specific programmes to compensate for the deficit in the workforce in some areas and soaring unemployment in others, so as to create attractive living and working conditions for the affected population. Moreover, a whole series of measures had to be implemented to attract skilled people such as doctors, teachers, and trainers to the affected areas; and new teaching methods had to be elaborated and implemented to give an environment-related education, develop the creative abilities of the upcoming generation, and promote new professional and economic activities in the private sector.

A system of social and psychological monitoring was created, a social information service and vocational training centres were set up and job placement was organized to help the resettled people and the unemployed living in contaminated areas. Specialists were trained to handle the social, economic, psychological and legal problems of the population in these areas. Religious monuments were restored and orphanages, convalescent homes and homes for the elderly were built.

A new "unified federal programme for 1996–1997 and to the year 2000 to protect the population of the Russian Federation from the consequences of the Chernobyl disaster" was elaborated. It respects the priorities laid down in previous programmes, including those of the Bryansk region. During the period 1996–2000, this programme has provided for the construction in the affected areas of 120 000 m^2 housing, kindergartens with a capacity of 5500, primary schools with a capacity of 7500, hospitals with 2000 beds, clinics for 2500 patients, an additional 1000 km of gas pipelines, and 1000 km of highways.

An experimental programme entitled "Kaluga priority" is currently being implemented in five districts of the Kaluga region with the objective of covering the expenditure incurred by the economic rehabilitation of the contaminated areas. The aim of the programme is to move from subsidies granted without repayment to a return on State investment using local financing.

3.3.5. Perspectives for the future

For the next twenty years, Government policy will be along the following lines. Before the year 2000, the Federation started to implement new principles of classification of contaminated areas, based upon the additional doses to the population due to the Chernobyl disaster and presupposing gradual reduction in compensation granted to its citizens. This will make it possible to reduce expenditure on such fixed compensation and use the means thus made available to address concrete environmental, social and economic problems at every level. During this period, active use must be made of additional regional sources to finance the rehabilitation measures (as for the 'Kaluga priority' programme).

During the second phase, from 2001 to 2015, the contaminated areas will benefit from the "concept for a sustainable social and economic development in Russia" currently being elaborated, which will have the major effect of creating an environment compatible with the prevailing contamination levels, so that in 2015 further major tasks of minimizing the consequences of the Chernobyl disaster can be undertaken and the concerned regions can reach an acceptable standard of social development. After the year 2015, the health consequences of the accident will still be monitored, and regular medical follow-up will be provided to the exposed individuals and their progeny so as to treat them medically and grant them vital financial compensation, benefits and allowances.

3.4. Situation in Ukraine

3.4.1. Effects on the well-being of the population

From the latest data as of 1 July 1995, in Ukraine about 3.1 million people, including about 950 000 children, have been affected by the Chernobyl accident. Social protection laws were passed "to diminish the negative impact of the Chernobyl disaster upon population health", on the principle that "the Chernobyl-related additional dose received by individuals of the critical population group, i.e. children born in 1986, should not exceed the dose which would have been received prior to the disaster under normal environmental conditions by more than 1.0 mSv per year, and 70.0 mSv during their lifetime". According to Ukrainian law, the contaminated territory is divided into four zones (Table XXIV).

In accordance with Ukrainian law, evacuation and resettlement have been carried out from 1986 to the present. The first stage of evacuation was completed in 1986 and involved 91 000 people from 76 settlements from the Kiev and Zhitomir regions, which were situated within the exclusion zone. From 1990, the resettlement plan included the resettlement from the obligatory resettlement zone of people living in 82 settlements of the Kiev, Rovno and Chernigov regions, i.e. 44 000 people or about 17 000 families. By 1 October 1995, 25 settlements were practically completely relocated, and 52 settlements were partly relocated (over 50% of residents). 11 523 families had been resettled, while 5419 families continue to live in the obligatory resettlement zone, including 1112 families with children. In addition to obligatory resettlement, Ukrainian law provides for voluntary resettlement of people living in the voluntary resettlement zone and in the radiological control zone. 12 369 families from these zones have been registered for resettlement, and about 9000 of these families were resettled during 1990–1995 [2].

To compare risk perception concerning the consequences of the Chernobyl accident with the perception of other causes of premature death, the inhabitants of Kiev city, who received no privileges or compensation, and the people of the village of Bogdany in the Kiev region, who had special privileges and compensation, were interviewed. Each respondent was asked to rank 15 risk situations from the most dangerous to the least dangerous in terms of premature death. Results show that the inhabitants of Kiev city put the Chernobyl accident hazards in second place along with electricity and motorcycle hazards, while the rural population of Bogdany put it in first place (Fig. 18).

To put risk perceptions in perspective, Table XXV presents the main causes of premature death in Ukraine with the number of deaths and corresponding risk coefficients. The projected risk from the Chernobyl accident is one or two orders of magnitude lower than the risk from other existing situations.

TABLE XXIV. CLASSIFICATION, CRITERIA AND LEGAL STATUS OF CONTAMINATED ZONES IN UKRAINE [2, 18, 19]

Category of contaminated zone	Criteria of zone definition	Legal status of zone (main items)			
Exclusion zone	Area evacuated in 1986 Cs * ≥ 1480 $kBq.m^{-2}$	Permanent residence is prohibited	Production of any commodity is prohibited	Transit passage for all transport is prohibited, entry (import) and exit (export) only on special permit	
Obligatory resettlement zone	Cs * ≥ 555 $kBq.m^{-2}$ or Sr * ≥ 111 $kBq.m^{-2}$ or Pu * ≥ 3.7 $kBq.m^{-2}$ where D_{eff} > 5 mSv per year				
Voluntary resettlement zone	185 ≤ Cs * ≤ 555 $kBq.m^{-2}$ or 5.5 ≤ Sr * ≤ 111 $kBq.m^{-2}$ or 0.37 ≤ Pu * ≤ 3.7 $kBq.m^{-2}$ where D_{eff} > 1 mSv per year	Enterprises, organizations and institutions, collective farms are exempt from taxes, preferential financing is provided	Application of pesticides, herbicides, or toxic chemicals is prohibited without special permit	The construction of new and the development of existing enterprises are prohibited.	
Radiological control zone	37 ≤ Cs * ≤ 185 $kBq.m^{-2}$ or 0.74≤ Sr * ≤ 5.5 $kBq.m^{-2}$ or 0.185 ≤ Pu * ≤ 0.37 $kBq.m^{-2}$ where D_{eff} > 0.5 mSv per year			The construction of new enterprises affecting public health and the environment and the development of such existing enterprises are prohibited.	The construction of sanatoria and convalescent homes is prohibited.
No restriction related to radiation	D_{eff} < 0.5 mSv per year				

* Soil deposition of ^{137}Cs (Cs), ^{90}Sr (Sr) or sum of plutonium isotopes (Pu).

TABLE XXV. MAIN CAUSES OF PREMATURE DEATH IN UKRAINE AND ESTIMATES OF PREMATURE DEATH RISKS

Risk situations		Number of deaths in 1993	Risk per year
Premeditated murder		4 000	7.7 10^{-5}
Fatal traumatic injury	— at home	22 000	4.2 10^{-4}
	— at work	2 373	9.1 10^{-5}
Traffic death		10 000	1.9 10^{-4}
Total		38 500	7.8 10^{-4}

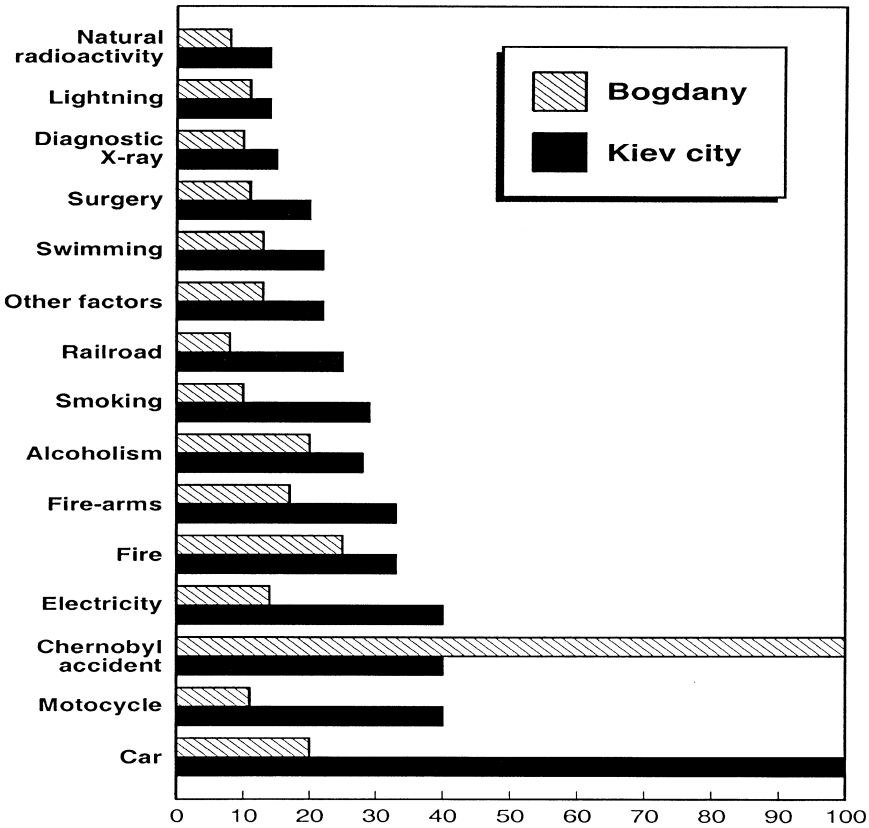


Fig. 18. Ranking of risk of premature death in various situations, by Kiev city inhabitants and inhabitants of Bogdany village contaminated with radionuclides due to the Chernobyl accident.

3.4.2. Effects on industrial and agricultural production

In Ukraine, the total area of land contaminated with a ^{137}Cs soil deposition higher than 37 kBq.m^{-2} amounts to 37 000 km^2 in eight regions. The area of contaminated agricultural lands is 12 000 km^2 (12% of the total contaminated arable land), the area of contaminated forests is 15 000 km^2 (40% of the total area). 1800 km^2 of agricultural lands, (including 549 km^2 in the exclusion zone), and 1570 km^2 of forest, (including 1100 km^2 in the exclusion zone), have been withdrawn from production. Over 600 farming enterprises are operating on soil with a contamination density higher than 37 kBq.m^{-2}.

3.4.3. Changes in agricultural practices in the contaminated areas

The main measures for diminishing the contamination of raw products are those of reclamation, such as liming acid soils, applying large amounts of mineral fertilizers, and cultivating and creating clean pastures. Land use has been changed, taking into account the soil contamination levels and transfer factors of radionuclides to plants. Fieldwork aimed at reducing dust formation and preventing soil erosion has been carried out using up-to-date technologies that ensure optimal land cultivation. The areas for food and industrial crops have been decreased, while the areas devoted to fodder crops are being expanded. These measures facilitate the best use of land, the implementation of resource saving systems of soil cultivation, and an increased production of less contaminated crops.

Feeding animals with clean fodder at the final stage before slaughter, or with fodder either concentrated or containing ferrocenes, has proved to be effective. The change in specialization of farming enterprises, using these methods, to cattle, fish, horse and fur-animal breeding is producing encouraging results. Cattle grazing on clean pastures minimizes the radionuclide content in milk during the grazing period. The quantity of milk contaminated over 370 $Bq.L^{-1}$ supplied to dairies from collective and private farms is shown in Fig. 19. In recent years, in order to obtain clean products, especially clean milk from private farms, liming was carried out on 100 km^2, and mineral fertilization on 120 km^2. Clean pastures have been assigned for grazing private cattle; farmers are supplied with concentrated fodder containing additives, and boluses of ferrocenes. In 1986, 6410 tonnes of meat contaminated above the permissible levels was delivered to slaughterhouses; this figure fell to 1280 tonnes in 1987, 168 tonnes in 1988, 34.5 tonnes in 1991, 5.2 tonnes in 1992, 5.2 tonnes in 1993, and 5.0 tonnes in 1994.

A network of radiological monitoring has been established in order to prevent the production and sale of foodstuffs with radionuclide concentrations exceeding the permissible levels. More than 800 specialized laboratories and stations are operated by the Ministry of Agriculture and Foodstuffs of Ukraine. Monitoring is implemented at all stages in agricultural production: on the farm, during processing, in retail trade, and for ready-to-use produce. Quality certificates are issued for food products which have been monitored.

At present, there is a problem in obtaining "clean" milk, i.e. below the TPL of 370 $Bq.L^{-1}$, from private cattle. Currently, 228 settlements still produce milk contaminated over 370 $Bq.L^{-1}$; there are 103 in the Rovno region, 68 in the Zhitomir region, 52 in the Volyn region, and 5 in the Chernigov region. The contaminated milk is produced by private farms but this is diluted with non-contaminated milk to obtain a ^{137}Cs concentration below the TPL.

In general, the whole system of protective measures in agriculture is being complied with. During the first seven months of 1995, alkalization and re-alkalization were carried out on 308 km^2 of meadows and pastures; 75 000 tonnes of sapropel and peat complexes were produced; mineral fertilizers were introduced on 80 km^2; 2500 tonnes of combined fodder were produced, and biological preparations were applied on 425 km^2.

An analysis of caesium radionuclide incorporation in most of contaminated areas of Ukraine shows a steady decrease since the first post-accident year. The sole exceptions are the Rokitno and Dubrovitsa districts of the Rovno region. The acid marshy soils of these districts cause increased biological mobility of caesium; as a result, the soil-to-plant transfer factors are ten times higher than those found in other areas. In addition, the way of life and historical traditions of that part of Ukraine are contrary to the implementation of measures that limit the consumption of local foodstuff, primarily milk, by the population. Other products contribute significantly less to internal irradiation.

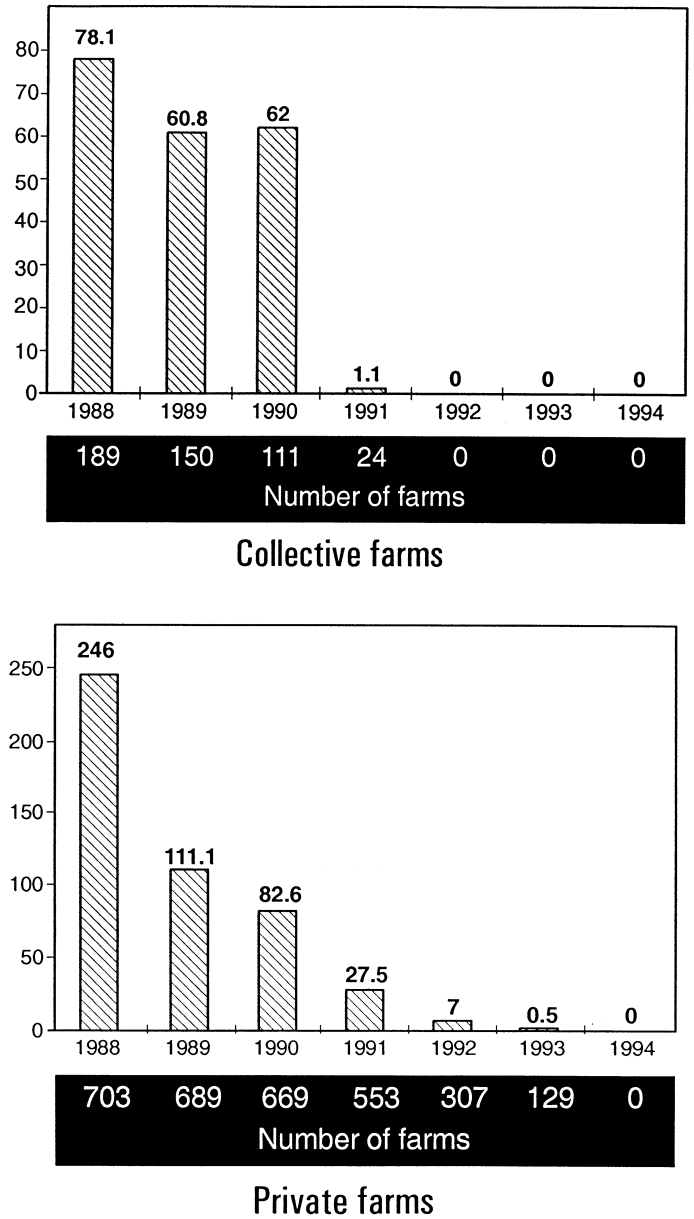


Fig. 19. Amount of milk with $^{134}Cs+^{137}Cs$ concentration above 370 Bq/L supplied to dairies, in kilotonnes (Ukraine).

The efficacy of giving the population clean food products to reduce internal exposure has been demonstrated by scientists at the Research Centre of Radiation Medicine of the Ukrainian Academy of Medicine in Kiev. In children from the Rokitno district of the Rovno region, whose caesium radionuclides whole body content ranged from 4.4 to 20 kBq, the introduction into the diet of vegetables, berries and non-fish seafood (sea kale, cucumaria), accelerated excretion of caesium radionuclides from the body and decreased the whole body content by up to 35%.

3.4.4. Conditions for safe living

In Ukraine, the first priority is the health of the population. Medical support is constantly being provided by 300 medical institutions, among which there are 77 district hospitals, 24 regional hospitals for adults and children, nine specialized dispensaries with 1080 beds, the Kiev regional hospital No. 2 with 240 beds, the Ukraine dispensary with

140 beds, specializing in treating acute effects of radiation, the Research Centre for Radiation Medicine of the Academy of Medical Sciences of Ukraine with 300 beds and the clinics of other research institutes of the Academy.

In accordance with the programme established by the “Chernobyl Ministry” of Ukraine’s "Priority measures for 1995 for organizing medical and sanitary aid for the population suffering as a result of the Chernobyl disaster", 2800 billion carbovanets (about US $20 million) for the purchase of sophisticated medical equipment was granted to medical facilities giving permanent help to suffering citizens. Twenty immunology laboratories have been equipped with automatic immunological analysers.

Stays in health resorts and specialized sanatoria have been a major influence on the improvement and recovery of people’s health. Since 1986, the exposed population has benefited from health improving measures. For children who suffer from chronic health disorders, the Ukrainian Ministry of Health Protection opened nine health centres with a capacity of 2500 beds, where some 17 000 children can rest yearly. With the help of the best health resorts, 11 institutes specializing in rehabilitation were set up with 650 beds to treat some 10 000 clean-up workers annually.

Sociological research shows, however, that the measures taken to mitigate the consequences of the Chernobyl accident are insufficient and not always efficient. For example, the resettlement has had a critical impact on mental health, social status and cultural habits, especially among the elderly. A sociological survey records that approximately 50% of the resettled population expressed the desire to return to their native land, even though it was contaminated and could endanger their health and way of life. Evacuating and resettling is an attempt to solve only the physical problem and does not reduce the level of social and psychological stress. It has created a whole series of new problems linked, above all, to the hardships of adjusting to new living conditions.

3.4.5. Perspectives for the future

Activities on mitigation of the Chernobyl accident consequences in Ukraine are regulated by the laws of Ukraine [18, 19] and the “Concept of the National Programme for Mitigation of the Chernobyl Accident Consequences and Social Protection of Citizens in 1994–1995 and for the Period until 2000” [20] approved by Parliament in 1991–1993.

The main objectives of the National Programme are:

- to reduce the health risk to Ukrainian citizens affected by the Chernobyl catastrophe;
- to stabilize the shelter facility and render it ecologically safe;
- to improve ecological conditions on the territories contaminated with radionuclides;
- to rehabilitate the contaminated territories and restore them to full economic activity.

Certainly, most of these objectives will apply to the subsequent period lasting until 2010. Additional special objectives for this prolonged period are:

- to assess the health status of the population affected by the Chernobyl catastrophe and render necessary medical aid;
- to maintain nuclear and radiation safety of the shelter facility and eventually render it ecologically safe;

- to monitor living conditions in areas contaminated with radionuclides, taking into account all ecological and hygienic factors;
- to implement agricultural countermeasures in the Ukrainian Polyssye in order to produce foodstuffs meeting sanitary standards;
- to rehabilitate abandoned land.

The long term funding of the National Programme is foreseen in the State budget of Ukraine.

REFERENCES TO SECTION 3

[1] Main Results of the Scientific Part of the State Program of Republic Belarus for overcoming the Catastrophe Consequences on Chernobyl NPP in 1996-2000. Year 1996 (Konoplya, E.F, Rolevich I.V., Eds), Ministry of Emergency of Republic Belarus, Minsk(1997) 164–175 (in Russian).

[2] UKRAINIAN NATIONAL REPORT, Ten Years After Chernobyl Nuclear Power Plant Accident, MinChernobyl, Kiev (1996).

[3] KONOPLIA, E.F., ROLEVICH, I.V., (Eds), Belarus National Report, The Chernobyl Catastrophe Consequences in the Republic of Belarus, Minsk (1996).

[4] BOGDEVITCH, I.M., Consequences of the Chernobyl Accident and Implication on the Use of the Contaminated Soils in Belarus, In: Social and Economical Implications on the Use of the Funds for the Agriculture, Minsk (1994) 40–46 (in Russian).

[5] BOGDEVITCH, I.M., SCHERBACOV, V.A., Effect of the Radioactive Contamination of Belarus Land on Production and Quality of Agricultural Produce, Proc. Academy of Agrarian Sciences of the Republic of Belarus **1** (1997) 30–40 (in Russian).

[6] KONOPLIA, E.F., et al., Concepts of the Management of the Exclusion and Resettlement Zones, Minsk (1994) 94 (in Russian).

[7] BOGDEVITCH, I.M., (Ed.), Guide for Agricultural Practice on Lands Contaminated by Radionuclides in the Republic of Belarus for 1997–2000, Minsk (1997) 76 (in Russian).

[8] BOGDEVICH, I.M., "Use of contaminated soils in Belarus, The evolution of the soils", The protection and the Increase of the Production Capabilities in the Present Social and Economical Situation (Proc. 1st Conf. of the Society of Pedology, Gomel, Belarus, 1995) 9–10 (in Russian).

[9] Instruction for Determination of the Additional Resources for Agriculture in the Radioactive Contaminated Zone, Ministry of Emergency of Republic Belarus, Minsk (1999) 26 (in Russian).

[10] BOGDEVICH, I.M., Agricultural Scientific Fundamentals in Contaminated Areas, In: The Chernobyl Disaster: Causes and Consequences, Skaryna (1992) 42–69 (in Russian).

[11] BOGDEVICH, I.M., et al., Guide of Industrial and Agricultural Productions in the Contaminated Territories of the Republic of Belarus 116, Minsk (1993–1995) (in Russian).

[12] BOGDEVICH, I.M., et al., Methods to Define the Technical Needs of Agriculture in the Contaminated Areas from 1993–1995, Minsk (1993) (in Russian).

[13] BABOSSOV, E.M., "Social aspects of the consequences of the Chernobyl disaster in Belarus", The Chernobyl Disaster: Causes and Consequences, Minsk, Skaryna (1992) 123–137 (in Russian).

[14] VLADIMIROV, V., (Ed.), Russian National Report "Ten Years of the Chernobyl Disaster, Results and Problems from Dealing with its Consequences in Russia", Moscow (1996) 33.
[15] ZAITSEV, A.K., et al., Reports on Sociological Study of the Population Affected by the Chernobyl Accident, Kaluga Institute of Sociology (1992–1994).
[16] ANNUAL STATISTICAL REPORT, The State Committee on Statistics of the Russian Federation (1992–1994).
[17] POVALYAEV, A.P., Main Results of Complex Analysis of the Situation in Territories of Russia Contaminated by the Chernobyl Accident, NSI Report, Moscow (1995).
[18] The Law of Ukraine "On the legal regime of the territory subjected to radioactive contamination from the Chernobyl accident", Kiev, 27 Feb. 1991.
[19] The Law of Ukraine "On the status and social protection of the citizens suffered as a result of the Chernobyl accident", Kiev, 28 Feb. 1991.
[20] Decree of the Parliament of Ukraine "On approval of the Concept of the National Programme for mitigation of the Chernobyl accident consequences and social protection of citizens in 1994–1995 and for the period until 2000", Register of the Parliament of Ukraine, Kiev (1993) No. 41 393.

4. RADIOBIOLOGICAL CONSEQUENCES OF IRRADIATION OF FLORA AND FAUNA IN THE EXCLUSION ZONE

4.1. General radiological conditions

The exclusion zone is composed of areas that received the most radioactive contamination following the accident at the Chernobyl nuclear power plant (NPP). These areas were evacuated and economic activity practically ceased. They include the 30 km zone and various regions of Belarus, the Russian Federation and Ukraine [1, 2, 3]: 2100 km² in Belarus, 170 km² in the Russian Federation and some 2040 km² in Ukraine. The maximum levels of soil contamination, measured in 1986, reached 370 $MBq.m^{-2}$ (10 000 $Ci.km^{-2}$) for ^{137}Cs, 5 $MBq.m^{-2}$ (135 $Ci.km^{-2}$) for ^{90}Sr and 0.1 $MBq.m^{-2}$ (2.7 $Ci.km^{-2}$) for plutonium radionuclides.

The exclusion zone is characterized by a very uneven distribution of radioactive particles with a wide range of physicochemical properties and radionuclide composition, all of which were determined by the conditions of radioactive release into the environment and the prevailing meteorological conditions when the radioactive fallout occurred. One typical element of the contamination of these territories is the presence of a large quantity of "hot particles" and of fallout of nuclear fuel particles in the area closest to the reactor. 24 000 people in Belarus and 91 000 in Ukraine were evacuated from this exclusion zone. What characterizes these territories today is the large number of temporary and permanent nuclear waste disposal sites, with a total activity of more than 15 PBq (400 000 Ci), as well as the presence of the shelter and the remaining operating power plant.

Over the past few years, the radiological situation in the exclusion zone has stabilized, thanks to the decay of short and medium lived radionuclides, the reduced migration of ^{137}Cs because of its increasing absorption and fixation by the soil, a decrease in the concentration of radionuclides in the ground air, and also a decrease in the number of particles dispersed by the wind. Today, the environment in the exclusion zone is mainly contaminated with the long lived radionuclides ^{137}Cs, ^{90}Sr, $^{238+239+240}Pu$ and ^{241}Am [4]. Notably, ^{90}Sr has become more mobile in the soil-vegetation system and groundwater in these territories, and its concentration has increased in the water table near temporary storage areas for radioactive waste. The circulation in the environment of ^{241}Am has increased, and this radionuclide, a decay product of ^{241}Pu, is characterized by high mobility and radiotoxicity. Other radionuclides have also become increasingly mobile in the environment, as a result of leaching from "hot particles".

Water fluxes are one of the major pathways by which radioactive particles migrate beyond the limits of the exclusion zone. For example, in 1986, the waters of the Pripyat river carried ^{137}Cs and ^{90}Sr at average annual concentrations of 22 $kBq.m^{-3}$ and 1.9 $kBq.m^{-3}$ respectively, and in 1995, these figures were still 0.1 $kBq.m^{-3}$ and 0.3 $kBq.m^{-3}$. Recently, it appears that the concentration of ^{90}Sr has tended to rise compared with the amounts recorded in 1989–1990. The quantity of radioactive particles migrating beyond the limits of the exclusion zone can reach peaks under some extreme conditions such as those prevailing during floods, forest fires, and dust and sand storms. Most radioactive particles are concentrated in the top 5–8 cm of the soil and in sediments in water systems. The migration of radionuclides through the water table did not lead to lasting pollution of large quantities of underground water resources. The water table is most contaminated in areas surrounding storage places for nuclear waste, where the concentration of ^{90}Sr reaches $1.1.10^6$ to $1.1.10^8$ $Bq.L^{-1}$ (30 $\mu Ci.L^{-1}$ to 3 $mCi.L^{-1}$), and that of plutonium isotopes 0.5 $Bq.L^{-1}$ in the water in contact with the waste.

4.2. Effects of radiation on the environment

Flora and fauna in the exclusion zone include more than 1100 species of plants, over 40 species of mammals, more than 70 species of birds and 25 species of fish, some of which are listed as endangered species. An accident of this magnitude, with a large radioactive release into the environment, has a severe impact on plants and animals in the vicinity of the damaged reactor. The irradiation of the flora and fauna close to the reactor was extremely acute and severe, amounting to several Gy per hour during the release, but subsequently falling to less than 1 mGy.h^{-1} (Fig. 20). The doses were high enough to induce changes at all functional levels, from the molecular and cellular level to the environmental level with complex effects on the population and ecosystem. Modifications of the ecosystem led to damage to, and the death of, biota in the most heavily polluted areas [4, 5, 6].

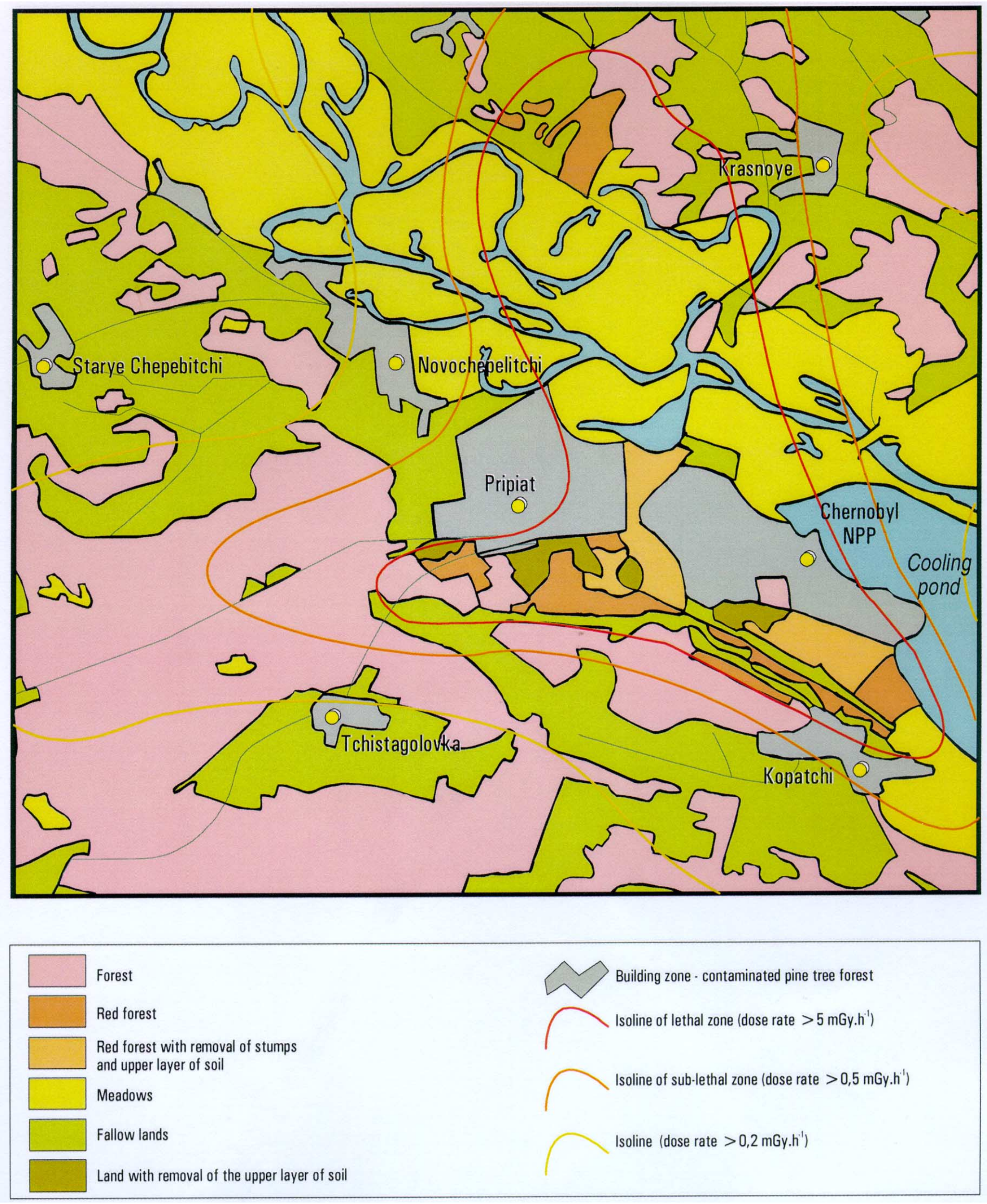


Fig. 20. Land use and lethal and sublethal dose rate isolines relevant to coniferous forests in the surroundings of the Chernobyl nuclear power plant on 1 June 1986.

In order to make an accurate estimate and prediction of the impact of radiation on the biota, one must know the doses they received. For many reasons, it was impossible to assess this immediately after the accident. It is therefore even harder to forecast and define the biological consequences of the Chernobyl accident in view of the insufficient dosimetric data. Moreover, the extremely heterogenous deposition of radioactive particles in the environment produced a wide range of doses to which the biota were subjected, and which in some cases, even in very small geographic areas, differed by one order of magnitude.

4.2.1. Impact of radiation on flora in the early phase of the accident

In order to evaluate the influence of the Chernobyl accident on the environment, it is necessary to bear in mind the fact that the radioactive particles were released at that time of year when natural growth is rapid and reproductive organs are developing — a time when flora and fauna are most sensitive to radiation. The maximal radioactive impact on nature occurred during the early period of acute radiation exposure (10 to 20 days following the accident), at which time most of the dose came from short lived radionuclides. During the second stage, which included the summer and early autumn of 1986, radioactivity in the upper layer of soil fell to 20–25% of its original value. The current third stage is characterized by a low dose rate chronic irradiation mostly from ^{134}Cs and ^{137}Cs. Plutonium isotopes and ^{90}Sr also have an important radiological impact in the exclusion zone.

Coniferous woods showed an exceptionally high sensitivity to radiation. During the two weeks following the accident, in an area of 5.8 km^2 downwind from the Chernobyl power plant, trees absorbed doses of 80–100 Gy in the needles and over 20 Gy in the apical meristem, leading to the death of pine trees and partial lesion of the crown of birch and alder. In the area closest to the reactor, small areas of deciduous forest were nearly totally destroyed. From 1986 to 1987, in an area of 37.5 km^2, where trees absorbed doses of 10–20 Gy in the apical meristem, 25–40% of the coniferous forest was wiped out; 90–95% of pine trees suffered from necrosis of buds and young sprouts, from a partial drying-out of their crowns, to a near complete interruption of growth processes and radiation induced morphological changes. From 1988 to 1989, some of the trees in this area recovered their reproductive function [4, 7, 8, 9].

The impact observed was due to the extremely high external irradiation in the first stage following the accident. A retrospective assessment of the doses absorbed by the forest leads to the conclusion that the lethal dose for common pine trees is 50–60 $Gy.a^{-1}$ and for European fir trees, 10–12 $Gy.a^{-1}$. Fig. 20 shows the lethal and sublethal dose rate isolines for coniferous trees in the surroundings of the Chernobyl NPP [10].

Reproductive organs showed a high sensitivity to radiation. In 1986, there was a clear relationship between the germination capacity of pine tree and fir tree seeds and the absorbed doses: the quantity and size of seeds, their germination power and growth rate diminished and the number of barren seeds rose proportionally with the absorbed doses. In 1987, at doses of 0.7–1.1 Gy, chromosome aberrations in generative tissues of trees were two to three times more frequent than those occurring spontaneously, and the viability of pollen was reduced by 30%. The number of morphological anomalies in pollen increased.

4.2.2. Radiation damage to coniferous forest

The high radiosensitivity of coniferous plants, increased by the fact that the accident occurred during a period of buds blossoming, was the reason for destruction of the ecological systems of pine (*Pinus silvestris*) woods in the most contaminated areas in the vicinity of the destroyed reactor. The main contribution in the injury of photosynthetic organs and growth tissues was due to the beta emitters which had been deposited on plant surfaces. The contribution of external gamma radiation to the total absorbed dose amounted to only 10%.

The 'zone of complete forest death' is characterized by 100% mortality of pine trees, and corresponds to those areas with over 5 $mGy.h^{-1}$ dose rate of gamma radiation on 1 June 1986. The calculated absorbed dose of gamma radiation in this zone amounted to 80–100 Gy in the needles and more than 20 Gy in the apical meristem. About 5.8 km^2 of forest was destroyed. The branches of the pines which perished had a bright reddish-brown colour. This "red forest" extends along the main trail of radioactive fallout for a distance of 5–7 km to the north, 2–3 km to the west, and 1.5–2 km to the south. Isolated patches can be found at distances of up to 9 km to the north and 6 km to the west of the destroyed reactor.

The deciduous forests and scrublands, the new growth of grass and the moss-lichen layer within the zone of complete coniferous forest death showed high ground desiccation, retardation of growth processes and damage to reproductive organs during the first vegetation season.

Within the 'zone of severe damage to the forest' (where the trees received a calculated absorbed dose of 30–80 Gy in the needles and 10–20 Gy in the apical meristem at a dose rate of 0.5–5 $mGy.h^{-1}$ on 1 June 1986), there was a complete wipe-out of young pine trees, with partial necrosis of young shoots on mature trees. Next to the saplings, lichen-pine plantations growing in poor, sandy soils suffered most. The area of pine forests in this zone is 37.5 km^2.

Within the 'zone of moderate damage to the forest', where the dose rate on 1 June 1986 was 0.2–0.5 $mGy.h^{-1}$, the calculated absorbed dose is estimated to be 20 Gy in the needles and 5–10 Gy in the apical meristem. This zone is typified by the suppression and death of the growth points of coniferous branches in the summer of 1986 and by the production of radiation changes, which were most severe in 1987. In this zone, 119 km^2 of pine forest was affected.

In the remaining part of the exclusion zone, and in a series of radioactive spots beyond its borders, there were no external signs of morphological changes in conifers but in 1986–1987 a drop in the germination of seeds was noted as were chromosome anomalies during meiosis.

A unique case of wood exposure in the exclusion zone near the Chernobyl NPP was observed by the authors of Ref. [11]. They measured activity concentration of ^{137}Cs and ^{90}Sr and calculated absorbed doses in parts of pine seedlings (roots, trunk, needles) planted in 1987–1988 in soil covering the “red forest” buried at a depth below 1.5 m, 1.5 km west of the NPP. In wood sampled in 1996, the maximum observed concentrations were 4.2 MBq kg^{-1} for ^{137}Cs in the youngest needles and 1.1 MBq kg^{-1} for ^{90}Sr in the oldest needles. The annual total absorbed doses in 1996 in different parts of pine trees were estimated to be 2–17 Gy; the lifetime dose for the needles (4 years) was about 44 Gy; 80–90% of the absorbed dose was caused by internal exposure although the dose rate at the sampling site was 15–45 μGy/h.

4.2.3. Restorative processes in perennial plants growing in the exclusion zone

It is difficult to assess the impact of the radiation on perennial plants in the exclusion zone, as they were subjected to a period of intense exposure in the spring of 1986, followed by less intense chronic irradiation, and also because their radiosensitivity changed during their annual development cycle. Interpreting the results is also complicated by the fact that during irradiation, restorative processes take place along with development of the radiation effects. After the period of severe irradiation, restorative processes in perennial tree and bush species were observed for 1–1.5 years. The intensity of such processes as the formation of roots, shoots and young growth, as well as physiological reactions of a compensatory nature, were used as criteria of the restoration process.

Perennial pine trees do not tend to form young growth. A pine crown has powerful restorative potential of a vegetative nature, having a large number of dormant buds which are protected all the year round by coniferous branches. Observations during the post-accident period 1986–1992 showed that, if a pine tree had received a dose greater than 14 Gy (a sublethal dose for a pine tree during the intense spring irradiation period), restoration could only occur in the form of the additional formation of shoots from previously dormant buds. This process began in 1987, a year after acute irradiation started, and was manifest by the appearance in the highest part of the crown of individual shoots in bunches on a very long branch situated on a short, thick growth centre. The role of these shoots is thought to be the provision of the minimum level of photoassimilation required to support the vital functions of the tree's aggregating organs and tissue (the roots, wood of the trunk and branches). This is confirmed by the excessively high intensity of photosynthesis in such coniferous branch shoots, three to four times higher than normal, suggesting the compensatory nature of this process. With each successive year, the number of such shoots in the crown of the tree has increased, indicating the possibility of the gradual restoration of the initial functions of a perennial plant. Starting in the 1988 growing season, in the zone of severe and moderate damage to the forest, intensive restoration occurred in older trees, although the previous year's growth of shoots was higher in the upper whorls than in the lower ones. The survival rate of severely contaminated trees depends on the previous year's growth of shoots, and if the growth is about 20% of the normal assimilation at the observed rates of growth, two to three years are required for the restoration of such trees. Survival is therefore possible for individual trees which currently have 5–10% of the usual number of shoots on green branches.

Changes in tree height are a post-radiation reaction to the death of the axially topmost shoot; its role is taken over by one of the side shoots in the whorl, usually the strongest one. This effect was noted in approximately 30% of pine trees (*Pinus excelsa*) which had received doses of 11–15 Gy. Data on the dynamics of compensatory and reproductive generation at different levels of radiation doses also suggest the possibility of the restoration of perennial plants in the exclusion zone which have exhibited new growth. Such indices as the healing of damage to branches and of saw cuts on branches of a certain diameter, and the amount of secondary growth on perennial plants after removing the topmost buds, were used as criteria of compensatory regeneration. The intensity of rhizogenesis in black currant (*Ribes nigrum*) and holly ivy (*Salix acutifolia*) cuttings was used as a criterion of the occurrence of reproductive regeneration in plants sprouting in soils with different levels of radioactive contamination. The results obtained show, at the dose levels observed in the exclusion zone, a real increase in the intensity of all types of regenerative processes in perennial plants.

The short lived beta emitters were the main contributors to the absorbed dose, and the major radiobiological effects appeared in contaminated plantations of ordinary pines and fir trees. However, in the first year, the maximum absorbed doses also had an effect on deciduous birch, alder and aspen, with their subsequent full recovery.

The number of buds, the growth of phytomass of the crown and the state of development of seeds can be used as indicators for evaluating damage to trees. Minor damage was found in terms of these indicators when the cumulative dose in the period of severe irradiation was up to 0.5 Gy. No visible signs of damage to the trees were observed. In some cases, the effects of the radiostimulation of growth appeared, but these were not of a clearly defined character. The situation returned to normal within the first year, and the state of the plantations could not be distinguished from that of the tree stock which had not been irradiated (Table XXVI).

In the 'zone of minor damage to the forest', a slowing down in the growth of shoots and branches and morphological changes in the vegetative organs were noted during the first year after the accident. The effect of the radiation was observed for two years but in the following year, the growth of the trees returned to normal. In the moderately contaminated tree stocks, the cumulative absorbed dose amounted to 5–10 Gy in the needles and 0.5–5 Gy in the apical meristem. A significant depression in the growth of shoots and branches was noted, and also a decrease in root size, stunting of the crown, multiple morphological changes and the death of parts of trees, predominantly those parts with low growth rates (Table XXVII).

TABLE XXVI. THE REACTION OF 30-YEAR-OLD PINE TREES TO DIFFERENT LEVELS OF RADIATION

Radiation levels	Number of buds on average tree		Growth of phytomass of crown of single tree (%)		
	1986	1994	1986	1987	1994
Severe	<5	55–75	<5	10–25	40–60
Moderate	5–25	>200	5–30	25–50	100
Minor	25–75	>200	30–70	50–95	100
No signs of radiation damage	>75	>200	>70	> 95	100

TABLE XXVII. THE RELATIVE SIZES OF BRANCHES IN TREE STOCKS AT DIFFERENT LEVELS OF RADIATION

Radiation levels	Sizes of axial shoots, as % of size before irradiation of branches		
	1986	1987	1994
Severe	66	182	115
Moderate	65	158	100
Minor	91	142	99
No signs of radiation damage	95	97	99

At the moment, no morphological signs of the contamination of the stocks of pine trees are to be seen over the entire zone. Different signs of damage to the growth of severely contaminated tree stocks have been caused by forestry management, rather than by the effects of radiation.

Damage to the generative organs of pines was noted. In the first year, damage in the structure of meristematic tissue was observed. The repair processes in these plantations took up to three years. The irradiation accelerated the processes of differentiation of trees in the tree stock.

Ionizing radiation has had a much greater effect on reproductive capability. The evaluation of the reproductive capability of trees subjected to different levels of radiation has shown that, when there is ^{137}Cs contamination of land of 185–3700 $kBq.m^{-2}$ (5–100 $Ci.km^{-2}$), no significant drop in fertility is observed. In tree stocks where contamination exceeds this level, a sharp decrease in the production of live seeds occurs, and when ^{137}Cs exceeds 18 500 $kBq.m^{-2}$ (500 $Ci.km^{-2}$), ordinary pine trees lose their ability to reproduce for two to three years. Five years after the accident, in the trees in plantations with a moderate cumulative dose (6–10 Gy), fertility had reached a normal level (Table XXVIII).

TABLE XXVIII. THE DYNAMICS OF LIVE SEEDS IN PLANTATIONS WITH A MODERATE ACCUMULATED DOSE (6–10 Gy.)*

Years	1987	1988	1989	1990	1991	1994
Average number of seeds in a cone	2.1	4.9	14.2	17.1	16.3	15.2

* The standard average number of live seeds in a cone is 17.2.

In plantations where the absorbed dose exceeded 20 Gy, the death of trees occurred in a very short period. This led to a sudden invasion of vermin, which later spread to adjoining areas. These tree stocks have now ceased to exist. In their place, grassland has been formed, and deciduous species have begun self-seeding, so a new tree stock is being formed. To summarize, four main zones of damage to the coniferous forests of pine and fir trees can be differentiated (Table XXIX).

Short term changes in growth were also observed in a ‘zone of perceptible change’ (doses to the apical meristem of 0.1–0.5 Gy).

Currently, processes of renewal of natural biocenoses (secondary succession) are ongoing. In cases where the self-sowing of agricultural cultures appeared in the exclusion zone within three years, sufficiently stable associations of *Arthropoda* have formed. Favourable conditions for the development and reproduction of useful entomological fauna, such as the presence of nectar-yielding plants and the absence of the use of toxic chemicals, has led to an increase in their regulatory role in natural and agricultural cenoses in the zone.

(a) Zone of complete forest death, with absorbed doses of 80–100 Gy in the needles and exceeding 20 Gy in the apical meristem.

(b) Zone of severe damage to the forest, with death of parts of trees, dessication of the needles, loss of buds, with typical absorbed doses of 30–80 Gy in the needles and 10–20 Gy in the apical meristem.

(c) Zone of moderate damage to the forest, with partial dessication of needles, decrease in growth, and morphological changes, with absorbed doses of around 20 Gy in the needles and 5–10 Gy in the apical meristem.

(d) Zone of minor damage to the forest with damage to reproductive organs of the trees, and morphological changes, with absorbed doses around 5–10 Gy in the needles and 0.5–5 Gy in the apical meristem.

TABLE XXIX. THE DYNAMICS OF THE CONDITIONS OF THE PINE FORESTS WITHIN THE EXCLUSION ZONE OF THE CHERNOBYL NPP IN 1986–1994

<table>
<tr><th>Level of impact, absorbed dose in the apical meristem (Gy)</th><th>1986</th><th>1987</th><th>1988</th><th>1989–1990</th><th>1991–1994</th></tr>
<tr><td>Noticeable
0.1–0.5</td><td>Change in growth</td><td colspan="4" rowspan="3">RECOVERY</td></tr>
<tr><td>Minor
0.5–5</td><td>Depression of growth</td></tr>
<tr><td>Moderate
5–10</td><td>Strong suppression of growth, morphoses, death of individual trees</td></tr>
<tr><td>Severe
10–20</td><td>Absence of population growth, needles turn brown, death of parts of trees</td><td>Individual trees survive, death of major portions of the forest</td><td>Recovery in the population growth of live trees, growth of decidous trees, morphoses, pest development</td><td>Population growth, grass cover, increase in leaf fall</td><td>Trunk fallout, formation of new plant communities</td></tr>
<tr><td>Complete death
> 20</td><td>Needles turning brown, plant death, pest development</td><td>Needles fall, bark peels, pest invasion</td><td>Bark peels, appearance of growth and self-generating of deciduous trees and grasses</td><td>Trunk fallout, formation of new plant communities</td><td>Trunk fallout, formation of new plant communities</td></tr>
</table>

Note on layout: in the Minor row, 1987 = "Morphoses"; in the Moderate row, 1987 = "Partial recovery of population, morphoses, absence of blooming", 1988 = "Population growth recovery, morphoses"; the remaining cells of these rows form the RECOVERY area.

An extensive chain of succession processes constantly takes place in the vegetable world. Anthropogenic factors such as radioactive pollution can intensify these processes. One element which plays an important part in these territories is the interruption of land cultivation. Species of flora which disappear are replaced by species better adapted to the new ecological conditions. For example, dicotyledonous plants are replaced by cereals. Generally speaking, every ecological niche is filled and the ecosystem acquires a new level of equilibrium.

The main diseases in cereals growing wild in the exclusion zone are helminthosporiosis (striated and reticular leaf spot), black spot and stem (linear) rust. In conditions where widespread rehabilitation is under way in the exclusion zone, any alternariosis which has appeared on wild *Cruciferae* can cause a significant drop in the harvesting of seeds from cultivated *Cruciferae*, especially cabbage.

Monitoring of the different vegetable populations shows that numerous plants have in many ways appeared resistant to the effects of radiation. Most representatives of the vegetable world located in the exclusion zone were able to survive, due to the activation of regenerating processes.

4.2.4. Mutagenic effects

4.2.4.1. Mutations in somatic and reproductive cells

The occurrence of mutations in somatic and reproductive cells is caused by the direct physical destruction or functional inactivation of chromosomes, often caused by radiolysis due to external and internal exposure. Increased frequency of breaks in DNA indicates damage to unique structures. During an investigation into grass populations in 1987, an increased number of single strand DNA breaks was found in radiosensitive mouse sweet pea (Vicia cracca) which had partly germinated in the area close to the destroyed reactor. This investigation involved subjecting the plants to a dose of radiation in addition to that already received and using alkaline unwinding and electrophoretic techniques.

The formation of genetic changes and their fixation in subsequent generations largely depends on the function of DNA repair systems. These systems play an especially important role in the pollen of these plants, which is particularly important because of the haploid nature of their nuclei. The effective functioning of DNA repair systems provides genomic stability, which is easily disturbed because of the vulnerability of mature pollen. A poorly functioning repair system, therefore, is evidence of genetic effects of radiation. Studies on the spontaneous restoration of DNA and the unplanned DNA synthesis induced by severe gamma irradiation, indicating repair, have shown that the formation of warty birch (*Betula pendula*) pollen leads to the suppression of dark DNA repair in the mature stored pollen. While such pollen retains its fertilization capability, a tendency towards accumulation of genetic imperfections can be expected in the plants.

In many investigations, an increase in chromosome abnormalities has been noted in the generative tissues of plants growing in the exclusion zone. A manifold increase was observed in the root meristems of two-year-old oenothera (*Oenothera biennis*) seedlings which were grown in laboratory conditions from the seeds of plants sprouting at a dose rate from 0.5 to 600 $\mu Gy.h^{-1}$. A directly proportional relationship between the number of mutations and the dose rate was shown, and numerous chromosome abnormalities were discovered which may have been the result of high linear energy transfer α-radiation.

While performing the investigations at the level of surface contamination from 120 to 400 $MBq.m^{-2}$ (3000 to 10 000 $Ci.km^{-2}$), a linear or almost linear relationship was observed between the total dose of beta and gamma radiation during the period from 26 April to 5 May 1986 (the seed harvest) of winter-sown rye plants (*Secale cereale*) and the frequency of cells with chromosome abnormalities in root meristems of second generation seedlings.

The same test was used to evaluate the effect of radiation on seeds of seven different species of plants gathered in the area immediately adjacent to the Chernobyl NPP. Here the dose rate was 20–30 $\mu Gy.h^{-1}$. In this investigation, chromosome abnormalities of between 1% and 8% were discovered, and an increase in the frequency of chromosome aberrations was observed with an increase in dose rate. No linear relationship was established, which may have been the result of the uneven distribution of radionuclides over the surface of the soil, or possibly of the influence of various chemical contaminants. It is interesting to note that, in the second year after the accident, the frequency of chromosome abnormalities in some species of plants increased 1.5–3 times, despite a two to threefold drop in the ambient dose rate. This indicates that the genetic hazard is not only from external exposure, but also from the internal exposure caused by the transfer of radionuclides from soil to plants.

In addition, an increase in the number of cells with chromosome and chromatic abnormalities was noted in the root meristem of aril crepis (*Crepis tectorum*) seedlings grown from seeds of plants gathered in the area around Chernobyl NPP with an ambient dose rate of 50–100 $\mu Gy.h^{-1}$ during the first year and 0.2–200 $\mu Gy.h^{-1}$ during the second year. In the first year's seedlings, 10.2–15.3% of cells had chromosome abnormalities, these cells often being observed with multiple abnormalities. In the second year, in areas of the maximum level of contamination, 1.4–2.2% of cells were discovered to have chromosome abnormalities. At minimum levels of radiation, 0.3–0.65% of cells had abnormalities, which corresponds to a spontaneous level. In addition, the appearance of plants with changed karyotypes was also observed, indicating evidence of active microevolutionary processes in chronically irradiated populations.

4.2.4.2. Increase in the quantity of sterile pollen in plants

An investigation in 1987 and 1988 of two populations of morning violets (*Viola matutina*) growing in two areas of the exclusion zone showed an increase by a factor of 1.5–2 in the number of sterile pollen grains. At a dose rate as high as 4–5 $Gy.a^{-1}$, partial female sterility of pine (*Pinus sylvestris*) was shown by:

- a fall in the gametophytic survival rate of seed buds pollinated in 1986; and
- a reduction in the embryonic survival rate of seed buds pollinated in 1985.

It is obvious that sterility, i.e. the inability of the organism to form gametes or a sufficient number of them, does not necessarily result in any genetic harm although the number of descendants falls. However, sterility caused by ionizing radiation, as a rule, results in gene or chromosome mutations which prevent meiosis, a basic step in gametogenesis. Direct evidence of the genetic effect of ionizing radiation on pollen is provided by the immediate occurrence of mutations. In barley (*Hordeum vulgare*) which had germinated in soil from the exclusion zone, a two to threefold increase in the frequency of waxy changes in the pollen was noted.

During the first months after the accident, when rye (*Secale cereale*) and barley (*Hordeum sativum*) plants were sprouting, the frequency of different kinds of chlorophyll mutations increased. Albino-type non-vital mutations were prevalent. In subsequent years, the seeds which had been gathered in the exclusion zone were sown again. In the rye and barley sprouting in the exclusion zone, the spontaneous level of chlorophyll mutations became greater (Table XXX.). At the same time, the mutations were not eliminated in succeeding generations because the seeds sown had been subjected to subsequent exposure.

TABLE XXX. THE PROPORTIONS OF ALBINO-TYPE CHLOROPHYLL MUTATIONS IN RYE (SECALE CEREALE) AND BARLEY (*HARDEUM VULGARE*)*, (%)

Culture	Reference sample	1986	1987	1988	1989
Kiev rye	0.01	0.14	0.40	0.91	0.71
Kharkov rye 03	0.02	0.80	0.99	1.20	1.14
Barley	0.40	0.90	0.74	0.80	0.91

* Seeds from the exclusion zone.

Over a period of three years, the frequency of morphological anomalies in four kinds of winter wheat (*Triticum vulgare*) increased by up to 40% in 1986–1987, but by less in 1988. The range of anomalies was fairly wide. In the first year after the accident, the most frequent anomaly (up to 49%) was the formation of partially-filled ears of wheat e.g. of the sterile zones. In 1987, the number of anomalies of this type reached 30%, but in the following generation it fell to 1.9%. It is common to encounter ears of wheat which have additional ears ("ruptures") and shortened ears. The widespread changes in the structure of the ear should also include square-head type anomalies. Plants with increased beardedness, uneven lengths of beardedness, "fir tree" ears, or changes in the colour of the stalks were also encountered.

There is no doubt that the morphological anomalies are those which, as a rule, mainly occur in generations of plants that have been exposed to radiation. Such anomalies are not usually inherited by subsequent generations. Nevertheless, their persistent appearance in every succeeding year up to and including 1994 suggests the possibility that many of these changes are of a genetic character and provide evidence that, as a result of the irradiation at the time of the radioactive releases, a mutational process has been occurring in plant populations.

The radioactive pollution of the environment created by the Chernobyl accident did not have any significant effect on most types of grasses, if one takes into account the inherent variability of the characteristics which define the viability of their seeds, such as the weight of the grain, the germinating capacity and the rate of growth. Genetic monitoring of various types of grasses and data from the cytogenetic analysis of their seeds show the occurrence of a number of radiation induced alterations in the genetic code, characterized by the elevated rate of the embryonic lethal mutations and chromosome aberrations in leaf and root meristems. Plants affected by high doses of ionizing radiation also suffered damage to their physiological and biochemical processes, e.g. the intensity of phytosynthesis changed, and the synthesis of protein and pigments was disrupted.

In many cases, it was observed that exposure resulting from contamination of soil by ^{137}Cs as low as 3700 Bq.m^{-2} was enough to induce morphological anomalies in growth and development processes of grasses and shrubs, so-called "radiomorphoses". Morphological anomalies in vegetation occur when morphogenetic processes are disrupted, and involve abnormal cell division. Abnormalities can appear, such as distorted and swollen bulges in stems, asymmetric and curled leaves, intensification of growth of lateral branches, dwarfism, bushiness and giantism. Some of the major diseases contracted by wild cereals in the exclusion zone are helminthosporiosis (meshed and striped stigmas), black spots, and linear stalk mildew.

Genetic effects were seen in viable seeds harvested in 1987 from contaminated tree stocks. At the time of the accident, female pine cones contained two kinds of reproductive cells that were responsible for the seed harvest in 1987 and 1988. Genetic disorders caused by radiation and abnormalities in chromosomes, both in number and mutations, have been shown in seed plantules in the first reproduction after the accident. In an area with the highest level of contamination, these effects were seven times the normal levels. In pine reproductive cells (megaspores) which had been subjected to severe irradiation in the first days of the accident, with dose rates of 5–500 $\mu Gy.h^{-1}$, the frequency of induced mutations of enzyme loci also exceeded the normal value by a factor of 4–17. The average frequency of mutations in pine populations in the exclusion zone was $6.1.10^{-3}$ mutations per gene.

4.2.5. Impact of radiation on fauna

Because of the vast biological diversity in the animal kingdom, the inherent specialization of animal groups (such as eating habits, habitat, and place in the food chain) and the number of different population structures, accumulation of radionuclides in the bodies of aquatic and land animals is extremely variable and also depends on such factors as species, age, sex and season. Moreover, these dependencies are often not easily identifiable and are accompanied by high levels of individual variability in the activity of radionuclides accumulated. Another reason for this variability is the varying characteristics of the radioactive particles deposited in the environment after the accident.

As in the case of vegetation, a large number of molecular and cellular alterations have been seen in wild and farm animals. A disruption in the cycle of animal physiological and biochemical processes has also been noted. However, profound pathological changes, often leading to lethal ones, were discovered only among species of animals particularly sensitive to radiation, and among those animals whose habitat was polluted by extremely high levels of contamination. [4, 12].

The radioactive contamination of the environment affected animals at the cellular and molecular levels. The cells of small mammals and amphibians living in the areas contaminated by radionuclides still show an increased number of mutations. It was noted in fresh water fish near the Chernobyl NPP that the growth, development and structure of their gametes was modified. Both somatic and germ cells of animals living in the contaminated zone have been undergoing a significant number of cytogenetic disruptions.

The consequences of radiation to animals can be enhanced by the selective accumulation of different radionuclides in specific organs. For example, the accumulated radiation doses in the thyroid gland of mammals, due to the concentration of ^{131}I, by far exceeded that of any other organ. The absolute values of radiation doses to cows' thyroid glands, in the area close to the Chernobyl NPP, reached a few hundred Gy, and led to the atrophy and near total necrosis of the thyroid of these animals.

4.2.6. Radiosensitivity of animals

Although vertebrates — especially mammals — are the most sensitive animals to radiation, there is no direct proof of a mass death of vertebrates in the area surrounding the reactor during the period that directly followed the accident. According to experimental data collected in the vicinity of the Chernobyl NPP in September 1986, the number of mouse-like rodents fell by a factor of three to five. The calculated absorbed dose in the relevant areas during the first month after the accident amounted to 22 and 860 Gy for gamma and beta exposure respectively.

In general, invertebrates are more resistant to the effect of ionizing radiation than vertebrates by one to two orders of magnitude. Nevertheless, three ecological groups of invertebrates suffered badly because of the specific properties of the irradiation and their habitats. The accumulation of radionuclides in the litter of coniferous forest burnt out small invertebrates (testaceous ticks and *Collembola*) in the relevant areas at about 3 km to the south of the Chernobyl NPP. In June 1986, their number fell by two orders of magnitude. There was also a sharp fall in the number of soil invertebrates better shielded from beta irradiation. The ratio of juvenile to mature invertebrates was changed drastically in favour of the latter. The absorbed dose of the order of 30 Gy had no immediate effect on adult animals, but had a noticeable effect on juvenile individuals. In the contaminated lichen epiphytes (*Hypogymnia physodes*) at the same location, absolutely no sign could be found of any testaceous or Argosidae ticks, or *Collembola*, which are normally found in this ecological niche.

Haematological studies of ground invertebrates indicate a change in their haematopoiesis with an increase in the number of dead blood cells, and cytological and morphological modifications. Morphometrical analyses show that the body size of some specimens of the mesofauna decreased by 25–50%.

The indicators of fertility of lake fish were lower than those of the fish in the Pripyat river. Some lake fish species displayed a disruption in the growth and development processes of germ cells. The lower radiation dose to aquatic organisms in lakes and rivers, compared to those in the Chernobyl cooling pond, does not seem to have led to damage at the individual or ecosystem level. Genetic alterations, such as the higher frequency of aberrant cells in frogs from the Chernobyl NPP area compared with frogs living in reference areas, were registered.

The European red-backed vole gave birth to a smaller number of offspring, and their growth was slower. Demographic analysis of other species of animals shows an imbalance between the sexes, a decrease in birth rates, weakness in offspring and other changes.

Inside the exclusion zone, changes in the number and structure of species in the animal kingdom can also be explained by the evolution of parasites. Parasitic pressure is much greater in heavily contaminated areas than in other reference ones. The parasites of small mammals, birds and insects are more numerous here than in adjacent areas and the number of those with epidemic and epizoological impact will increase.

4.2.7. Changes in the microbiological composition of soil and water

Monitoring of the taxonomic structure and quantity of soil micromycetes was undertaken between 1986 and 1992 in the exclusion zone and in the Vyshgorod district of the Kiev region. From 670 samples in soddy-podzolic and sandy loam soils, more than 3000 fungi were cultured and 180 species from 72 geni were identified.

During the period 1986–1988, when there was a general drop by a factor of two to three in the number of fungus diaspores and the length of fungus mycelia in the soil at all seven observation points within the exclusion zone, the prevalence of dark-coloured fungus mycelia at a depth of up to 10 cm was noted.

From 1989 onwards, the number of fungus micromycetes approached the known values for "clean" regions. Among the fungus biomass light-coloured micromycetes dominated by mass, which was typical of the micromycetes of this region prior to the accident. However, in a taxonomic structure review of fungus complexes from 1989 to 1992, the dominant strain was found to be the dark-coloured fungi. This group of fungi can be a biological indicator of an unfavourable ecological situation, although the immediate reason for the changes observed and their direct connection with irradiation have not been established.

Despite the radioactive contamination of water and especially river bed sediments, the doses received were insufficient for the damage to live organisms to be of any ecological significance. The biological diversity of the planktonic algae and higher aquatic vegetation was preserved completely. A few warm winters in succession after 1987, together with the lack of any solid freeze-up, and the hot summer seasons with water temperatures rising to 2°C above the average over a period of several years, led to the growth in the biomass of phytoplankton by one order of magnitude compared with the level in 1986–1987. This prompted the reproduction of Rotifera (*Rotatoriadae*), mosquito midges (*Chironomidae*) and viviparous molluscs (*Viviparus sp*.), the spread of duckweed (*Spirodela polyrrhiza*) and water lilies of both yellow (*Nuphar lutea*) and white (*Nymphaea alba*) varieties. These outbreaks usually stopped suddenly, and were followed by a decrease in numbers. The increased flow in the Pripyat river in the summer of 1988 led to a temporary drop in the biomass of the primary producers in the water reservoir and to a severe loss of humic substances from the swamped river basin.

4.3. Prognosis for the ecological situation for the next 10 years

4.3.1. Contamination by the resuspension of particles

The transfer of radionuclides by water and wind and by extreme seasonal weather conditions such as floods, tornadoes, squalls and dust storms, and the dispersion of air by forest fires will not lead to long term contamination beyond the exclusion zone. The destruction of the shelter building as a result of an earthquake or human activity, or flooding of the "Podlesny" burial place for radioactive wastes and other buildings could lead to additional radioactive contamination of the exclusion zone and the adjacent territories.

4.3.2. Contamination of forests

The area in the exclusion zone covered by forest will expand to 65–70% of the whole zone. Pine forests planted in the 1950s now occupying the majority of the forested plains have become mature and and will be subject to extensive self-thinning. The areas of meadowland will be significantly reduced and will become less compacted and, to a large extent, will give way to birch and aspen forests and groves. Swampland will also be replaced gradually by deciduous forests. These changes will create a stable and relatively fire-resistant vegetation layer. As a result of the destruction of ameliorative water drainage systems and the construction of dams by beavers, the level of groundwater will rise, and marshlands will occupy 10–15% or more of the territory [4, 7]. Decontaminated areas will be converted into dry meadows planted with willow or into dry pine forests. Where this programme is successful, it will favour a reduction in the extent of dusty territories.

4.3.3. Animals

The animal world will stabilize as regards numbers of forest animal species, with an increase in the number of predators. It will remain necessary to conduct an epidemiological inspection on carriers of tularaemia, rabies and leptospirosis.

4.3.4. Contamination of soils

The density of surface radionuclide contamination of the territory as a whole with ^{137}Cs and ^{90}Sr will gradually decrease because of radioactive decay and vertical migration in soil and the radionuclides will spread more or less uniformly through the 10–30 cm surface soil layer. The probability of contamination of the atmosphere with ^{239}Pu will be reduced by a factor of three to ten. The role of the processes involved in the surface transfer of contamination will be significantly reduced as a result of the spreading vegetation layer. In the absence of strong run-off on the swamplands, the reduction of radioactive contamination will be largely achieved by radioactive decay.

4.3.5. Surface and underground water contamination

Groundwater will be cleansed by the filtering of radionuclides through the aeration zone. In areas of minimal filtration through the aeration zone, some of the radionuclide contamination will be transferred to the groundwater; however, concentrations of radionuclides in groundwater will not reach the established action levels in the greater part of the exclusion zone. In the immediate future, the transfer of radionuclides by underground water may become comparable with transfer due to the washing of the surface by run-off water, but there will be a reduction in their concentrations as a result of decay and dispersal. The end result of this will be that concentrations of radionuclides in drainage zones and river valleys will be reduced towards the end of the period envisaged in the prognosis. The assessed ten-year prognosis does not suggest the underground route for the migration of radionuclides, including the most mobile component, ^{90}Sr, as the major pathway in the contamination of the waters of the river Dnieper.

REFERENCES TO SECTION 4

[1] Conception of the Chernobyl Restricted Zone on the Territory of Ukraine, Kiev (1995) 24.
[2] KONOPLYA, E.F., et al., Concepts of the Management of the Exclusion and Resettlement Zones, Ministry of Emergencies and Population protection from the Chernobyl NPP Catastrophe Consequences, Minsk (1994) 94 (in Russian).
[3] KONOPLIA, E.F., ROLEVICH, I.V., (Eds), Belarus National Report, The Chernobyl catastrophe consequences in the Republic of Belarus, Minsk (1996).
[4] BARYAKHTAR, V.G., (Ed.), Ukrainian National Academy of Science, The Chernobyl Catastrophe, Kiev, Naukova Dumka (1995) 560.
[5] GRODZINKSIY, D.M., et al., Anthropological Radionuclide Anomalies and Plants. Kiev, "Libid" (1991) 160.
[6] KUCHMA, N.D., et al., Radioecological and Forestry Aftermath of Ecosystem Contamination, Chernobyl, Preprint (1994) 53.
[7] KOZUBOV, G.M., TASKAYEV, A.I., Radiation Influence on Forest Fauna in the Region of the Accident at the Chernobyl Nuclear Power Plant, Siktivkar, KNTs UrO, USSR Academy of Sciences (1990) 136.
[8] TIKHOMIROV, F.A., SIDOROV, V.P., Radiation impact on the forest in the zone of the Chernobyl nuclear power station, Thesis of the 1st International Conference, Zeleny Mis (1990) 18.
[9] KOZUBOV, G.M., TASKAYEV, A.I., FEDOTOV, I.S., Map of the Radiation Impact on Coniferous Forests in the Region of the Accident at the Chernobyl Nuclear Power Plant, M-b 100 000, Siktivkar (1990).
[10] DAVIDCHUK, V.S., et al., The Landscape of the Chernobyl Zone and an Assessment Thereof under Conditions of Radionuclide Migration, Kiev, Naukova Dumka (1994).
[11] BUZINNY M., LOS, I., SHEPELEVICH, K., The distribution of ^{137}Cs and ^{90}Sr in the biomass of pine trees planted in 1987–1988 in the near zone of the Chernobyl nuclear power plant, Applied Radiation and Isotopes **52** (2000) 905–910.
[12] ALESINA, M.Yu., RYASENKO, V.I., RIMORENKO, P.I., Radiobiological Effects in Various Organs and Tissues of Animals in the Radionuclide Contamination Zone as a Result of the Accident at the Chernobyl Nuclear Power Plant, Chernobyl, preprint (1994) 64.

5. REMEDIAL ACTIONS TO REDUCE LONG TERM EXPOSURE

5.1. Criteria for intervention in the USSR (1986–89) and in Belarus, the Russian Federation and Ukraine (1990–1995)

The protection and rehabilitation measures used in the territories of Belarus, the Russian Federation and Ukraine that were contaminated as a result of the Chernobyl accident may be divided into 12 groups:

0*. Sheltering and iodine prophylaxis, which are not discussed in this publication;

1*. Evacuation and resettlement;

2*. Decontamination of the soil, buildings and installations;

3*. Burial of the radioactive waste resulting from the decontamination measures, as well as the highly contaminated waste from industrial and agricultural production;

4*. Restriction of free access to the areas with high levels of radioactive contamination and the prohibition of economic activity;

5*. Changing the type of forestry and agricultural activities and providing safe conditions for workers;

6*. Ban or limitation of the consumption of contaminated foodstuffs;

7*. Reduction of radioactive contamination of agricultural products from the public sector;

8*. Reduction of radioactive contamination of agricultural products from private domestic production;

9*. Organization of public services in populated areas;

10*. Information to the population;

11*. Social and other supplementary measures.

(*) — number heading in Table XXXI corresponds with numbers listed here.

In Table XXXI, the dates on which decisions were reached by the Government of the USSR and authorized ministries regarding the basic and derived accident standards, i.e. intervention levels, are listed. The decisions took five different forms:

(a) Standards (S), of the USSR Ministry of Public Health, which should have been effected throughout the territory of the former USSR;

(b) Administrative decisions (AD) with an indication of the populated areas affected. Usually these are decisions or decrees of the Government or other State bodies;

(c) Departmental directions and instructions (DD), which contained certain limits and instructions of either a recommended or an obligatory nature relevant to the activities of a particular department;

(d) Conceptual standpoints (C) are decisions of the National Commission on Radiation Protection of the USSR (later of Belarus, the Russian Federation and Ukraine) regarding the basic intervention levels, which necessitated administrative decisions and changes to laws in order to be observed; and

(e) Decisions of legislative bodies (L) which directed the undertaking of certain countermeasures by executive bodies or which directly determined the operational intervention criteria.

TABLE XXXI. DATES ON WHICH DECISIONS INVOLVING PROTECTIVE MEASURES WERE APPLIED AND TYPES OF DECISION

Date	Source	Type of decision	Criteria	Protection measures										
				1	2	3	4	5	6	7	8	9	10	11
27 Apr 86	[1]	AADL	Annual dose	)										
06 May 86	[2]	TPL	^{131}I in foodstuff						M	M	M			
12 May 86	[3]	AADL	100 mSv/year	♦	)	)	M	M	)	M	M	M	♦	M
15 May 86	[4]	LERP	Dose rate (10, 30, 50, 200 μ Sv/h = 1, 3, 5, 20 mR/h)		)	)		M						
16 May 86	[5]	TPL	Gross beta activity in foodstuffs						M	)	)		♦	
30 May 86	[6]	TPL	Gross beta activity in foodstuffs						)	)	)		♦	
30 May 86	[7]	DD	Dose rate and radioactivity in foodstuffs			M	M	M	M	M	M		M	
12 Jun 86	[8]	LERP	Dose rate		)	)	)	)				M		
22 Aug 86a	[9]	AD	^{137}Cs in the soil	)									♦	)
22 Aug 86b	[10]	AD	^{137}Cs in the soil (555 $kBq.m^{-2}$ = 15 $Ci.km^{-2}$)		)	)	)	M	)	)	)	)	♦	)
24 Oct 86	[11]	TSCL	Dose rate and surface contamination		)	)						M		
23 Apr 87	[3]	AADL	Annual effective dose: 30 mSv		M	M	M	M	)	)	M	M	♦	
29 Jul 87	[12]	TSCL	Dose rate and surface contamination		)	)		)				M		
12 Aug 87	[13]	AD	^{137}Cs in the soil and social factors (555 $kBq.m^{-2}$ = 15 $Ci.km^{-2}$)		)	)	)	M	)	)	)	)	♦	M
15 Dec 87	[14]	TPL*	^{134}Cs and ^{137}Cs in foodstuffs						)	)	)		M	

23 May 88	[15]	DD	^{134}Cs and ^{137}Cs in the soil and in foodstuffs			)	)	)	M	)	)		)	
18 Jul 88	[3]	AALD	Annual effective dose: 25 mSv		M	M		M	M	M	M	M		
19 Jul 88	[16]	TSCL	Dose rate and surface contamination		)	)		)				M		
13 Sep 88	[17]	AD	^{137}Cs in the soil and social factors (555 $kBq.m^{-2}$ = 15 $Ci.km^{-2}$)		)	)	)	M	)	)	)	)	M	)
06 Oct 88	[18]	TPL	^{134}Cs and ^{137}Cs in foodstuffs						)	)	)			
22 Nov 88	[19]	LADL**	Lifetime effective dose: 350 mSv	)	)	M	)	M	M	)	)	)	)	)
24 May 89	[20,21]	AD	Lifetime effective dose: 350 mSv	)									M	)
20 Oct 89	[22]	AD	Social and health care	M									M	)
30 Dec 89	[23]	AD	^{137}Cs in the soil (555 $kBq.m^{-2}$ = 15 $Ci.km^{-2}$) and social factors		)	)	)	M	)	)	)	)	M	)
26 Jan 90	[24]	AD	Cs radionuclides in milk						)	)	)		M	)
11 May 90	[25]	TSCL	Surface contamination, particles.$min.^{-1}$ cm^{-2}			M		)				M		
22 Jan 91	[26]	TPL*	^{137}Cs and ^{137}Cs in foodstuffs						)	)	)		M	
19 Feb 91	[27]	DD	^{134}Cs and ^{137}Cs in the soil and in foodstuffs		M		M	)	M	)	)		)	
08 Apr 91	[28,29]	AADL	1 and 5 mSv/year	)	M	M	M	M	M	)	)	M	)	)
12 May 91	[30]	USSR law	^{137}Cs in the soil (37, 185, 555, 1480 $kBq.m^{-2}$ = 1, 5, 15, 40 $Ci.km^{-2}$); additional annual dose	)	♦	♦	)	)	M	M	M	M	)	)

* In Ukraine and Belarus there was a stricter level of control.
** This measure was not passed in Belarus.
) Decision was reached directly or was derived from other decisions.
M Decision was dependent on the completion of similar measures.
♦ Decisions could require similar measures in the future.

The following types of dose and derived criteria were set by the USSR authorities in different sanitary guides or laws:

(a) Limits on the environmental radiation parameters (LERPs);

(b) Annual additional dose limits (AADLs);

(c) Lifetime additional dose limits (LADLs);

(d) Temporary permissible levels of radionuclide concentration in foodstuffs (TPLs);

(e) Temporary surface contamination limits (TSCLs).

Included as criteria in Table XXXI are the major characteristics of environmental radioactive contamination and radiation doses presented in the documents used from 1986 to 1991 in the areas of the USSR which were contaminated after the Chernobyl accident. As a rule, the derived values are the results of a conservative assessment using basic dose intervention levels. In several cases, not numerical radiological values but administrative decisions were used to set criteria, as in the definition of the "zone of radioactive contamination".

Starting in 1989, the methods for determining the criteria for intervention and the planning of protection measures in Belarus, Russia and Ukraine diverged slightly. This was largely due to differences in the levels of radioactive contamination in various areas, some differences in the ecological pathways of population exposure and different specific national standards in radiation protection. Currently in all three States, new concepts based on accumulated national experience and on internationally accepted standards are being or have already been developed.

The basic documents governing the use of countermeasures in the Republic of **Belarus** from 1990 to 1995 are:

(a) The Concept of Living of the Population in Areas that Suffered from the Accident at the Chernobyl Nuclear Power Plant, approved in April 1991 by Decree No. 164 of the Council of Ministers of the USSR.

(b) The Republic Concept of Living in the Areas Contaminated by Radionuclides as a Result of the Catastrophe at the Chernobyl Nuclear Power Plant, approved on December 19, 1990 by the Bureau of the Presidium of the Academy of Sciences of Belarus.

The essence of Concept (a) was the establishment of a three-tier system of additional annual effective dose to the population:

(1) If the effective dose does not exceed 1 mSv per year, the conditions for people to live and conduct their normal activities are not limited and no intervention is required;

(2) If the effective dose is between 1 and 5 mSv per year, a set of protection measures designed to gradually reduce exposure levels is undertaken;

(3) If the effective dose is 5 mSv per year or higher, inhabitants of contaminated areas must be resettled.

In accordance with the Republic Concept, (b), contaminated territory in Belarus was divided into the following zones:

(1) The exclusion zone — zone of the evacuation of inhabitants in 1986 from the areas adjacent to the Chernobyl NPP;

(2) The obligatory (immediate) resettlement zone — areas with a ^{137}Cs deposition greater than 1480 $kBq.m^{-2}$;

(3) The obligatory (subsequent) resettlement zone — areas with a ^{137}Cs deposition from 555 to 1480 $kBq.m^{-2}$;

(4) The voluntary resettlement zone — areas with a ^{137}Cs deposition from 185 to 555 $kBq.m^{-2}$ where the dose could exceed 1 mSv per year; and

(5) The radiological control zone with institutional control — areas with a ^{137}Cs deposition from 37 to 185 $kBq.m^{-2}$ where the dose should not exceed 1 mSv per year.

Radiation protection measures, including resettlement, should be undertaken progressively in accordance with programmes developed by the Government of Belarus, taking into consideration the risk of exceeding the following annual dose limits :

1991 — 5 mSv;
1993 — 3 mSv;
1995 — 2 mSv;
1998 — 1 mSv.

The provisions of the Republic Concept were used to develop corresponding laws and programmes designed to mitigate the effects of the accident at the Chernobyl plant.

In **Russia** in the fall of 1989, in accordance with assessments then in effect [19], a decision was reached on the resettlement of the inhabitants of several areas with a total population of approximately 7000 people. Almost simultaneously, decisions were reached regarding benefits and the voluntary resettlement of the inhabitants of several areas in which an excess temporary permissible level (TPL) in milk was found [24, 31, 32]. These decisions led to an expansion of the list of populated areas subject to the mandatory implementation of the indicated countermeasures and resulted in an increase in the number of people subject to these measures to 200 000. After the Law on the Social Protection of Citizens Suffering from Radiation as a Result of the Catastrophe at the Chernobyl Nuclear Power Plant was approved in 1991 [30], the creation of zones was completed on the basis of the level of soil contamination [33, 34, 35]. A State programme for the regulation of countermeasures was developed, the provisions in it for implementing this law being dependent on contamination zone designation. Economic activities in the contaminated areas were similarly regulated [36]. Altogether, there were more than 2.6 million people in the zones of radioactive contamination. In addition, in 1993 new permissible levels for the content of ^{137}Cs in food products [37] and new standards for surface contamination were set. In Russia a new Concept [38] was published in 1995, which preserves the lower limit of intervention and establishes a higher level (20 $mSv.a^{-1}$) for undertaking such measures as mandatory population resettlement.

In 1991 in **Ukraine**, the Concept of Living of the Population on the Territory of Ukraine with Increased Levels of Radioactive Contamination as a Result of the Chernobyl Catastrophe and the Laws on the Legal Regime of the Areas which experienced Radioactive Contamination as a Result of the Chernobyl Catastrophe and on the Status of the Social

Protection of Citizens Who Suffered as a Result of the Chernobyl Catastrophe were adopted. The basis for the quantitative criteria used in these documents is discussed in Section 3.2.

In analysing the criteria for intervention in all three republics, it should be borne in mind that:

(a) the conservatively derived intervention levels were used on several occasions to reach decisions for the extension of regions where countermeasures were to be undertaken;

(b) often in reaching these decisions the "social factor" was taken into consideration and, on this basis, the number of populated areas subject to countermeasures was increased;

(c) the majority of the decisions did not provide for ending the post-accident phase on the basis of dose;

(d) during the period prior to 1989, no measures called for disseminating information to the population; information was provided only to the managers of the effort and to those inhabitants of the populated areas directly affected by the countermeasures.

5.2. Comparison of CIS criteria with international criteria

Following the Chernobyl accident, a number of protective measures were taken in the former USSR to limit the radiation exposure of the population. Although international guidance and criteria existed before the accident, experience in their application was very limited, especially in the application of long term protective measures. The magnitude of the Chernobyl accident and the extent of the areas affected by it raised issues that had not been previously confronted. Inevitably, under these circumstances, an evolutionary approach had to be developed for the practical implementation of the criteria.

The protective measures included early countermeasures such as sheltering, administering stable iodine and evacuating those people who might be exposed to the plume. Long term countermeasures, such as resettlement, foodstuff restrictions, and decontamination of settlements were taken to mitigate the effects of lower but still significant levels of radiation dose from surface and soil contamination. The levels at which these measures were introduced were based on different rationales, and the basic intervention philosophy in the three republics has been under constant development since the accident. In addition to radiation protection principles, social protection considerations play a significant part in the different concepts being developed.

Recently, **Belarus** scientists have developed protective measures in the rehabilitation period for the population living in territories of the Republic of Belarus affected by the Chernobyl accident. With this approach, where the annual individual effective dose does not exceed 1 mSv, living conditions and economic activities should not be limited by radiation protection measures. The environment and agricultural production should be monitored in order to estimate accurate radiation doses to the population and to implement, if necessary, limited local protection measures.

In those areas where the annual individual effective dose exceeds 1 mSv but is lower than 5 mSv, practical measures aimed at further reduction in individual and collective dose should be implemented. These measures would include, in addition to radiation monitoring of the environment and of agricultural production, local decontamination of sites where the external exposure is the dominating exposure pathway. Where the annual average individual effective dose exceeds 5 mSv, residence is not recommended and economic activities are limited.

In the **Russian Federation**, new basic recommendations applicable to the existing contaminated territories and possible future accidental situations are being developed. The recommendations draw on all the experience gained in the remediation of the consequences of nuclear accidents and nuclear weapons tests. The intervention levels form a three-tier system. The introduction of countermeasures is compulsory to prevent people from receiving doses above the upper dose level. Below the lower dose level, no countermeasures would normally be introduced. Between the lower and upper dose levels, decisions on the introduction of countermeasures should be based on justification and optimization considerations. In addition to the general recommendations on intervention strategy and intervention levels, specific recommendations on the methodology of risk analysis for post-accident situations and the optimization of strategies of protective and rehabilitation measures are being developed for approval. Annual dose levels of 1, 5 and 20 mSv are regarded as the intervention levels for the whole Russian Federation. The protective actions related to these levels are:

(a) No special protective actions have to be implemented if the annual dose in settlements is below 1 mSv;

(b) Radiological control has to be provided in territories where the annual doses are in the range of 1–5 mSv;

(c) Effective protective actions should be introduced for the settlements where the annual doses are in the range of 5–20 mSv;

(d) The possibility of resettlement must be considered if the annual dose exceeds 20 mSv.

This concept has been adopted by the Government; however, for the concept to be implemented, the current laws must be modified.

In a large part of the affected territory of **Ukraine,** the annual individual effective dose does not exceed 1 mSv. This dose level is identical to the dose limit for exposure of the population from practices and is used in many countries, including Ukraine. However, because the exposure from the Chernobyl accident and the exposure from non-accidental sources are considered separately, the social welfare provisions for inhabitants receiving the same dose depends on the origin of the source of the exposure.

5.2.1. Present international guidance (see Annex II)

At the time of the Chernobyl accident, international guidance on protection of the public after a nuclear accident in which radionuclides had been dispersed into the environment existed. However, this guidance was not very clear and did not address the difficult social problems which arise after such a disaster.

According to the current international guidance from the ICRP and the IAEA, intervention levels are based on the dose that is expected to be averted (avertable dose) by the introduction of a specific countermeasure over the period when it is in effect. If an intervention level is exceeded, i.e. if the expected avertable individual dose is greater than the intervention level of dose, then the specific protective action is likely to be appropriate for that situation. Intervention levels are specific for accident situations. Action levels refer to different protective measures or strategies such as agricultural countermeasures or radon reducing measures in houses, and are derived from the dose averted by the remedial action compared with the dose that would have been incurred had the countermeasure not been implemented.

5.2.2. CIS guidance versus present international guidance

In line with international guidance, CIS guidance on intervention has evolved conceptually over the last ten years from a system of "limitation" towards a system of "action levels". At present, the intervention guidance in the CIS is based on action levels expressed as annual doses above which different protective actions are needed. For any exposure situation there will always be a fixed ratio of avertable dose to action level. An action level for resettlement of, say, 20 $mSv.a^{-1}$ would be equivalent to an avertable lifetime dose of 300–400 mSv over the following 70 years if the effective environmental half-life is 10–15 years as experienced in the different regions of the CIS contaminated with ^{137}Cs. The guidance from the ICRP and the IAEA indicates that permanent resettlement should be introduced if the lifetime dose without intervention would exceed 1 Sv.

CIS action levels are thus another way to express avertable doses, and, conceptually, they are in line with international guidance. However, the numerical values differ somewhat from international numerical guidance with a tendency for CIS levels to be lower than those recommended internationally. This difference is most marked in foodstuff action levels. Furthermore, international numerical guidance is based on generic optimization and — unlike the CIS guidance — it does not include social protection considerations although the principle of justification states that "the proposed intervention should do more good than harm, i.e. the reduction in detriment resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention".

5.3. Effectiveness of the completed protection and rehabilitation measures and prospects for their future use

The principles for establishing intervention levels on the basis of "cost–benefit" analysis set forth in ICRP and IAEA publications were well-known among specialists in radiation protection. These principles were virtually always taken into account when developing ways to reach decisions. However, with the exception of certain rare cases, reasons existed which did not allow the full completion of optimized measures. Furthermore, on many occasions responsible bodies reached political decisions which contradicted conclusions reached by "cost–benefit" analysis and sometimes, for example with the problem of providing information to the general population, contradicted internationally accepted practice. As a result, the analysis of all of the countermeasures taken over a ten-year period from the perspective of "cost–benefit" analysis is very important, but difficult in practice. The price structure which existed in the USSR, its fundamental change in Belarus, Russia and Ukraine over the past five years, and its probable movement towards world prices within a few years, are the major reasons for these difficulties. On the other hand, the completed countermeasures provide unique experience with regard to undertaking such steps on an unprecedented scale and to their impact. In the following sections, the basic countermeasures completed in Belarus, Russia and Ukraine are examined in varying degrees of detail. The text refers to all three countries unless otherwise stated.

5.3.1. Evacuation and resettlement

During the initial phase after the accident, decisions on countermeasures were reached in accordance with the principles of preventing the population from receiving high radiation doses and of not exceeding the criteria applied to protect the population in the event of a reactor accident [1]. In accordance with these criteria, 115 000 people were evacuated in Ukraine and in Belarus, beginning on 27 April 1986. Evacuation on the territory of Russia in accordance with these criteria did not occur although, in the fall of 1986, a total of 186 people from four settlements were resettled. These measures were introduced late and were ineffective in preventing exposure of the thyroid.

In 1989, because of the impossibility of complying with the maximum lifetime dose limit for the inhabitants of populated areas in the Bryansk, Kiev, Zhitomir, Mogilev and Gomel regions, the Government of the USSR reached a decision, based on new criteria [19, 20, 21], on the resettlement of these people during the period 1989–1993. Thereafter, the Governments of Belarus, Russia and Ukraine decided resettlement issues independently.

Currently in **Belarus**, most of the measures to resettle people from the obligatory and voluntary resettlement zones have largely been completed. Altogether, 415 populated areas have been resettled, including 273 in the Gomel region, 140 in the Mogilev region and two in the Brest region.

In **Russia**, large scale resettlement initially took place in accordance with an assessment made in 1989 [20, 21]; later, after the adoption of a new assessment in 1991 [28, 29] and of a law in 1992 [39], this countermeasure applied only to the inhabitants of obligatory resettlement zones. In addition, the right to voluntary resettlement was granted to the inhabitants of the zone of that name. As a result of the completion of the resettlement programme, over the years up to and including 1995, more than 47 000 people left the contaminated areas. During the same period, only 7600 people left settlements which were subject to obligatory resettlement. It is important to note that, notwithstanding the offer of new housing to the resettled individuals, compensation for the damages and other payments, a certain percentage of the inhabitants refused resettlement. Moreover, in the contaminated regions of Russia, there is currently a net increase in population in the resettled areas because of migration from other countries. In accordance with the 1995 Concept [38], which has not yet been reflected in law, there is no further justification for the resettlement of the inhabitants of the contaminated zones. As a result, the resettlement of the inhabitants of the contaminated areas in Russia may effectively be considered closed.

In **Ukraine**, in accordance with the laws adopted in 1990, approximately 30 000 people from 96 populated areas (about 17 000 families) were subject to mandatory resettlement. At the beginning of 1995, 11 523 families had been resettled and 5419 families remained living in areas with contamination higher than the national criteria for resettlement. In addition to the mandatory resettlement of the inhabitants from the obligatory (subsequent) resettlement zone, the laws of Ukraine provided for resettlement of people from the voluntary resettlement zone and from the radiological control zone. From these zones, 12 369 families were on the list for resettlement. Approximately 9000 of these families were resettled during 1990–1995. For two regions in Ukraine (Rovno region — 44 populated areas subject to the resettlement plan, and Zhitomir region — 37 such areas), an assessment of the effectiveness, in terms of dose reduction, of evacuation and resettlement was conducted. The actual collective dose, not including the thyroid dose caused by radioactive iodine, was 1970 man Sv for these populated areas from 1986 to 1991. The dose averted by resettlement for the inhabitants of these populated areas was 630 man Sv. Thus, the ratio of the collective dose over 70 years to the collective dose for 1986–1991 (2600/1970 man Sv) results in an effectiveness for the given measures of approximately 1.3.

According to the calculated doses presented in [40], the level of averted collective dose from 1991 to 2056 for all 92 populated areas subject to resettlement in Ukraine was determined to be 715 man Sv. This assessment of the averted dose indicates a total of 35 deaths from oncological diseases averted among the population of 29 000 people over a 65-year life span, (i.e. an average of 0.5 deaths per year) compared to a natural mortality rate of 55 cases per year in the country for this group of the population.

As early as 1987–1988, specialists had discussed the high cost and low effectiveness of such a radical measure as resettlement. However, the decisions and measures on resettlement which were reached later were introduced for other reasons. Such decisions were reached under the powerful pressure of public opinion and legislative bodies, and they took place only when a portion of the population could not live on the contaminated areas because of the increased sources and levels of stress.

The subsequent examination conducted in Ukraine of the reaction to resettlement among the already resettled inhabitants and among people awaiting resettlement has shown that:

- the level of psychosocial tension in both groups remains high;
- the intervention measures undertaken, including evacuation and resettlement, have increased the level of psychosocial tension among the population;
- since 1993, among people whose resettlement was not provided for by the adopted laws, a reduction in the level of psychosocial tension has been recorded.

As a result of polls conducted by Ukrainian specialists, the negative attitudes towards resettlement reflect uncertainty regarding the future and loss of social and personal contacts. 83% of the resettled people feel less happy than those who have continued living in the same areas where their forefathers lived, even though these areas are contaminated; 42.5% of the people approved of the idea of resettlement, 28% disapproved of it and 26.5% had not formed an opinion.

A review of people resettled during 1991–1992 showed that the population adjusted to resettlement with difficulty when they were resettled to a number of different areas, sometimes far from one another. This led to a need to grant the right to voluntary resettlement for a larger group of populated areas where contamination was below the levels for obligatory resettlement. In view of the prevailing conditions, however, it made sense to limit the offer of voluntary resettlement to a significantly smaller number of populated areas, and to offer compensation to people in other areas.

5.3.2. Decontamination of land, buildings and installations

Decontamination of the populated areas included removing contaminated soil, replacing it with 'clean' soil, dismantling items which could not be cleaned, asphalting streets, roads, sidewalks, replacing roofs and burying waste generated at temporary storage areas. Work on decontamination began at the end of May 1986. It was undertaken primarily by the chemical branch of the USSR armed forces and the civil defence forces and was carried out according to the zone of radioactive contamination in which the populated area was located. Since 1986, standards for the levels of surface radioactive contamination of various areas (buildings, transportation facilities, etc.) intended to be used as criteria for the completeness of the decontamination effort began to be established. The permissible levels of contamination were based on the radiation dose limits for the whole body and skin [1]. The creation of standards for surface contamination had several goals, including the introduction of corresponding sanitary–hygienic measures. In Table XXXII, the changes in the permissible levels of surface contamination for various types of items in populated areas are presented. Decision making on decontamination was based primarily on two criteria:

- the radioactive contamination zone in which the item was located (almost all of the decontamination work was conducted in the obligatory resettlement zone); and
- the social and economic significance of the decontaminated item.

Sometimes decisions were based on the fact that the established standard for surface contamination had been exceeded.

TABLE XXXII. PERMISSIBLE DOSE RATE LIMITS FOR THE SURFACE CONTAMINATION OF VARIOUS ITEMS (μGy.h^{-1}, 1m FROM THE SURFACE) ESTABLISHED AFTER THE CHERNOBYL ACCIDENT

Item	12 June 1986	24 Oct. 1986	29 July 1987	19 July 1988	11 May 1990
Roads	15	2	2	1	–
Interior surfaces of buildings	3	1	0.4	–	0.1
Open inhabited areas and exterior surfaces of buildings	7	5	5	2	–

In 1986, outside the exclusion zone, 412 localities were decontaminated (Belarus — 204, Russia — 126 and Ukraine — 82). In 1987, decontamination work became more organized and was undertaken along with capital repairs and infrastructure construction in populated areas. In 1987, 132 localities and 27 000 kilometres of roadway were decontaminated. In 1988, 643 localities were decontaminated (Belarus — 440, Russia — 91 and Ukraine — 112). Beginning in that year, decontamination was undertaken in populated areas with relatively low levels of contamination and this inevitably led to a reduction in the effectiveness of the measures undertaken. In 1989, decontamination work was conducted in 430 populated areas (Belarus — 215, Russia — 87 and Ukraine — 128) [1]. In the following years, the scale of decontamination work in the contaminated areas was reduced. From 1986 to 1987, it was possible to obtain a major improvement in the situation through radical reduction of dose rates in various frequently visited points in populated areas. This resulted in a lowering of the external dose for various professional and some age groups, (for example, children) by an average of 30%. By 1989, the full decontamination of populated areas had been virtually completed. The obtainable average external dose reduction coefficient in populated areas did not exceed 10%.

In **Belarus,** it has not yet been possible to complete the decontamination work, because of the large scale of the radioactive contamination and the lack of resources. In recent years, decontamination work has been conducted only in the areas and on those objects which are the most important. First, socially important items were decontaminated, such as areas around children's preschool facilities, schools, health care and health resort facilities, recreational locations and areas with high concentrations of people, food production enterprises, other industrial facilities and local areas with unusually high contamination. From

1991 to 1995, more than 150 socially significant items with a total decontaminated area of 450 000 m^2 were cleaned; another 480 more items were discovered, including some in industrial enterprises, which required decontamination, in addition to private living areas in the contaminated regions; 390 ventilation systems in 21 enterprises with a cleaned area of 57 000 m^2 were decontaminated, and more than 1300 units of industrial equipment still remain to be decontaminated. It was planned to complete the decontamination of the socially significant items and industrial equipment and to begin the decontamination of private living areas by the year 2000.

The optimized decontamination measures undertaken in the populated areas were effective in lowering the dose from external exposures. Further decontamination steps are hindered by the absence of effective resource-conserving technology for cleaning and waste processing for a broad range of items and a larger volume of contaminated materials. A serious problem is the search for technology to clean soil while preserving its biological value. Without the development of such technology, the task of rehabilitating the contaminated land cannot be completed.

In **Russia** and **Ukraine** from 1990 to 1995, large scale traditional decontamination work was not conducted. The State programme provided for the decontamination only of local areas of high radioactive contamination which were permanently inhabited, and the decontamination of farms and other agricultural facilities. Similar work is planned for the coming years.

5.3.3. Burial of radioactive waste

The waste concerned is industrial and agricultural with a high radionuclide content or waste generated by decontamination measures. In accordance with sanitary rules in effect before the accident [41], solid waste is considered radioactive if its specific activity is greater than 7.4 $kBq.kg^{-1}$ for sources of alpha radiation, 0.37 $kBq.kg^{-1}$ for transuranium elements, 74 $kBq.kg^{-1}$ for sources of beta radiation, and 3.7 $kBq.kg^{-1}$ for sources of gamma radiation.

Another criterion was the dose rate of 1 $\mu Sv.h^{-1}$ at a distance of one meter from a contaminated surface. Work with radioactive waste was regulated by special sanitary rules. If one considers ^{137}Cs alone, soil with a contamination density of 555 $kBq.m^{-2}$ in the upper five-centimetre layer would be classified as radioactive waste. Naturally, after the accident, it was not possible to organize the burial of everything which previously fell under the definition of radioactive waste, nor was it possible to organize large scale monitoring of waste. Simpler methods were widely adopted.

The soil and materials which were generated by the decontamination work were subject to burial. The burial volume grew with the expansion of the decontamination work. For example, in the Russian Federation, 9000 m^3 and 147 900 m^3 of soil were buried in 1986 and 1988 respectively. In 1986, in the conduct of agricultural activities, waste from the initial reprocessing of raw materials was buried in accordance with recommendations. Much farm waste, including manure, was stored as compost for long term storage and subsequent radiological assessment. The authorities [15] accepted the burial of trash from populated areas, land from roadside ditches, absorbing materials, air filters from machines, extremely contaminated items and used clothes. Temporary instructions [15] recommended the burial of ash formed from the burning of waste from the initial reprocessing of wood with a contamination higher than 185 $kBq.m^{-2}$, and clothes with a dose rate greater than 10 $\mu Gy.h^{-1}$. Burial was recommended in special trenches with clay seals and a clay base, outside naturally low-lying areas and with deep groundwater levels.

The selection of the areas for burial was made with the approval of the sanitary and water inspection authorities and the veterinary service. For populated areas a burial on site or centralized removal was recommended for all waste, including residues after harvesting, ash and household waste. Similar recommendations were made in instructions issued subsequently.

From 1992 to 1995, under the State programme within the contaminated regions of the **Russian Federation**, the following work was undertaken:

- the construction of new and the re-equipment of previously created areas of temporary burial of radioactive waste from reprocessing products from agricultural and forest activities;
- the elimination by burial in the exclusion or obligatory resettlement zones of low economic value items which had high levels of radioactive contamination and which were inflammable or otherwise dangerous. To date, 270 structures have been disassembled and buried.

In **Belarus**, the decontamination of materials and the dismantling of buildings has generated approximately 26 000 tonnes of solid radioactive waste annually which requires burial in specially equipped depositories. The decontamination of industrial equipment has produced up to 20 000 additional tonnes of liquid radioactive waste annually which requires special reprocessing and storage. In Belarus it is accepted that the burial of waste from decontamination may be undertaken in accordance with the level of its activity, the type and condition of the sites for the burial of radioactive waste, sites for the burial of waste from decontamination (SBWDs) and sites for the burial of waste from dismantling buildings and structures. In addition, from 1986 to 1988, 69 temporary storage sites were created in the Gomel region, some without the required ecological assessment.

In the Belarus exclusion and obligatory resettlement zones, seven active SBWDs based on standard plans, each of 30 000–50 000 m^3, have been created. The unused volume of these SBWDs consists of approximately 120 000 m^3, which allows decontamination work to be carried out for another 1.5–2 years. Through the year 2000, the creation of several more SBWDs with a total volume of 120 000 m^3 has been proposed. At all burial sites, inspections of their condition are conducted in accordance with standard procedures, which include monitoring the groundwater around the depository.

In spite of the large quantity of radionuclides which fell on Belarus territory, the specific activity of buried material usually does not exceed 37 $kBq.kg^{-1}$. At the same time, the quantity of industrial and socially important items subject to decontamination is large and, as a result, there is a significant amount of waste generated. Apartment buildings and private houses in cities and villages in the contaminated zone annually generate approximately 18 000 tonnes of ash contaminated with radionuclides. At purification sites in small towns located in areas with a contamination density greater than 185 $kBq.m^{-2}$, more than 30 000 m^3 of sediment from contaminated effluent have been formed. The use of the forests each year results in the formation of hundreds of thousands of tonnes of contaminated wood. As a result of the radiation monitoring, 1500 units of industrial equipment which required decontamination were discovered. To date, the question of the isolation of these types of waste has not been resolved owing to the absence of technological solutions and lack of financial resources.

To reduce the risk of abandoned buildings and structures catching fire in abandoned settlements, much effort is being devoted to the dismantling of wooden buildings and their subsequent burial. From 1991 through 1994, 51 settlements were completely dismantled, and 2480 houses were buried. An additional 11 000 houses are scheduled for burial. This will be accompanied by the processing and subsequent re-use of building materials and construction facilities under strict radiation inspection.

The question of the radioactive waste within the exclusion zone in **Ukraine** is important. The total activity of radionuclides at more than 800 waste burial sites is of the order of 150 TBq (380 kCi), with a volume of 1 million m^3. The reliability of these sites is a cause for concern, and the problem needs to be solved.

5.3.4. Limits on free access by the population and the termination of economic activity

In 1986, access to the exclusion zone was limited. In 1988, the limit for full termination of agricultural activity [15] was set at 2960 $kBq.m^{-2}$. Woods were allowed to grow on arable land. In accordance with subsequent recommendations [27], agricultural land with a level of radioactive contamination greater than 1480 $kBq.m^{-2}$ was excluded from crop production. Since 1988, any type of forest-based economic activity has been prohibited on forested land contaminated with a density greater than 1480 $kBq.m^{-2}$, with the exception of measures undertaken to strengthen the protection of forests from fire, disease and forest pests. As a result, the abandoned areas consist of:

in Belarus — the Polessye Radiological and Ecological Reserve (Belarus exclusion zone) with an area of 2150 km^2 and a resettlement zone with an area of 4210 km^2;

in Russia — the exclusion zone of 170 km^2 and 576 km^2 of arable land and 445 km^2 of forest excluded from economic activities;

in Ukraine — the exclusion zone with an area of 2040 km^2 of which 549 km^2 consists of arable land and an obligatory resettlement zone of 1450 km^2.

The fundamental threat of secondary contamination as a result of the dispersion of radionuclides comes from the significantly greater contamination in the exclusion and obligatory resettlement zones. For instance, according to the data of Ukrainian specialists, the primary radionuclide migration paths outside the limits of these zones are:

- river flow made up of surface run-off, and the removal of radionuclides with underground water;
- air (wind) transport;
- biological transport;
- technological transport.

The main radionuclide migration path beyond the exclusion zone is surface run-off. From 1989 to 1995, the annual average radionuclide run-off from the Pripyat river to the Kiev reservoir was 4–16 TBq of ^{90}Sr, of which the contribution from the exclusion zone was approximately 60%, and 2–5 TBq of ^{137}Cs, of which the contribution from the exclusion zone exceeded 20%. Thick vegetation cover on undisturbed soil areas and in forests completely prevents wind transportation although, in the event of a fire, there is an increase in the movement of radionuclides. Biological transport of radioactive contamination beyond the limits of the exclusion zone does not exceed several tens of GBq.a^{-1} of ^{137}Cs and ^{90}Sr, and technological transport accounts for even less than 37 GBq.a^{-1} (1 Ci.a^{-1}). Migration of radionuclides in underground water has not led to a stable level of contamination of groundwater on much of the exclusion zone. The migration of radionuclides into groundwater is much greater in regions where radioactive waste burial sites are located. At some sites, concentrations of ^{90}Sr in groundwater at the level of 1–100 kBq.L^{-1} have been detected. The radionuclide migration process from the land surface is prolonged and the maximum concentration of ^{90}Sr in groundwater is expected 20–30 years after the Chernobyl catastrophe.

Countermeasures for preventing the transport of radionuclides include:

- fire prevention measures, including extensive effort to prevent and extinguish fires;
- security measures to prevent unauthorized access and activities;
- water inspection and preservation measures on the territory.

Fire prevention measures include:

- constructing non-flammable barriers in forest cuts;
- ploughing around the perimeter of evacuated villages;
- constructing fire prevention pools;
- maintaining roads leading to the zones where the risk of fire is highest;
- flooding peat areas;
- air- and ground-based patrolling;
- creating fire-chemical stations.

Security measures have been undertaken in the zones of initial evacuation and subsequent resettlement for the purpose of preventing unauthorized access by citizens, the removal of items without the required documentary authorization and the provision of necessary sanitary and fire prevention precautions. The provision of security measures in the exclusion and obligatory resettlement zones is enforced at access control points at the intersection of roads around the perimeter of the zone, the use of security structures and signs and also by systematic patrolling. Water preservation measures are undertaken by keeping the technical structures of water control in working order to prevent any excess water on the territory leading to an increase in the run-off of radionuclides.

5.3.5. Changes in agricultural and forestry activities

The recharacterization of forest and agricultural activities was initiated for several reasons:

- Departmental instructions and directives were created which prohibit the movement of various types of products with a specific contamination level. For instance, it is prohibited to grow grain, beans, linen and buckwheat in agricultural areas with a contamination density greater than 925 kBq.m-2, to collect forest food products, medicinal herbs, and boughs from coniferous trees or to produce vitamin flour from coniferous trees in forests with a 137Cs deposition greater than 185 kBq.m-2.
- The observance of some departmental instructions and directives has seriously complicated various types of activities. For example, gathering wood by cutting

branches and peeling bark on site is allowed only in winter, and burning the resulting waste only where trees are cut for subsequent burial.

- Selling raw materials is difficult because of the complex procedures required to comply with hygiene requirements for the subsequent processing or use of products from such activities as sheep raising, tobacco and hop growing, and gathering wood fuel.

The changes in agricultural activities were limited in nature. None of the collective farms changed its profile completely. Only a partial change in type of cultivation and stock raising took place. The area for cultivating grains and beans was limited. In the zone with more than 555 $kBq.m^{-2}$ (obligatory resettlement), the raising of buckwheat and hops was prohibited and sheep raising was curtailed. Here the changes are particularly significant. In the Bryansk region alone, the production of wool was reduced from 603 tonnes per year from 1981 to 1985, to 74 tonnes per year from 1991 to 1993 [42]. However, this reduction was caused by both the Chernobyl accident and the economic crisis in the 1990s, the impact of which on agricultural and forest production is difficult to differentiate.

Almost all directives maintained certain recommendations for the safe conduct of work in agricultural and forestry activities. For forestry workers, for instance, there were special limits on doses. In May 1986, agricultural workers in the contaminated regions were issued with individual protective clothing, and decontamination of clothing after working under extremely dusty conditions was organized. The position of radiologist was introduced into regional and local services. In 1986, regular weekly decontamination of agricultural equipment was widely conducted. Several examples can be cited of measures which have positively influenced working conditions and contributed to dose reduction. In the contaminated areas of Russia, the T–150K tractor has been developed with air conditioning. The hermetically sealed cabins of the tractors meet the standards of permissible ambient air pollution inside the cabin under dusty conditions. The use of protective clothes, light respirators and more powerful protective measures became more widespread for jobs involving intensive dust production.

5.3.6. Limitation of consumption of contaminated food products and drinking water

Temporary permissible levels (TPLs) for the radionuclide content of food products and drinking water [1, 2, 5, 6, 14, 18, 26] were established to limit the incorporation of radionuclides into humans living in the contaminated regions. The changes in the list of products for which TPLs were specified, the products subject to inspection and the permissible levels are shown in Table VI. It should be noted that although drinking water is included in many TPLs, problems with its radioactive contamination did not actually arise. In 1990, the practice for the development of TPLs in the three republics became slightly different.

From 1990 to 1992 in **Belarus**, the "Republic inspection levels for the content of radionuclides in food products and drinking water" were determined so that, given the permanent content of radionuclides in food products at the standard permissible level, the annual dose from internal exposure would be no more than 1.7 mSv. For example, the concentration of radioactive caesium in milk and milk products was not to exceed 185 $Bq.L^{-1}$ and in meat, meat products and potatoes, 592 $Bq.kg^{-1}$. Stricter standards were adopted in 1992 to further reduce the annual dose from internal exposure. The permissible levels for the content of ^{137}Cs for milk and milk products was reduced to 111 $Bq.L^{-1}$, for potatoes, to 370 $Bq.kg^{-1}$, and for bread, from 370 to 185 $Bq.kg^{-1}$ (Table VII). Higher levels were allowed for agricultural raw products and animal fodder (Table VIII).

In 1993 in **Russia**, new standards for food contamination, TPL 93 [37] (Table IX), were adopted to simplify the inspection systems. A single level of 370 $Bq.L^{-1}$ for milk, milk products and several other types of products was established. For all remaining food products, including meat, belonging to the "other" category, the permissible limit was 600 $Bq.kg^{-1}(L^{-1})$. There was an exception for children's food — 185 $Bq.kg^{-1}(L^{-1})$. As an example, the results of monitoring contaminated products conducted by the sanitary services of the Bryansk region are shown in Table XXXIII [43].

From 1990 in **Ukraine**, TPL 91 has been in force although in various regions local executive bodies have introduced stricter limits. The practical implementation of the limits is directly related to the large scale inspection system which is used virtually universally by the food industry, veterinary services, agrochemical laboratories and sanitary services. The veterinary and sanitary inspection network encompasses all administrative regions. Since the second half of 1986, inhabitants have been able to receive analysis results concerning the radionuclide content in food products brought for inspection. If inspected products did not meet the TPL, they were not allowed to be sold or otherwise used for public consumption. Thereafter, as a rule, such products were either reprocessed or used as cattle feed or, in some cases, destroyed.

Even stricter measures than the inspection system were adopted in some areas. In the Bryansk region in Russia, for example, in September 1986, 1300 head of cattle and approximately 1500 pigs and sheep were confiscated from the population (in return for compensation) and transferred to collective farms, and fowl was purchased and used for industrial processing. The goal of limiting the consumption of contaminated food products resulted in multiple limitations which prohibited the collection of mushrooms, berries, medicinal herbs and hay in forests. These prohibitions continue to be in force today.

The results of monitoring support the policy of maintaining the limits in the more contaminated areas. From 1994 to 1995 in the Bryansk region [43], for example, the following maximum levels of ^{137}Cs content were registered in food products in the private sector: milk — 3.1 $kBq.L^{-1}$, meat from domestic animals — 7 $kBq.kg^{-1}$, meat from wild animals — 28.8 $kBq.kg^{-1}$, dried mushrooms — 345 $kBq.kg^{-1}$, marinated mushrooms — 2.7 $kBq.kg^{-1}$, jam — 3.7 $kBq.kg^{-1}$ and forest berries — 4.4 $kBq.kg^{-1}$.

The effectiveness of the limitation system has been relatively high. The average internal dose during 1986 in the "strict control" (obligatory resettlement) zone was 15 mSv and during 1989 for 95% of the inhabitants of this zone, the internal doses were less than 2.5 mSv. However, various indirect adverse effects were caused by overly strict limitation of the content of caesium radionuclides in agricultural produce. These included economic losses and insufficiently balanced diets. No consideration was given to applying the intervention level to the constant consumption of contaminated foodstuffs at the TPL level. These issues are analysed in detail in Ref. [44]. The permissible level of gross beta activity in milk, which entered into force [6] on August 1, 1986 (370 $Bq.L^{-1}$), was not accompanied by requirements or recommendations, such as compliance with the pasture rules for obtaining cleaner products. As a result, even a single delivery of contaminated milk exceeding the TPL was treated as evidence that it was impossible for that area to provide clean products.

5.3.7. Countermeasures in agriculture

The first detailed recommendations [7] that were prepared for the contaminated regions of Ukraine began to be used in Russia and Belarus at about the same time. In addition, a larger number of temporary regulations, memoranda and instructions which regulated various types of activities and technological processes were also prepared. In 1988, the

TABLE XXXIII. NUMBER OF FOOD SAMPLES MONITORED IN THE BRYANSK REGION, RUSSIA, AND PERCENTAGE OF RESULTS HIGHER THAN TPL [43]

Year	No. of samples	Total	Foodstuffs						
			Water	Milk and milk products	Meat and meat products	Bread products	Green vegetables	Berries fruits	Others
1986	Total	36728	3706	11545	7079	906	4348	4727	4423
	% above TPL	14	4.8	23.6	11.8	–	3.0	20	6.0
1987	Total	42443	5411	13356	9322	1539	4506	2305	7543
	% above TPL	10.0	–	26.0	2.0	–	0.2	5.5	4.1
1988	Total	41367	2742	16641	8759	1735	4331	926	6233
	% above TPL	10.8	–	19.8	2.2	–	0.6	2.1	15.2
1989	Total	45769	1577	19543	3502	789	6415	2100	11843
	% above TPL	7.6	–	16.2	0.6	–	–	3.8	1.8
1990	Total	63231	1277	28304	8827	1716	8556	4330	10221
	% above TPL	8.3	–	9.4	0.9	–	1.0	9.8	19.7
1991	Total	46319	502	16703	9662	2596	7084	1830	7246
	% above TPL	4.6	–	6.5	1.8	–	0.8	6.8	9.0
1992	Total	48882	1882	18150	8578	2759	11062	3246	3205
	% above TPL	2.2	–	2.4	1.5	–	0.7	7.1	6.3
1993	Total	38818	1480	14617	5341	2299	8796	1588	4697
	% above TPL	3.1	–	1.8	1.2	–	0.2	18.5	12.5
1994	Total	39984	2251	13541	5196	2287	10619	1394	4696
	% above TPL	1.6	–	1.5	1.0	–	0.1	7.6	6.2
1995	Total	31473	1870	9045	3995	2224	7886	1833	4620
	% above TPL	0.8	–	1.0	0.4	–	–	3.4	2.1

introduction of countermeasures entered a new phase when it became possible to plan and recommend them on the basis of estimates of contamination of crops and it was made mandatory to follow these recommendations [15]. The recommendations for the period 1991–1995 allowed the application of a set of organizational principles to the planning of crop sowing and to the estimation of crop contamination levels, including their reduction during subsequent processing. The recommendations also provided for agrotechnical, agrochemical and technological measures to reduce the contamination of plant products. All recommendations for the conduct of plant cultivation used the soil contamination in a given area as the criterion for undertaking measures. In animal breeding, the criteria for undertaking countermeasures were the TPLs or departmental standards for animal feed based on the TPLs.

The technological cycle of agricultural production allows the introduction of countermeasures to reduce the transfer of radionuclides at different stages in the food chain: from soil to plants; from fodder to livestock; and from raw materials to processed foodstuffs. The simplest and most easily implemented countermeasures are those on arable land. The use of mineral and organic fertilizer does not require additional equipment or changes in cultivation technology and it improves the physical and agrochemical condition of the soil and also increases yields. A comparative assessment of the effectiveness of countermeasures on arable land applied in Belarus is presented in Table XXXIV.

The expenditure incurred for basic protection measures in plant breeding has been estimated. Table XXXV shows assessments of their effectiveness in terms of roubles spent to avert collective internal dose of 1 man Sv, for the consumption of crops grown in the most widely found soil type in the contaminated area. The reduction in the application of these countermeasures inevitably leads to an increase in contamination of agricultural products [43]. In the contaminated areas of the Bryansk region, when grain cultivation was introduced in 1991, 81 kg of K_2O per hectare was used and the activity concentration of ^{137}Cs in grain was 26 $Bq.kg^{-1}$. In 1993, with a reduction in use to 18 kg K_2O per hectare, the activity of ^{137}Cs in grain increased to 70 $Bq.kg^{-1}$. In the Krasnaya Gora district, due to breaking off of the supply of potassium fertilizer for use in potato cultivation, activity of ^{137}Cs in 1993 was 107 $Bq.kg^{-1}$ compared to 37 $Bq.kg^{-1}$ in 1991.

Other combined measures like deep ploughing and hoeing with the simultaneous addition of lime and potassium fertilizer reduced crop contamination three to fourfold, and special ploughs produced up to a tenfold reduction in the contamination of natural grazing land.

TABLE XXXIV. REDUCTION FACTOR OF RADIONUCLIDE TRANSFER FROM SOIL TO PLANTS AS A RESULT OF APPLICATON OF AGRICULTURAL COUNTERMEASURES (DATA FROM BELARUS)

Countermeasures	^{137}Cs		^{90}Sr
	Mineral soil	Peaty soil	Mineral soil
Liming	1.5–3.0	1.5–2.0	1.5–2.6
Application of double dosages of potassium–phosphorus fertilizers.	1.5–3.0	1.3–3.0	1.2–1.5
Application of organic fertilizer	1.3–1.6	–	1.2–1.5
Combined application of lime, with organic and mineral fertilizer.	2.3–3.5	–	1.5–1.8

TABLE XXXV. THE COST–EFFECTIVENESS OF COUNTERMEASURES ON TURF PODZOL SLIGHTLY LOAMY SOIL: EXPENDITURES FOR AVERTING 1 MAN SV IN MILLIONS OF ROUBLES (5000 ROUBLES = 1 USD) [45]

Culture	Product	^{137}Cs soil deposition ($kBq.m^{-2}$)	
		185–555	555–1480
Liming			
Winter wheat	grain	35	12
Spring barley	grain	24	8.5
Oats	grain	84	30
Winter rye	grain	29	10
Corn	silage	1.4	0.5
Annual grass	silage	5.5	1.9
Silage	silage	0.2	0.08
Perennial grass	silage	1.8	0.6
Hay	silage	2.4	0.8
Pasture	grass	0.6	0.2
Additional use of phosphate–potassium fertilizer			
Winter wheat	grain	168	95
Spring barley	grain	94	65
Oats	grain	354	252
Winter rye	grain	129	71
Potatoes	tuber	6.1	3.0
Corn	silage	8.4	4.8
Single-year grass	hay	20	17
Silage	silage	1.0	0.80
Multi-year grass	hay	10	5.7
Hay	hay	5.1	2.5
Pasture	grass	1.2	0.6
Complete use of measures (nitrogen–phosphate–potassium fertilizer + lime)			
Winter wheat	grain	131	69
Spring barley	grain	75	48
Oats	grain	281	184
Winter rye	grain	105	55
Corn	silage	7.6	4.2
Annual grass	hay	14	11
Silage	silage	0.7	0.5
Perennial grass	hay	10	5.3
Hay	hay	5.6	2.6
Pasture	grass	1.4	0.6

As milk and diary products are dietary staples, their contamination by radionuclides can contribute significantly to internal exposure. Consequently, the application of countermeasures in meadows and pastures makes the most significant contribution to lowering the internal dose to people living in contaminated areas. Thus, an effective countermeasure for the reduction of individual doses is the creation of cultivated meadows and pastures. The recommended method for cultivating the land combined with different ways of liming the soil and adding mineral fertilizer has resulted in a continual three to fourfold reduction in the uptake of caesium and strontium radionuclides from mineral soils. The major improvement of meadows with peaty soil also sharply reduced the uptake of ^{137}Cs by cultivated grasses.

The technology has not yet been developed to rehabilitate contaminated land used for grazing cattle in river flood plains. For many areas, this grazing land is the primary source of food in drought years, leading to greater contamination of animal-based products, because the soil–grass transfer factor for flood plains is higher than for dry pasture. Moreover, not all natural pasture may be cultivated. In these cases, selective adsorbents which prevent the absorption of radionuclides from the gastrointestinal tract were added to animal feed. Much more widely used, and better known, caesium-selective adsorbents are those belonging to the trivalent salt group of cyanoferric acid (e.g. Prussian Blue). Their use results in a two to fivefold decrease in the content of radionuclides of caesium in milk and in the muscle mass of cattle. Up to 1996 in Belarus, 100 000 boluses of cyanoferrates and 4000 tons of mixed fodder for 30 000 head of cattle were produced and implemented annually.

Since 1994 in the Bryansk region, caesium binding compounds (cyanoferrates) in boluses and other forms have been widely used. In 1994, approximately 19 tonnes of similar medications were delivered for 10 000 cows. In the southwest areas of the Bryansk region, the final (pre-slaughter) feeding of cattle and pigs on clean feed and *in vivo* monitoring of the caesium radionuclide content in animals were introduced. This countermeasure at first produced a sharp drop in the production of contaminated meat and in later years practically eliminated the problem.

Initial technological processing of raw materials and treatment of prepared foodstuffs were introduced to reduce food contamination. For example, grinding grain into white flour reduces the content of radionuclides twofold for wheat, rye and barley, and threefold for oats, and the processing of grain into spirits practically eliminates the content of radionuclides in the final product. Processing potatoes into starch can reduce the content of radionuclides in the finished product to as little as 2%. Processing milk into butter reduces the radionuclide content to 1–3%, and into cream to 5–7%. In this way, the introduction of a series of countermeasures at different stages in food production can significantly reduce the internal dose to the population by as much as a factor of ten. From 1986 to 1994 in **Russia**, in four of the more heavily contaminated regions the following countermeasures were implemented in agricultural technologies:

- Contaminated soil was limed in an area of 1 334 800 hectares.
- Fertilizers were increased on 1 526 500 hectares.
- Meadows and pastures were improved on 130 900 hectares.

The greatest effort was directed to the most contaminated areas of the Bryansk region with:

- the liming of 417 000 hectares;
- the introduction of increased amounts of combined fertilizer on about 900 000 hectares; and
- the cultivation of natural pasture on 94 500 hectares.

Almost everywhere, planning of feed rations was based on the actual contamination of fodder components with radionuclides. Inspections of cattle grazing areas were conducted, on the basis of which a regime for cattle grazing was developed.

The measures taken cut out the production of vegetable food exceeding the radiological standards, except in the most contaminated areas of the Bryansk and Kaluga regions. Each year in the Bryansk region, potatoes, fruit, vegetables and corn have always met the standards and, since 1991, so has grain. In recent years in the Kaluga region, the production of contaminated products has almost ceased. In the southwest areas of the Bryansk region, the percentage of contaminated products which exceeded the established standards is shown in Tables XXXIII and XXXVI.

TABLE XXXVI. PERCENTAGE OF FODDER AND FOOD PRODUCED IN THE SOUTHWEST PART OF THE BRYANSK REGION EXCEEDING RUSSIAN RADIOLOGICAL STANDARDS

Year	Hay (%)	Milk (%)	Meat (%)
1986	79	86	15
1987	34	69	9
1991	13	8	0.07
1994	5	0.7	0.07

In order to obtain products that meet the limits, milk with contamination exceeding the limits is processed into butter and other products, and meat is converted to meat meal and bone meal used as animal fodder.

It is assessed that the implementation of agricultural protective measures in the Russian obligatory resettlement zone contaminated between 555 and 1480 kBq m^{-2} by ^{137}Cs reduced the internal collective dose by more than 50% [45].

In Belarus, the experience of conducting agricultural activities in contaminated areas shows that the use of agricultural improvement and organizational countermeasures results in products which comply with the permissible levels of caesium and strontium.

5.3.8. Measures for the reduction of contamination of food produced on private land plots

In addition to the constraints on day-to-day life, recommendations were developed and remain in effect for agricultural activity on private land plots. These include rules for working in private gardens and garden plots, procedures for the preliminary preparation of products grown for domestic use, rules for the maintenance and feeding of domestic animals, rules for processing mushrooms and berries, and procedures for the domestic reprocessing of animal products. In the most contaminated areas, liming and the use of potassium fertilizer were undertaken not only on collective farms but also on private land plots.

Local authorities were frequently advised to cultivate pastures for cattle. However, for a variety of reasons, not all recommendations were followed. As a result, milk — one of the primary components of the diet — was frequently found to be contaminated above the established action levels. In the private sector, when cattle were kept in stalls and fed with hay, it was usually grown on unrehabilitated land. During periods on pasture, cattle frequently grazed close to villages and in areas which were difficult for development, and on natural pastures in areas where it was difficult, if not impossible, to undertake improvement work.

Between 1989 and 1990, attempts were made to introduce ferrocin filters to 1500 households with a high radioactive caesium content in milk in Belarus, the Russian Federation and Ukraine. Filtering through ferrocin-containing fibrous material was used once, and reduced the internal dose by 50–90%. However, they were not widely distributed. At present, the feeding of boluses containing cyanoferates to cows is widespread and ensures a manifold reduction in the caesium content of milk. The medication is distributed free of charge. The population actively uses these medications since they guarantee that radiation inspection is passed when the milk is sold.

5.3.9. Measures to improve populated areas

Certain decontamination measures completed between 1986 and 1989 led directly to the improvement of populated areas. Beginning in 1989, decontamination measures were based not only on the actual level of radioactive contamination but also on social indicators. In the following years, decontamination based on such indicators was conducted in all three countries, along with the following measures: the construction or repair of water treatment and sewage facilities, the connection of gas supplies, the construction of roads, the construction of communal housing, and the installation of streets and recreational areas.

5.3.10. Information to the population

The policy of the authorities on information to the population was inadequate. During the first two years after the accident, there was no information in the mass media on the problems in the contaminated areas. At the same time, people living in these areas were constantly subject to a variety of limitations, reminders and instructions which differed from usual practice. The growing fear was exacerbated by the introduction of the "glasnost" policy, under which people often received inaccurate information. At the end of the 1980s, virtually the entire public was misinformed about the problems in the contaminated areas. Executive bodies, such as the Supreme Soviet of the USSR, decided on the requirements to develop a socially acceptable way of life. The Government agreed to expand the zone of post-accident measures and, as a result, lost confidence. From 1991 to 1995, the completion of various programmes involving the affected population did not improve the situation. People’s trust in State sources of information on the analysis of the problem is estimated to be quite low.

The negative effects of official policies on disseminating information resulted in people applying restrictions in many more areas than the radioactive contamination would have warranted. These self-limitations included reducing in the time children spent in the open air and in forests, and the cessation of production and consumption of certain food products.

5.3.11. Social and other supplemental measures

Various measures have been undertaken in the contaminated territories which have directly or indirectly led to the reduction of doses, or which might generally be considered protective. Since 1986, measures to improve the health of children, such as the organization of vacations in sanitoria and rest homes, have been undertaken. The population received many types of benefits and compensation which were supposed to increase the quality of life: these are discussed in more detail in Section 1. In the contaminated areas, measures were taken to reduce the radiation doses during medical diagnosis and treatment. Special rationing (diet) programmes were provided not only to increase production through improved agricultural practices but also to lead to a wider availability of products with curative properties.

REFERENCES TO SECTION 5

[1] Chernobyl. Five Difficult Years: Collection of Materials (1992).

[2] Temporary Permissible Content of Radioactive Iodine (Iodine 131) in Drinking Water and Foodstuffs during the Period of Elimination the Impact of the Accident, May 6, 1986, Russia NCRP, 340.

[3] BELAEV, S.T., DEMIN, V.F., KUTKOV, V.A., BARIAKHTAR, V.G., PETRIAEV, E.P., “Characteristics of the development of the radiological situation resulting from the accident, intervention levels and countermeasures”, The radiological consequences of the Chernobyl accident, (A, Karaoglou, G, Desmet, G.N, Kelly, H.G. Menzel, Eds), Rep. EUR 16544 EN 19–28 (1996).

[4] Map of Possible Doses of Gamma Radiation on May 10, 1986 (See [1]) 140–141.

[5] Temporary Permissible Level for the Content of Radioactive Substances and of foodstuffs (medical raw materials), May 16, 1986 (See [1]) 340.

[6] Temporary Permissible Levels for the Content of Radioactive Substances in foodstuffs, Drinking Water and Medicinal Plants (Total Beta Activity), May 20, 1986 (See [1]) 341.

[7] Temporary Recommendations for the Conduct of Agricultural Production in the Ukrainian SSR in the Areas Affected by Radioactive Contamination, Gosagroprom USSR, 1986.

[8] Temporary Levels of Permissible Radioactive Contamination of the Soil, External and Internal Surfaces of Buildings after Decontamination Work, Approved June 12, 1986.

[9] Decree No. 1005–285 of the Central Committee of the Communist Party of the Soviet Union and the Council of Ministers of the USSR dated August 22, 1986 "On Additional Measures for the Labor Development, Life Assurance and Daily Social Services of the Population Evacuated from Populated Areas in Connection with the Accident at the Chernobyl Nuclear Power Plant and the Compensation for their Material Damages, In the book "Reporter of Informational and Normative Materials on Issues to be Addressed in the Russian Federation as a Result of the Chernobyl Catastrophe", Moscow (1993) 38–47.

[10] Decree No. 1006–286 of the Council of Ministers of the USSR dated August 22, 1986 "On the Improvement of the Material Living Standards of the Population Living in Populated Areas with Limits on the Use of Locally Produced Agricultural Products in Connection with the Accident at the Chernobyl Nuclear Power Station", Ibid (52–57).

[11] Temporary Permissible Levels of Radioactive Contamination of Various Items, Approved October 24, 1986.

[12] Temporary Inspection Levels of Radioactive Contamination of Various Items in Populated Areas subject to a Limited Living Activities, July 29, 1987 (See [1]) 346.

[13] Regulations 1779r of the Council of Ministers of the USSR dated August 12, 1987, "On the Addition of Supplemental Populated Areas to the List of Populated Areas Governed by the Decree 1006–286 of the Council of Ministers of the USSR dated August 22, 1986, related to the Strict Control Zone", Ibid, 87–93.

[14] Temporary Permissible Levels of the Total Content of Cesium-134 and Cesium-137 Radionuclides in Food and Drinking Water (TPL-88), December 15, 1987 (See [1]) 343.
[15] Management of the Conduct of Agriculture under Conditions of Radioactive Contamination of Portions of the Territory of the RSFSR, UkSSR and BSSR during the Period 1988–1990, Gosagroprom USSR, Moscow (1988).
[16] Temporary Permissible Limits of Radioactive Contamination of Various Items in Populated Areas, July 19, 1988 (See [1]) 347.
[17] Regulations No. 1834r of the Council of Ministers dated September 13, 1988 "On the Addition of Supplemental Populated Areas to the List of Populated Areas Governed by the Decree 1006–286 of the Council of Ministers of the USSR dated August 22, 1988, related to the Strict Control Zone", Ibid, 98–99.
[18] Temporary Permissible Levels of the Total Content of ^{134}Cs and ^{137}Cs Radionuclides in Food and Drinking Water (TPL 88), October 6, 1988 (See [1]) 343.
[19] AVETISOV, G.M., "Policy of the National Commission on Radiation Protection after the Chernobyl Accident", CEPN Report No 225, 1994, 113–136.
[20] Regulations No, 912r of the Council of Ministers dated May 24, 1989, "On the Resettlement from 1989–1993 of Inhabitants of the Populated Areas in Regions with Radioactive Contamination Where Safe Living is not Longer Possible", Ibid, 118.
[21] Regulations No, 878r of the Council of Ministers dated October 5, 1989, "On the Resettlement from 1989–1993 of Inhabitants of the Populated Areas in Regions with Radioactive Contamination Where Safe Living is not Longer Possible", Ibid, 148–149.
[22] Decree No. 886 of the Council of Ministers of the USSR and the BTsSPC dated October 20, 1989 "On Additional Measures for the Strengthening of the Protection of Health and the Improvement of the Material Status of the Population Living in Areas Suffering from Radioactive Contamination as a Result of the Accident at the Chernobyl Nuclear Power Station", Ibid, 108–110.
[23] Regulations No. 2284r of the Council of Ministers dated December 30, 1989 "On the Addition of Supplemental Populated Areas to the List of Populated Areas Governed by the Decree 1006–286 of the Council of Ministers of the USSR dated August 22, 1988, related to the Strict Control Zone", Ibid, 122–123.
[24] Regulations No. 89r of the Council of Ministers of the RSFSR dated January 26, 1990 "On the Approval of the List of Populated Areas in Which the Consumption of Milk and Other foodstuffs which are Produced Locally of by Individual Households", Ibid, 187–191.
[25] Temporary Standards for the Radioactive Contamination of Human Skin and the Surfaces of Various Items in Populated Areas in the Controlled Regions of the RSFSR, UkSSR and the BSSR Created in Connection with the Accident at the Chernobyl Nuclear Power Station during December 1993, May 11, 1990 (See [1]) 349.
[26] Temporary Permissible Levels of the Total Content of Caesium and Strontium Radionuclides in foodstuffs and Drinking Water established during the period from April 1990 to December 1993 (TPL 91), January 15, 1991 (See [1]) 344.
[27] Recommendations for the Conduct of Agricultural Activities under Conditions of Radioactive Contamination of the Territory as a Result of the Accident at the Chernobyl Nuclear Power Station during the Period 1991–1995, Moscow (1991).
[28] A Concept of Living Conditions for people in the Regions Affected by the Chernobyl Accident, Ibid [19] 331–338.
[29] Decree No. 164 of the Cabinet of Ministers of the USSR dated April 8, 1991 "On Compensation for the Population Living in Regions Harmed by the Accident at the Chernobyl Nuclear Power Station", Ibid, 244.
[30] Law of the USSR dated May 12, 1991 "On Social Protection of Citizens Harmed by the Results of the Chernobyl Catastrophe", Ibid, 228–242.

[31] Decree No. 1 of the State Economic Committee of the RSFSR dated September 28, 1990 "On the Approval of the List of Populated Areas in which a Rate Increase (Salary Scale) and other Benefits will be Introduced", Ibid, 207–227.
[32] Regulations No. 190r of the Council of Ministers of the RSFSR dated March 11, 1991 "On the Addition of Populated Areas in the Bryansk and Kaluga Region Executive Committees to the List of Areas Located in Regions Suffering from Radioactive Contamination in which the Consumption of Milk is Limited", Ibid, 369.
[33] Regulations No. 237r of the Government of the RSFSF dated December 28, 1991 "On the Approval of the List of Populated Areas included in Areas of Radioactive Contamination", Ibid, 276–345.
[34] Regulations No. 363r of the Government of the Russian Federation dated February 25, 1992, Ibid, 436–440.
[35] Regulations No. 537-r of the Council of Ministers of the Government of the Russian Federation dated April 5, 1993.
[36] Regulations No. 1008 of the Government of the Russian Federation dated December 25, 1992 "On the Regime for the Territory Suffering from Radioactive Contamination as a Result of the Catastrophe at the Chernobyl Nuclear Power Station", Ibid, 431–435.
[37] Temporary Permissible Levels of the Total Content of ^{134}Cs and ^{137}Cs Radionuclides in foodstuffs (TPL 93), Gossanepidnadzor of Russian (1993).
[38] IVANOV, E.V., et al., “Concept of radiological, medical and social protection of the population of Russia affected by accidental exposure”, One Decade after Chernobyl: Summing up the consequences of the accident , IAEA-TECDOC-964, Vienna (1997) 520–523.
[39] Law of the Russian Federation “On the Social Protection of Citizens Who Suffered Radiation Effects as a Result of the Catastrophe at the Chernobyl Nuclear Power Station on July 18, 1992”.
[40] LIKHTAREV, I., KOVGAN, L., Dose Effectiveness of Countermeasures after the Chernobyl Accident, Main Approaches and Estimates (Proc. Int. Mtg on Environmental System Monitoring: Basic Problems, Kiev, Ukraine, 1994), UNESCO (ROSTE) 276–286.
[41] Basic Sanitary Rules for treatment of radioactive substances and sources of ionizing radiationOSP-72/87, M. Energoatomizdat (1988).
[42] Russian Statistical Yearbook 1994, Statistical Reporter, Goskomstat of Russia (1994).
[43] SHAPOSHNIKOVA, E.N., et al., The Results of Radiation Control of Agricultural Products, Foodstuffs and Environmental made by Bryansk Centre of State Committee of Sanitary and Epidemiology Inspection in 1986–1995, Bryansk (1996).
[44] The International Chernobyl Project, Technical Report by the International Advisory Committee, Vienna (1991).
[45] GLINKA, YE.V., VLASOV, D.K., PAVALYAYEV, A.P., Assessment and Report of the Effectiveness of Countermeasures Taken in the Agricultural Production Field in Areas with Varying Levels of Radioactive Contamination, Report by NVF Agrosystem, Ministry of Agricultural Production (1995).

6. CONCLUSIONS

6.1. Radiological impact

6.1.1. Radionuclide release and deposition

The accident at Unit 4 of the Chernobyl nuclear power plant resulted in a release to the environment of radioactive materials whose total activity amounted to approximately 12.5 EBq (1EBq = 10^{18} Bq), and included 6.5 EBq of noble gases. The activities of radioiodine (^{131}I) and radiocaesiums (^{134}Cs and ^{137}Cs) released represent 50–60% and 30–35% respectively of the core inventory at the time of the accident. Recent release estimates of these radiologically important radionuclides exceed estimates made in 1986 by a factor of 2.3–2.7.

The areas contaminated with ^{137}Cs, their number of inhabitants and the prognosis of future individual effective doses of external and internal exposure of the inhabitants are presented in Table XXXVII according to ^{137}Cs soil deposition levels used for management purposes.

TABLE XXXVII. SUMMARY OF THE RADIOLOGICAL CONDITIONS AS AT 1 JANUARY 1995 (ALL THREE COUNTRIES)

Soil deposition of ^{137}Cs (kBq m^{-2})	Area size (km^2)	Population (millions)	Estimated effective dose in 1996–2056 (mSv)
37–185	115.9	5.3	1–5
185–555	19.1	1.3	5–20
555–1480	7.2	0.13	20–50
>1480	3.0	–	>50
Total	145.2	6.7	–

Due to the specific features of the accident, i.e. the long duration of the release of radioactive products into the atmosphere, the complex changes in physical and chemical conditions and the change in meteorological conditions, the local and distant area contamination was non-uniform, both in the fallout density and radionuclide composition, and in its physico-chemical characteristics. The deposition patterns were mosaic-like, with spots of high radionuclide concentration, often determined by local precipitation.

6.1.2. Radionuclide migration

The vertical migration of the ^{137}Cs and ^{90}Sr in the soil of natural meadows has been rather slow, and most of the radionuclides are still contained in its upper layer (0–10 cm). However, in peaty soils radionuclide migration is faster: eight years after the accident, the maximum radionuclide concentration was measured at a depth of 3–5 cm. On average, in the case of peat soils, 40–70% of the ^{137}Cs and ^{90}Sr is found in the 0–5 cm layer; in the case of mineral soils, up to 90% of the ^{137}Cs and ^{90}Sr is found in this layer. The ^{137}Cs effective clearance half-life for the 0–10 cm soil layer varies from 10 to 25 years. Generally, the processes of soil clearance of ^{90}Sr are 1.2–3.0 times faster than those of ^{137}Cs, but vary with distance from the reactor. The clearance half-life for ^{90}Sr is estimated to be 7–12 years.

Radioactive material is transported beyond the limits of the exclusion zone mainly by water movement. Regular monitoring data show a steady decrease in the radionuclide content of water bodies with time. For example, in 1986, the waters of the Pripyat river at Chernobyl carried ^{137}Cs and ^{90}Sr at average annual concentrations of 22 Bq L^{-1} and 1.9 Bq L^{-1} respectively but by 1995, this had fallen to 0.1 Bq L^{-1} and 0.3 Bq L^{-1}.

During the spring run-off and rainstorm floods, the radionuclide concentration increases by up to four times in the rivers whose main drainage basins are situated within the most contaminated areas. Between 10% and 40% of the total ^{137}Cs activity in water is transported by suspended solids. The activity concentration of radionuclides is higher in the bottom deposits than in water organisms, and concentrations in water are lower than those in deposits and organisms.

In 1986, maximum radionuclide concentration was reached in agricultural plants due to direct aerial contamination, after which it gradually decreased. Since 1987, transfer coefficients of ^{137}Cs decreased on average by a factor of 1.5–7.0. Beginning in 1989, the soil-to-plant transfer coefficients of ^{137}Cs showed a tendency to stabilize. Five years after the Chernobyl accident, the ^{137}Cs soil-to-plant transfer had become stable. The process of ^{137}Cs sorption in the soil solid phase slows down with time. The main mechanism of durable radionuclide trapping in the soil is its inclusion into the crystal lattice of clay minerals. The subsequent decrease in the ^{137}Cs transfer into plants and animal products occurs at a slower rate.

The differences in radionuclide accumulation in plants were determined mainly by different soil properties. The accumulation in herbiage of ^{137}Cs from soddy-podzolic and sod soils is 1.2–3.2 times lower than from the soddy-gley and soddy-gley peat ones. The maximum values of the transfer coefficient for ^{137}Cs have been found in peat-boggy soils. These values are 1.5–6.0 times higher than in automorphic soils.

Forest occupies 30–40% of the contaminated areas and initially played the role of a filter in intercepting the fallout. Of the deposition in the forest, 60–90% was intercepted by the foliage. However, half of the radioactive material intercepted by the foliage reached the ground within one month of the accident. The leaf litter is now the most contaminated part of the forest ecosystem, as 45–90% of the forest contamination is concentrated in it. Nine years after the accident, almost all the ^{137}Cs initially deposited is found in the 5–8 cm of the upper layer of the soil.

The total activity accumulated by the vegetation in 1994–1995 is assessed at 6–7% of the radioactive deposition in the forest as a whole. Deciduous trees have a tendency to accumulate more radioactive material than conifers. The contamination of arboreal and herbaceous vegetation of the forest ecosystems typically halves in 15 years. On the greater part of the territories of the three countries affected by the Chernobyl accident, the ^{137}Cs concentration in disbarked wood has not exceeded the national permissible levels.

The main contribution to human dose from the contamination of the forests remains the consumption of contaminated mushrooms, which may give rise to a significant fraction of the internal dose in certain regions of Belarus, the Russian Federation and Ukraine. The transfer of caesium radionuclides to mushrooms depends on mushroom species and soil properties and can range from 0.001 to 0.1 $(Bq.kg^{-1})/(Bq.m^{-2})$. The specific activity of ^{137}Cs in mushrooms decreases very slowly with an effective clearance half-life of 14–26 years close to radioactive decay period. An increase in the annual internal dose of the residents has been observed during the past few years caused by the increase in the consumption of natural food products (mushrooms and berries) whose ^{137}Cs contamination often exceeds the national permissible levels.

6.1.3. Present and future human exposure

According to recent assessments, 1.7 EBq of the core inventory of 3.1 EBq of ^{131}I was released into the air. The volatile iodine radioisotopes with a short half-life disappeared some days or weeks after the accident. However, the resulting doses to the thyroid over this short period from radioiodines have led to a significant increase in the incidence of thyroid cancer in the three affected countries. The highest dose values were found in children. The average dose to the thyroid in young children from the most contaminated rural settlements amounted to 3 Gy and in some children evacuated from settlements in Belarus, the individual thyroid dose even exceeded 10 Gy.

External exposure of inhabitants of contaminated areas from radionuclides deposited on soil, plants and buildings is more difficult to control by countermeasures than internal exposure. Monitoring of external exposure included environmental measurements of dose rate and radionuclide deposition, individual dose measurements and modelling. Models for external dose assessment took account of the radionuclide deposition on soil, the radioactive decay and vertical migration of long lived radionuclides in the upper soil layer, the presence of snow, absorption of gamma radiation in an inhabited environment, and human behaviour. The mean effective external dose in a rural environment was estimated to be 40–70 μSv per $kBq.m^{-2}$ of ^{137}Cs in 1986–1995 depending on radionuclide composition of the fallout and is predicted to be about 30 μSv per $kBq.m^{-2}$ of ^{137}Cs in 1996–2056. The dose to urban inhabitants is lower by a factor of 1.5–2.

Since the summer of 1986, the internal dose has been caused mainly by ingesting foodstuffs contaminated predominantly by ^{134}Cs, ^{137}Cs and ^{90}Sr, and to a lesser extent by inhalation of plutonium and ^{241}Am with dust particles. The ratio of internal to external dose depends on soil conditions and the contamination level and ranges from 0.3 to 1.4. The effective dose from ^{90}Sr is estimated to amount to several per cent of the dose from ^{137}Cs, while the effective dose from plutonium and ^{241}Am is estimated to amount to only a fraction of a per cent. In addition, the internal dose already accumulated in 1986–1995 accounts for about 90–95% of the 70 year committed internal dose (1986–2056).

Both external and internal dose rates will decrease with time because of radioactive decay and migration processes in the environment. The effective dose forecast for 1996–2056 is two to three times lower than the effective dose already received in 1986–1995. The contribution of the external and internal doses for 1996–2056 accounts respectively for 70–95% and 5–30% of the total effective dose for this period, depending on the dominating soil type and taking into account the termination of countermeasures since 1996. The effective half-life of the dose rate reduction is estimated to be of the order of ten years, according to monitoring data. An annual dose of 1 mSv in 1996 will thus correspond to a lifetime dose to a newborn in 1996 of about 15 mSv. The lifetime doses to the population living in the most contaminated areas are thus estimated to be lower than the average individual dose from natural background radiation, which would be of the order of 100–200 mSv over the same period.

6.2. Factors affecting life in the contaminated regions

6.2.1. Effects on well-being

Social and economic consequences of the Chernobyl accident during the past ten years should be considered in the light of major changes in all spheres of life, first in the former USSR, and now carried over to Belarus, Russia and Ukraine. Since 1988, the move from a centralized, State controlled economy with collective property towards a market economy with multiple forms of property has caused a constant decrease in production and, inevitably, an uncontrolled decline in the standard of living. This decline has had a negative impact on demography: the birth rate has decreased and the mortality rate has begun to rise.

Despite large scale countermeasures in 1986–1993, predominantly funded from State budgets, local restrictions led to a significant deterioration in the quality of human life. In 1986, all the cattle from private farms located in contaminated parts of the Bryansk region were mandatorily purchased by the State, so people lost a significant source of animal food. Radiation control restricts the production of vegetable food on private plots. The use of local wood for construction and heating, and the gathering and consumption of traditionally popular natural food (fungi, berries, lake fish) are restricted or prohibited, depending on area contamination. These restrictions directly deteriorate the well-being of the population. State compensation is not sufficient to reimburse these losses.

The countermeasures applied since 1986 introduced severe restrictions on normal life for the populations living and working in the more highly contaminated areas. These restrictions will remain in effect for the immediate future. Radioactivity controls of agricultural products are permanently in place. Moreover, the attitude of potential consumers towards products from these areas makes it virtually impossible for the rural population to sell its produce locally or to export it. As a consequence, income has decreased and unemployment in rural areas has increased.

6.2.2. Effects on industrial and agricultural production

The Chernobyl accident and the measures introduced to combat its consequences set back the social and economic development of the three affected States. The controls imposed to manage the radioactive contamination of vast tracts of land impede normal practices in industry and agriculture, at a high financial cost. Large sums, amounting to a significant proportion of the annual budgets in Belarus and Ukraine, are needed to address the accident's consequences.

The contaminated areas of Belarus, Russia and Ukraine are predominantly rural. Agricultural countermeasures have significantly changed the structure of agricultural production in these areas. In particular, traditional cattle breeding has been partially replaced by less profitable plant breeding. In the zone with soil deposition of more than 555 $kBq.m^{-2}$ of ^{137}Cs, the cultivation of buckwheat and hops has been prohibited and sheep raising has been curtailed. These changes have lead to a reduction of income which is difficult to distinguish from the reduction due to the impact of the economic crisis in the 1990s. Contamination of food products with radionuclides has additionally decreased these products’ market value. Moreover, because of the economic problems, changes in agricultural activities have been limited, with only partial changes in the type of cultivation and stock raising taking place on collective farms.

In 1986, regular weekly decontamination of agricultural equipment was widely conducted. Since May 1986, agricultural workers in the contaminated regions have been issued with individual protective clothing, and decontamination of clothing after working under extremely dusty conditions has been organized. In the contaminated areas of Russia, the T–150K tractor has been developed with air conditioning. The hermetically sealed cabins of the tractors provide standards of ambient air pollution inside the cabin under dusty conditions. The use of protective clothes, light respirators and more powerful protective measures has become more widespread for jobs involving intensive dust production.

6.2.3. Conditions for safe living

Since 1986, medical examinations of the population undertaken in the contaminated areas, together with the development of health care facilities, have revealed increased incidence of diseases of the endocrine, haematopoietic and other body systems. For most of the diseases, the highest incidences were found in the disaster 'liquidators' (clean-up workers). Many of these diseases are not known to be caused by radiation and their reported increased incidence may well be the result of increased surveillance combined with the deterioration in living standards. In children, a significant increase in primary morbidity with thyroid cancer caused by internal exposure with radioiodine has been recorded in all three countries since 1990.

The social and psychological state of the residents is characterized by high anxiety, irritability and inability to adjust. There is fear of the future for their children and for themselves, fear of unemployment, and a general feeling of hopelessness. Social and psychological stress is also affecting resettled people, especially the elderly. Evacuation and resettlement have solved the exposure problem but they have created a series of new problems linked, above all, to the hardships of adjusting to the new living conditions.

The demographic situation in the contaminated areas is worsening. Many workers are migrating to relatively "clean" areas with the result that labour resources are abundant in some areas and scarce in others. In addition, a large number of teachers, physicians and agronomists have left, creating a critical shortage of skilled workers. The age distribution has also shifted towards the elderly, as these migrants are usually young. This, combined with the health concerns for future generations, has reduced the birthrate so that the demographic changes are unlikely to be reversed in the near future.

The State programmes provide for a broad set of actions in the contaminated territories: protection of human health; specific measures for the exclusion and resettlement zones; dose reduction involving measures in agriculture, food processing and forestry; economic rehabilitation of the territories; and restoration of the social and socio-psychological status of the population. A system of social and psychological monitoring has been created, a social information service and vocational training centres have been set up and job placement has been organized to help the resettled people, as well as the unemployed, living in contaminated areas. One of the measures greatly influencing the improvement and recovery of people’s health has been the organization of stays in health resorts and specialized sanatoria.

6.3. Impact on fauna and flora in the exclusion zone

6.3.1. Radiological conditions

The exclusion zone consists mainly of a 30 km zone around the Chernobyl NPP and also more distant areas in the three States. The areas affected are 2100 km^2 in Belarus, 2040 km^2 in Ukraine and 170 km^2 in the Russian Federation. This zone is characterized by a non-uniform deposition of radioactive material with "hot spots" up to 370 000 kBq.m^{-2} of

^{137}Cs, 5000 $kBq.m^{-2}$ of ^{90}Sr, and 100 $kBq.m^{-2}$ of plutonium radionuclides. The distribution of radioactive particles is very uneven and the range of their physicochemical properties and radionuclide composition is wide. A large quantity of "hot particles" and of nuclear fuel particles are present in the area closest to the reactor.

The irradiation of the flora and fauna close to the reactor was acute and extremely severe, amounting to several Gy per hour during the release, but subsequently falling to less than 1 $mGy.h^{-1}$. The maximum radioactive impact on nature occurred during the early period of acute radiation exposure (10–20 days following the accident), at which time most of the dose came from short lived radionuclides. During the second stage, which covered the summer and early autumn of 1986, radioactivity in the upper layer of soil fell to 20–25% of its original value. The current third stage is characterized by a low dose rate of chronic irradiation mostly from ^{134}Cs and ^{137}Cs. Plutonium isotopes and ^{90}Sr also have a significant radiological impact in the exclusion zone. The extremely heterogenous deposition of radioactive particles in the environment produced a wide range of doses to which the biota were subjected, and which in some cases, even in very small geographic areas, differed by one order of magnitude.

Some consequences of the Chernobyl accident for the natural plant and animal populations are determined by secondary ecological factors resulting from changes in human activities. In particular, the termination of economic activities and of hunting and poaching altered the types and numbers of birds and commercially hunted mammals. In general, the number of birds and animals increased greatly compared with adjacent inhabited areas. Inside the exclusion zone, the former agricultural areas have become local reserves of vermin, mostly grain-eaters and omnivores, and of pathogenic fungi. The mix of species of useful insects depends on the various types of phytophagous insects present. In general, the number of species of phytophagous insects has not decreased compared with those existing in the pre-accident period.

6.3.2. Effects of radiation on biota

The release of radioactive materials occurred at the time of year, spring, when natural growth is rapid and flora and fauna are most sensitive to radiation. During the first two weeks following the accident, in a 5–6 km^2 area close to the Chernobyl power plant, trees absorbed doses of 80–100 Gy, leading to the mass death of radiosensitive coniferous trees (“red forest”) and partial damage to the crowns of birch, alder and other deciduous trees. Trees' reproductive tissues showed high sensitivity to radiation. In 1986, there was a clear relationship between the germination capacity of pine tree and fir tree seeds and absorbed doses. From 1988 to 1989, some of the trees in this area recovered their reproductive functions. Most other plant populations in the exclusion zone have not demonstrated any adverse effects that would threaten their survival.

A large number of molecular and cellular abnormalities and disturbance of the cycle of physiological and biochemical processes have been reported in wild and farm animals in the exclusion zone. However, profound pathological, lethal changes were discovered in only a few species of animals soon after the accident.

In the exclusion zone, the indicators of absolute and relative fertility of lake fish were lower than those of the fish in the Pripyat river. Some fish species in these lakes displayed a disruption in the growth and development processes of reproductive cells. As is usual following radiation exposure, chromosomal aberrations occurred in various species of reptiles and amphibians, e.g. a higher frequency of aberrant cells in frogs was found compared with those living in uncontaminated areas.

Invertebrates are generally more resistant to the effects of ionizing radiation than vertebrates. However, some groups of invertebrates were adversely affected because of the impact of radiation on their habitats, and the ratio of numbers of invertebrates and vertebrates was changed drastically in some areas in favour of the latter in 1986.

6.3.3. Prognosis for the next ten years

The present and future radioactive contamination of the exclusion zone results from long lived radionuclides, the total activity of which will be reduced slowly through radioactive decay. It is therefore to be expected that radiation effects will tend to decrease with time. The transfer of radionuclides by water and wind, and by extreme seasonal weather conditions such as floods, tornadoes, squalls and dust storms, and the dispersion of air by forest fires will not lead to long term contamination beyond the exclusion zone.

The area in the exclusion zone covered by coniferous and deciduous forests will increase to 65–70% of the whole zone. The areas of meadowland and swampland will be correspondingly significantly reduced and gradually replaced by forests. These changes will create a stable and relatively fire-resistant vegetation layer. As a result of the destruction of ameliorative water drainage systems and the construction of dams by beavers, the level of groundwater will rise, and marshlands will occupy 10–15% or more of the territory. Where this programme is successful, it will favour a reduction in the extent of dry, barren territories with their revegetation.

The animal world will stabilize as regards numbers of forest animal species, with an increase in the number of predators. Given the absence of the pressure of hunting and poaching, favourable conditions for large numbers of commercially hunted mammal species will be preserved. The growth in their number will significantly slow down compared with the increase in the first stage.

In the event of the re-establishment of agriculture in the exclusion zone, a stable community of arthropods will develop over a three-year period. Positive conditions for the development and reproduction of useful insect populations, such as the presence of pollen-bearing insects and the absence of the use of pesticides, will lead to an increase in their regulating role in the natural and agricultural zones.

6.4. Remedial actions to reduce long term exposure

6.4.1. Criteria for intervention in the CIS

In the Soviet Union and later in Belarus, the Russian Federation and Ukraine, population exposure due to the Chernobyl accident was based on annual limits of the additional effective dose considered similarly to modern action levels and established annually by ministries of health according to recommendations of national radiological protection commissions: 100 mSv for the first year after the accident, 30 mSv for the second year, and 25 mSv for 1988 and for 1989. In May–June 1986, an annual limit of thyroid dose in children of 300 mSv was used to establish the permissible level of ^{131}I content in food products. In 1989, a lifetime additional effective dose limit of 350 mSv was established as a criterion for resettlement. From 1991, action levels of 1–5 mSv were used for the substantiation of different countermeasures. The derived action levels of radioactive contamination of environmental objects, food products, surfaces, etc. were determined by dosimetric and radioecological modelling.

Over the past decade there has been, both internationally and in the CIS, considerable progress in developing intervention levels for protective measures following accidents involving releases of radioactive materials into the environment. The current thinking in the CIS on intervention is compatible with thinking internationally. The ICRP and IAEA generic intervention levels for permanent resettlement are given in terms of an avertable effective lifetime dose of 1 Sv. In the CIS, action levels of 5 and 20 mSv per year are used for resettlement, corresponding to an avertable lifetime dose of 75 and 300 mSv if the effective environmental clearance half-life is about 10 years. For foodstuff countermeasures, CIS action levels are between a few tens to a few hundreds of becquerel of ^{137}Cs per kilogram, which is lower than the internationally recommended generic action levels.

6.4.2. Effectiveness of the completed countermeasures

Over the years since the accident, a colossal amount of work has been completed to protect the population and to rehabilitate the land in all three countries. Each year, expenditures for this work make up a significant part of the national budgets of Belarus and Ukraine. The implementation of protection measures has resulted in a significant drop in the radiation doses to the population living in the contaminated areas and in the collective dose to the populations of the three countries. At present, however, the economic crisis prevents the implementation of even the most effective protection measures.

6.4.2.1. Evacuation and resettlement

During the initial phase after the accident, in accordance with acting criteria in Ukraine, Belarus and Russia, 116 000 people were evacuated, beginning on 27 April 1986. This urgent action prevented overexposure of inhabitants of areas adjacent to the Chernobyl NPP. In 1989–1995, about 198 000 inhabitants of the most contaminated regions in three countries were resettled to non-contaminated areas because of the impossibility of complying with the maximum lifetime dose limit. The dose forecast for 70 years (1986–2056) was developed using a conservative model based on available radioecological data. Now resettlement as a protection measure is no longer effective from the perspective of preventing radiation doses to the population and has been discontinued.

6.4.2.2. Decontamination of land, buildings and installations

In 1986, outside the exclusion zone, 412 localities were decontaminated and in 1987–1989, 1205 other populated areas located in the most contaminated areas were decontaminated mainly by civil defence forces. Reduction of annual external doses for various professional categories and some age groups (for example, children), varied between 10% and 30%. By 1989, the full decontamination of populated areas had been virtually completed.

In Belarus, decontamination work has been regularly conducted since 1989 in areas and on objects which are socially important, such as children's facilities, schools, health care facilities, and some industrial areas. In Russia and Ukraine from 1990 to 1995, large scale decontamination work was not conducted. The State programmes provided for the decontamination only of local areas affected by high radioactive contamination which were permanently inhabited, and the decontamination of farms and other agricultural facilities. Similar work is planned for the coming years.

6.4.2.3. Burial of radioactive waste

Generally, the soil and materials generated by the decontamination have been buried. Burial was permitted in special trenches with clay seals and a clay base, at locations outside naturally low-lying areas and with deep groundwater levels. Annually in Belarus, the decontamination of materials and the dismantling of buildings in the exclusion zone has generated 26 000 tonnes of solid radioactive waste and the decontamination of industrial equipment has produced up to 20 000 additional tonnes of liquid radioactive waste, all of which requires special reprocessing and storage. It is necessary to take steps to ensure the safety of the temporary burial sites constructed during the first years after the accident and, if necessary, arrange for this waste to be reburied. There are over a thousand such burial sites registered by local authorities.

6.4.2.4. Limits on free access and the termination of economic activity

In 1986, access to the exclusion zone was limited. In 1988, the limit for the full termination of agricultural activity was set at 2960 $kBq.m^{-2}$ of ^{137}Cs and agricultural land with a level of radioactive contamination greater than 1480 $kBq.m^{-2}$ was excluded from crop production. Since 1988, any forest-based economic activity has been prohibited in forests contaminated with a density greater than 1480 $kBq.m^{-2}$. As a result, the abandoned areas in three countries cover 5400 km^2 of the exclusion zone and 6700 km^2 of the resettlement zone, in total more than 12 000 km^2. Security measures have been undertaken in the abandoned areas in order to prevent unauthorized access by citizens and the removal of contaminated items, to take sanitary precautions and to prevent fires.

6.4.2.5. Limitation of the consumption of contaminated food products and drinking water

Permissible levels (TPLs) for the radionuclide content of food products and drinking water were established in May 1986 and regularly revised to limit the internal exposure of people living in the contaminated and adjacent regions. In order to implement TPLs, regular monitoring of food contamination was performed on farms and in food industry enterprises, shops and markets. Numerous restrictions for food consumption were implemented and food products were processed to reduce radionuclide content. In the Bryansk region in Russia, in September 1986, 1300 head of cattle and approximately 1500 pigs and sheep were confiscated and transferred to collective farms under radiological control. It should be noted that problems with radioactive contamination of drinking water did not actually arise. The goal of limiting the internal exposure resulted in multiple limitations which prohibited the collection of mushrooms, berries, medicinal herbs and hay in forests. These prohibitions continue to be in force today.

The results of monitoring support the policy of maintaining the limits in the more contaminated areas: internal doses to the population were reduced by a factor of 1.5–3. These limitations were extremely important in the early period after fallout and later on in areas with poor soils where, due to high soil-to-plant transfer of radionuclides, internal exposure dominated. However, some indirect adverse effects were caused by overly strict limitation of the content of radionuclides in agricultural produce. These included economic losses and insufficiently balanced diets.

6.4.2.6. Countermeasures in agriculture

The main countermeasures for reducing the contamination of raw products and food are those of reclamation: liming acid soils, applying large amounts of mineral fertilizers, and cultivating and creating clean pastures. Land use has been changed, taking into account the soil contamination levels and transfer factors of radionuclides to plants. Fieldwork aimed at reducing dust formation and preventing soil erosion has been carried out using up-to-date technologies that ensure optimal land cultivation. The areas for food and industrial crops have been decreased, while the areas devoted to fodder crops are being expanded. These measures facilitate the best use of land, the implementation of resource saving systems of soil cultivation, and an increased production of less contaminated crops. Practice has shown that special agronomic, agrochemical and reclamation measures on contaminated agricultural land may decrease the caesium transfer to crop production by a factor of 1.4–4. The reduction in the application of these countermeasures inevitably leads to an increase in the contamination of agricultural products. Other combined measures, such as deep ploughing, hoeing and the simultaneous addition of lime and potassium fertilizer, have reduced crop contamination three to fourfold, and special ploughs have produced up to a tenfold reduction in the contamination of natural grazing land.

The contamination level of animal products depends on the type of feed, the fodder make-up, the type of storage and the contamination levels of fodder crops and soils. Feeding animals with clean fodder at the final stage before slaughter has proved to be very efficient in the contaminated territories. The prolongation of such a feeding period from two to seven months (depending on animal age and the caesium content in muscle) makes it possible to obtain practically 'clean' meat. Feeding with concentrated fodder leads to a decrease in the radionuclide content in animal produce by a factor of 2–4, while the introduction of caesium binding compounds into cattle fodder decreases the radionuclide content in milk by a factor of 4–5.

By 1994, the contamination of agricultural produce from collective farms had clearly diminished. Less than 1% of the dairy produce and a few tonnes of meat produced in the public sector in that year exceeded the action levels set by the authorities. All the produce, (cereals, tubers, root crops) from the arable soils on land which was not taken out of agricultural use were below the national intervention levels.

6.4.2.7. Measures for the reduction of contamination of food produced on private land plots

Recommendations for agricultural activity on private land plots include rules for working in private gardens and garden plots, procedures for the preliminary preparation of products grown for domestic use, rules for the maintenance and feeding of domestic animals, and procedures for the domestic reprocessing of animal products. In the most contaminated areas, liming and the use of potassium fertilizer were undertaken not only on collective farms but also on private land plots. At present, the feeding of boluses containing cyanoferates to cows is widespread and ensures a manifold reduction in the caesium content of milk.

6.4.2.8. Information to the population

The policy of the authorities on information to the population was inadequate. In the first two years after the accident, there was no information in the mass media on problems in the contaminated areas. At the same time, people living in these areas were constantly subjected to a variety of limitations, reminders and instructions which differed from usual practice. As a result, there is little confidence in State sources of information on the consequences of the Chernobyl accident. The completion of various programmes involving the population over the past five years has not improved the situation. Consequently, people in the affected areas have been applying restrictions in more areas than the radioactive conditions would warrant. These self-limitations include reducing the time children spend in the open air, and forgoing the of consumption of certain food products.

6.5. Perspectives for the future

The principal objective for future State actions in the affected regions is the economic and social rehabilitation of contaminated areas. This will require the development of new concepts and rehabilitation measures as well as the implementation of accumulated experience. Remedial measures must enable the local population, especially land workers, to live and work safely in these areas. In order to achieve a gradual return of the contaminated territories' production facilities into the economic cycle, substantial investment is required. As a result of radioecological monitoring, it is expected that the compensation system currently in force will be reconsidered; and some of the funds could be redirected to new industrial projects and agricultural developments. The rehabilitation programmes must create conditions attractive enough for the younger workforce, especially engineers and qualified workers, to return.

The major efforts of rehabilitation must concentrate on contaminated areas where people are living. Owing to the importance of the agricultural sector in the contaminated territories, the first objective is to obtain produce that satisfies the relevant national permissible levels. It is necessary and quite possible to create conditions where the environmental contamination will not result in the exclusion of important dietary components from consumption. For potentially contaminated milk, for example, it is possible to improve cultivated pastures and use caesium binding compounds. It is useful to continue optimizing the countermeasures to reduce the level of radionuclides in agricultural produce, in accordance with the results of cost–benefit analyses. The limits on the consumption of forest products such as mushrooms, berries and game meat should be continued provided that it is possible to monitor all these items. A greater role could be played by recommendations to the public to use the best methods (in radiological terms) for processing natural food products.

The long term countermeasures still being implemented include resettlement of people and decontamination of populated and production areas. Resettlement is a very expensive countermeasure, but existing regulations and laws would still allow future resettlement although the protective effect is marginal in terms of the radiation doses averted. However, sociopolitical and psychological factors may well contribute to and even dominate decisions on resettlement, and for the next few years, it is reasonable to preserve the option of voluntary resettlement from selected populated areas. Decontamination activities may be continued on the most socially important sites. They aim at both lowering external radiation doses and improving social and psychological conditions.

The social and economic condition of people living and working in the contaminated territories is totally dependent upon State subsidies and assistance of many kinds. This situation is difficult to maintain. There is a widespread decline in the standard of living in the most contaminated regions in spite of the compensation offered by State programmes. It will almost certainly deteriorate further because of the probable reduction in State assistance programmes in the future, especially if there is no shift to regional financing and supply.

The economic revival and subsequent social development of these areas will be linked to the stabilization and further sustainable development of the economies of the States concerned. Thus, countermeasures must be optimized within the current framework of reduced financing, and benefits and compensation should be terminated in those areas where the radiation conditions may be regarded as fully satisfactory.

The psychological and emotional tension caused by fear of radiation and anxiety for the future has had a detrimental impact on the health of the population in the areas affected by the

Chernobyl accident. One of the major reasons for stress is people's fear for their future and the future of their children from what they perceive as the hazardous consequences of living in a contaminated area. It is, therefore, vital to inform the population of the current radiological situation concerning radiation related health hazards. It is necessary to initiate an active information policy, which would enable people in these areas to understand the changes in the status of the territory, including the termination of benefits and compensation in areas with low levels of contamination.

Annex I

AREAS AND ZONES DISCUSSED IN THE REPORT

I–1. Introduction

In describing the situation and the measures taken in the USSR and, subsequently, in Belarus, the Russian Federation and Ukraine, many different designations are used to identify different areas or zones. These designations are of different kinds — some are basic geographical areas and administrative units, others are areas or zones defined on the basis of the consequences of the Chernobyl accident or the measures taken or in force after the accident. This section is intended to explain the main designations used in the report.

I–2. Geographical areas

The 'polessye' is a geographical region of low-lying plains, which extends from the east of Poland to the Urals and covers a total area of about 200 000 km^2. The western part of the polessye is known as the **Ukrainian and Belarus Polessye** (or the Pripyat–Desna Polessye, after its two main rivers). The Ukrainian and Belarus Polessye extends approximately from Mogilev, Belarus, in the north to Kiev, Ukraine, in the south, an area which includes most of the areas with significant contamination.

I–3. Administrative areas

Belarus, the Russian Federation and Ukraine are divided, as were the republics of the Soviet Union, into administrative **regions** (*oblast*s), which are named after their major city. For example, regions mentioned in this report include the Brest, Gomel and Mogilev regions of Belarus, the Bryansk, Kaluga, Orel and Tula regions of Russia and the Chernigov, Kiev, Rovno and Zhitomir regions of Ukraine. Each region is divided into **districts** (*rajon*s), which are also normally named after towns or cities; for example, districts referred to in the report include the Bragin, Chechersk, Khojniki and Narovlya districts of the Gomel region, Belarus, and the Gordeevo, Klimovo, Klintsy, Krasnaya Gora and Novozybkov districts of the Bryansk region, Russia. The Chernobyl nuclear power plant is located in the Chernobyl district of the Kiev region, Ukraine.

I–4. Areas defined by countermeasures after the accident

In the first days after the accident (27 April–7 May 1986), residents were evacuated from a circular zone of 30 km radius around the reactor site. This is known as the **30 km zone**, and has an area of about 2800 km^2. A number of settlements outside the 30 km zone were also evacuated in the days after the accident and later in 1986, and areas around these settlements were (and, as of 1996, still are) excluded from cultivation. The term **exclusion zone** is used in this report to refer to the whole area evacuated in 1986, which includes the 30 km zone. The exclusion zone has a total area of more than 4000 km^2: 2100 km^2 in Belarus (known as the (State) Polessye Radiological and Ecological Reserve, but also referred to for clarity in this report as the **Belarus exclusion zone**), 2040 km^2 in Ukraine and 170 km^2 in Russia (the latter two areas both known simply as the 'exclusion zone', but referred to for clarity in this report as the **Ukrainian exclusion zone** and **Russian exclusion zone** respectively).

I–5. Areas defined on the basis of current radiological conditions

In each of the three republics, land is 'zoned' according to the current level of radionuclide soil deposition. Criteria are specified for ^{90}Sr, ^{137}Cs and plutonium, but in most cases the zoning corresponds to levels of ^{137}Cs. The zones are based on the same ranges of ^{137}Cs activity, but are given different names in the three republics. For clarity in this report, however, specific names have been chosen and are used throughout the report to refer to zones with a particular level of contamination in any of the three republics, as follows:

- Where the **^{137}Cs level is above 555 kBq/m^2**, permanent residence and the production of commodities are legally prohibited. These areas are called 'resettlement zones' in Belarus, 'relocation zones' in Russia ('obligatory relocation zones' above 1480 kBq/m^2) and 'obligatory resettlement zones' in Ukraine. Most of the exclusion zone is in these zones. For the purposes of this report only, these zones are referred to either together as **obligatory resettlement zones**, or separately as **obligatory (subsequent) resettlement zones** (for ^{137}Cs levels **between 555 and 1480 kBq/m^2**), and **obligatory (immediate) resettlement zones** (for ^{137}Cs levels **above 1480 kBq/m^2**);

- Where the ^{137}Cs level is **between 185 and 555 kBq/m^2**, existing enterprises can operate but cannot be developed, and new enterprises cannot be introduced. These areas are called 'right to be resettled zones' in Belarus, 'right for relocation' zones in Russia and 'guaranteed voluntary resettlement zones' in Ukraine. For the purposes of this report only, these zones are all referred to as **voluntary resettlement zones**;

- Where the ^{137}Cs level is between **37 and 185 kBq/m^2** (corresponding to 1–5 mSv/a), the restrictions on enterprises apply only to those affecting public health and the environment, sanitoria and convalescent homes. These areas are called 'periodic control zones' in Belarus, 'favourable social and economic status zones' in Russia and 'reinforced radiological control zones' in Ukraine. For the purposes of this report only, these zones are all referred to as **radiological control zones**.

- To summarize:

^{137}Cs soil deposition	Designation in Belarus	Designation in Russian Federation	Designation in Ukraine	Designation in this report
37–185 kBq/m^2 (1–5 Ci/km^2)	Periodic control	Favourable social and economic status	Reinforced radiological control	**Radiological control**
185–555 kBq/m^2 (5–15 Ci/km^2)	Right to be resettled	Right of relocation	Guaranteed voluntary resettlement	**Voluntary resettlement**
555–1480 kBq/m^2 (15–40 Ci/km^2)	Subsequent resettlement	Relocation	Obligatory resettlement	**Obligatory (subsequent) resettlement**
> 1480 kBq/m^2 (> 40 Ci/km^2)	Immediate resettlement	Obligatory relocation	Obligatory resettlement	**Obligatory (immediate) resettlement**

Annex II

INTERNATIONAL CRITERIA FOR LONG TERM COUNTERMEASURES AS FOR 1996

II–1. Introduction

Following the accident at Chernobyl, it became evident that some clarification of the basic principles for intervention was necessary. In particular, there was a need for a simple set of internally consistent intervention levels that could have some generic application internationally. Such a set of values was considered desirable to increase public confidence in authorities charged with dealing with the aftermath of an accident.

Over the past decade, considerable progress has been made in developing internationally recognized principles for decisions on protective measures following accidents involving radioactive material, and in providing quantitative guidance for applying these principles, notably by the ICRP [1, 2], the IAEA [3], and the WHO/FAO [4]. However, experience has shown that, in spite of these efforts, discrepancies remain in the application of both principles and guidance.

II–2. International guidance on intervention at the time of the Chernobyl accident

At the time of the Chernobyl accident, international guidance existed on protection of the public after a nuclear accident in which radionuclides had been dispersed into the environment. However, this guidance was not very clear and it did not adequately address the difficult social problems that would arise after a serious disaster.

II–2.1. International guidance from ICRP and IAEA

The basic principles set out by the ICRP [5] and the IAEA [6] for planning intervention in an accident and for setting intervention levels at the time of the Chernobyl accident were:

(a) *Serious deterministic effects* should be avoided by setting the countermeasures to limit individual dose to levels below the thresholds for these effects;

(b) *The risk from stochastic effects* should be limited by introducing countermeasures to achieve a positive net benefit to the individuals involved;

(c) *The overall incidence of stochastic effects* should be limited, as far as reasonably practicable, by reducing the collective effective dose.

Upper dose levels above which the introduction of the countermeasure was almost certain and lower dose levels below which introduction of the countermeasure was not warranted were given for irradiation of the whole body and individual organs (two-tier system). Between the recommended upper and lower dose levels, specific intervention levels were expected to be set by national authorities. The intervention levels covered both the early and intermediate phases after an accident. For the late phase, no values were recommended on the grounds that the main questions facing the decision maker would be whether and when normal living could be resumed and that the situations would vary too widely for any relevant generic numbers to be given. The ICRP [5] and IAEA [6] intervention levels for the intermediate phase (the first year after the release), including resettlement and control of foodstuffs, are given in Table II–1.

TABLE II–1. ICRP [5] AND IAEA [6] INTERVENTION LEVEL RANGES FOR INTRODUCING LONG TERM COUNTERMEASURES

Long term countermeasures	Whole body	Single organs
Resettlement [a)]	50–500 mSv per year	not anticipated
Control of foodstuffs [a)]	5–50 mSv per year	50–500 mSv per year

[a)] The projected dose for resettlement and foodstuff control were defined only for the first year.

II–2.2. Main problems in past international recommendations

A number of problems were identified when applying the international guidance on intervention levels after the Chernobyl accident, both in the USSR and in Western Europe. Although the basic principles were conceptually correct, confusion was created because the doses to be compared with the intervention levels were interpreted as doses *received* and not as doses *averted*. Thus, the intervention levels were wrongly interpreted as dose limits. In addition, there were major difficulties in the application of the principles and numerical guidance given by the ICRP [5] and the IAEA [6]:

- It was unclear whether the intervention levels for foodstuffs should apply to the total doses from all food items or to the doses from each of the food items separately; in addition, it was not clear whether the intervention levels were given in terms of doses committed from food intake in a few weeks or in a year.
- It was unclear whether it was the total projected dose or the avertable dose which should be compared to the intervention level.
- It was unclear how the principle on limitation of risk from stochastic effects to individuals (principle b) and the principle on limitation of overall incidence of stochastic effects (principle c) were related.
- It was unclear for how long resettlement was supposed to be enforced.

The question of the resettlement time period was unclear as the dose levels for resettlement [5, 6] were given as projected doses in the first year after the accident, but the intervention levels were supposed to apply to the intermediate accident phase, i.e. about a few weeks.

The dose levels given for control of foodstuffs [5, 6] were generally interpreted to signify that if appropriate countermeasures were introduced, then the committed effective equivalent dose from total food intake during the first year after the accident would probably have been between 5 and 50 mSv. A variant of this interpretation was that the committed effective equivalent dose for each type of foodstuff consumed during the first year would probably lie between 5 and 50 mSv if proper countermeasures were introduced.

The intervention levels for foodstuffs were, however, as for resettlement, concerned with countermeasures in the intermediate phase only. A reasonable interpretation was therefore that the recommended foodstuff levels were the committed effective equivalent dose from food intake during the intermediate phase above which it would be worthwhile banning these foodstuffs.

The ICRP and IAEA recommendations [5, 6] did not address the long term problems of recovery and rehabilitation at all. This is a very important issue after a major nuclear accident or radiological emergency where long lived radionuclides are dispersed in the environment. However, the decisions on recovery and rehabilitation involve not only radiation protection issues but also many human and economic considerations that have to be taken into account by the responsible authorities.

II–3. Current status on internationally agreed intervention principles

The latest recommendations from the ICRP [1] outline the systems of protection for *practices* and *interventions*. Human activities that *add* radiation exposure to what people normally incur due to background radiation, or that increase the likelihood of their incurring exposure, are termed *practices*. The human activities that seek to reduce the existing exposure, or the existing likelihood of incurring exposure which is not part of a controlled practice, are termed *interventions*.

The system of radiological protection for intervention is based on the following general principles [1]:

(a) The proposed intervention should do more good than harm, i.e. the reduction in detriment resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention.

(b) The form, scale, and duration of the intervention should be optimized so that the net benefit of the reduction of dose, i.e. the benefit of the reduction in radiation detriment, less the detriment associated with the intervention, should be maximized.

Justification is the process of deciding that the disadvantages of each component of intervention, i.e. of each protective action or, in the case of accidents, each countermeasure, are more than offset by the reductions likely to be achieved in the dose.

Optimization is the process of deciding on the method, scale and duration of the action so as to obtain the *maximum net benefit*. In simple terms, the difference between the disadvantages and the benefits, expressed in the same terms, e.g. monetary terms, should be positive for each countermeasure adopted and should be *maximized* by setting the details of that countermeasure.

The dose limits recommended by the ICRP are intended for use in the control of practices. The use of these dose limits, or of any other predetermined dose limits, as the basis for deciding on intervention might involve measures that would be out of all proportion to the benefit obtained by the intervention. The principles (a) and (b) cited above can lead to *intervention levels* or *action levels* which give guidance to the situations in which intervention is appropriate.

The avertable dose by the protective action, ΔE, can be defined as the difference between the dose *without* any action and the dose *after implementation* of a protective action. If a protective measure were introduced at time t_1 and lifted at time t_2, the avertable dose, ΔE would be equal to the time integral of the dose per unit time over this time interval, Δt. The concept of an avertable dose is shown in Fig. II–1.

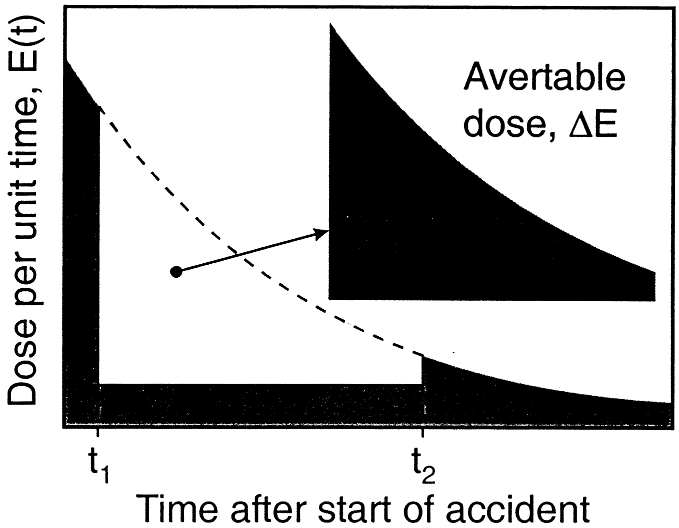


Fig. II–1. Avertable dose and effective dose accumulated per unit time as a function of time when the protective measure is introduced at time t_1 and lifted again at time t_2.

Only the avertable doses from those pathways that can be influenced by the protective action should normally be taken into account in judging whether to take the action or not. Intervention cannot reduce doses already received, and it is therefore not appropriate to include doses already received at the time when a decision is to be taken on introduction of protective measures. However, it is recognized that past doses may affect social perceptions and so may influence decisions through consideration of social factors.

II–3.1. Intervention levels and action levels

Intervention level (IL) and action level (AL) are the terms for levels at which action is taken. There are, however, differences in the strict meaning of these terms which should be emphasized.

II–3.1.1. Intervention levels

The *intervention level* can be defined as follows [7]:

> *The intervention level is the level of avertable dose at which a specific protective action or remedial action is taken in an emergency exposure situation or a chronic exposure situation.*

Intervention levels refer to the dose that is expected to be averted (avertable dose) by a *specific countermeasure* over the period when it is in effect. If an intervention level is exceeded, i.e. if the expected avertable individual dose is greater than the intervention level, then it is indicated that the specific protective action is likely to be appropriate for that situation. Intervention levels are specific to accident situations.

The intervention level for a specific countermeasure can be calculated from the optimization as indicated above. The outcome of optimizing a protective action continuing over a prolonged period would be the intervention level for *lifting* the countermeasure as well as the time interval over which it would be in action. The optimized intervention level would be expressed either as an avertable *individual dose per unit time* or as an avertable *collective* *dose per unit mass* of a given foodstuff, both given at the end of the interval for which the countermeasure would have to be in action.

II–3.1.2. Operational intervention levels

Because of the inherent difficulty of forecasting doses that could be averted, there is a merit in establishing surrogate quantities e.g. *dose rate*, *surface contamination density* etc. The relationship between these quantities and the avertable dose will vary considerably with the circumstances of the accident and nature of contamination, e.g. *types of radionuclides*, *environmental half-lives*, *transfer factors of deposited activity*, *location factors* and *filtering factors* for housing conditions. The term *operational intervention level (OIL)* is reserved for such quantities that can be more easily assessed at the time of decision on intervention. OILs are related to the dose that could be averted by a *specific protective action* like evacuation, resettlement and banning of foodstuffs.

II–3.1.3. Action levels

Action levels refer to different protective measures or strategies (combinations of measures) like agricultural countermeasures or radon reducing measures in houses, and they relate to the dose without any remedial actions taken. The action level can be defined as follows [7]:

> *The action level is the level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic or emergency exposure situations*

An action level is set such that the dose averted by taking the remedial action is always worthwhile in terms of the costs and other disadvantages involved. In other words, if an action level is set too low, remedial actions may be taken in circumstances where the dose savings are not worthwhile.

Action levels are thus levels above which remedial actions are taken and below which they are not. Justified action levels would begin at the minimum value of the avertable individual dose at which the remedial action is just beginning to do more good than harm. The concept of an action level is illustrated in Figure II–2.

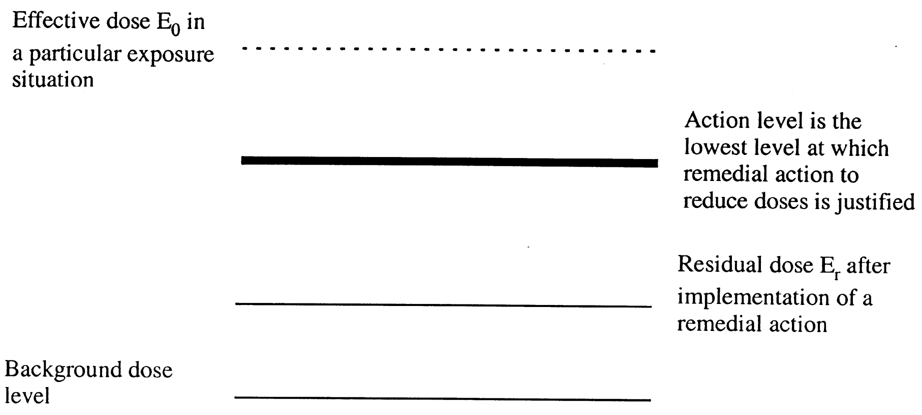


Fig. II–2. System for intevention in chronic exposure situations. The action level (AL) is related to the maximum aceptable dose without any remedial action. The avertable dose is given as $\Delta E = E_o - E_r$.

An action level is therefore the lowest level at which remedial actions to reduce doses is justified. If an action level is exceeded, it is indicated that some form of remedial action specific to the situation considered is likely to be appropriate. Action levels have, therefore, the same character as operational intervention levels.

II–3.2. Justification and optimization of intervention/action levels

The initial introduction of protective actions may involve significant costs. Therefore, it may well be that a small scale intervention of short duration is costly without being effective. As the scale and duration are increased, the effectiveness initially increases without a marked increase in costs. Eventually, further increases will fail to achieve increases in benefits comparable with their costs and the net benefit again begins to fall. There is then a range of values of the possible intervention level of individual dose averted, within which there is an optimum level. If the net benefit at that optimum is positive, intervention of the defined type, scale and duration is justified. This is illustrated in Fig. II–3.

When intervention is justified, i.e. when the net benefit is positive, there is normally a range of justified intervention/action levels and the optimized value would fall within that range. When intervention is not justified, even though countermeasures can still minimize the harm, such measures are neither justified nor optimized as the net benefit is negative.

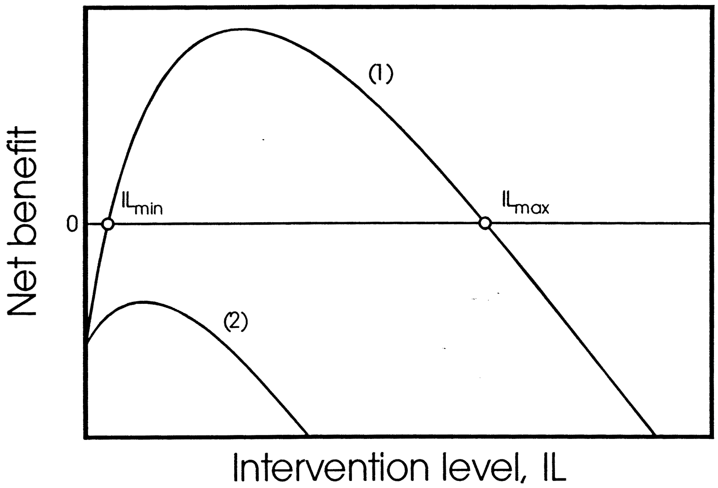


Fig. II–3. Net benefit of intervention as a function of intervention level for a justified (1) and an unjustified (2) intervention.

II–4. Intervention and action levels for long term countermeasures

Recommendations from the ICRP [2] and the IAEA [3] on intervention levels for long term countermeasures are shown in Tables II–2 and II–3. The values from the IAEA represent the international consensus achieved on intervention levels as recommended by six international organizations [7]. Withdrawal and substitution of foodstuffs can be developed according to the principles of justification and optimization, and the outcome would be intervention levels. For foodstuff restrictions, the intervention levels for radionuclides such as ^{137}Cs are in the range of a few hundred Bq to a few tens of thousands of Bq per kg foodstuff [3]. It is, however, important in the process of optimization that consideration be given to other measures that could reduce levels of contamination still further. The outcome of optimization would in such cases be action levels. Recommended action levels for agricultural countermeasures are given in Table II–3 [3, 7].

TABLE II–2. SUMMARY OF RECOMMENDED INTERVENTION LEVELS FROM ICRP PUBLICATION 63 [2] AND IAEA SAFETY SERIES NO. 109 [3] FOR LONG-TERM COUNTERMEASURES

Protective measures	IAEA generic optimized intervention levels	ICRP range of optimized values
Temporary relocation	Initiate at 30 mSv in a month Suspend at 10 mSv in a month	Almost always justified at a dose level of 1 Sv Optimized range of 5–15 mSv per month
Permanent resettlement	If lifetime dose would exceed 1 Sv	–

TABLE II–3. ACTION LEVELS ($Bq.kg^{-1}$) FOR FOODSTUFFS FROM IAEA SAFETY SERIES NO. 109 [3]

<table>
<tr><th>Radionuclides</th><th>Foods destined for general consumption</th><th>Milk, infant foods and drinking water</th></tr>
<tr><td>$^{134, 137}Cs$, $^{103, 106}Ru$, ^{89}Sr</td><td rowspan="2">1</td><td>1</td></tr>
<tr><td>^{131}I</td><td rowspan="2">0.1</td></tr>
<tr><td>^{90}Sr</td><td>0.1</td></tr>
<tr><td>^{241}Am, $^{238, 239}Pu$</td><td>0.01</td><td>0.001</td></tr>
</table>

II–5. The need for further international guidance and lessons learned

There are still unresolved issues for different intervention situations, especially for long term exposure situations; these issues would involve optimization of both radiation protection and overall health protection. So far, no internationally agreed numerical guidance has been established on action levels for protection against different chronic or semi-chronic exposure situations from natural and artificial radionuclides in the environment (except for radon in dwellings).

Although there is no explicit guidance for generic action levels for chronic and semi-chronic exposure situations due to radioactive residues from previous activities and events, generic guidance can be derived implicitly from guidance established for other situations, e.g. intervention levels for permanent resettlement or non-action levels for activity in foodstuffs. Moreover, the typical levels of doses caused by chronic exposure to unavoidable natural background radiation could also be used as a reference for purposes of comparison.

Non-radiological protection factors such as public anxiety and risk perception play an important role in decision making, where their interaction with radiological factors influences the level of protective actions to be introduced. From the experience in the CIS following the Chernobyl accident, the need for socialpsychological countermeasures is obvious. However, the quantification of non-radiological protection factors needs further development.

Explicit guidance is not provided on how psychological and social factors should be included in the optimization of overall health protection. However, the optimization of radiation protection and certain psychological and social protection should probably not be carried out independently as overall health protection would include measures of both radiological and non-radiological nature. Overall health protection should thus be based on an optimized countermeasure strategy, which would be the responsibility of the decision maker(s) with guidance from experts in radiation protection and experts in social and psychological sciences. This is illustrated in Fig. II–4.

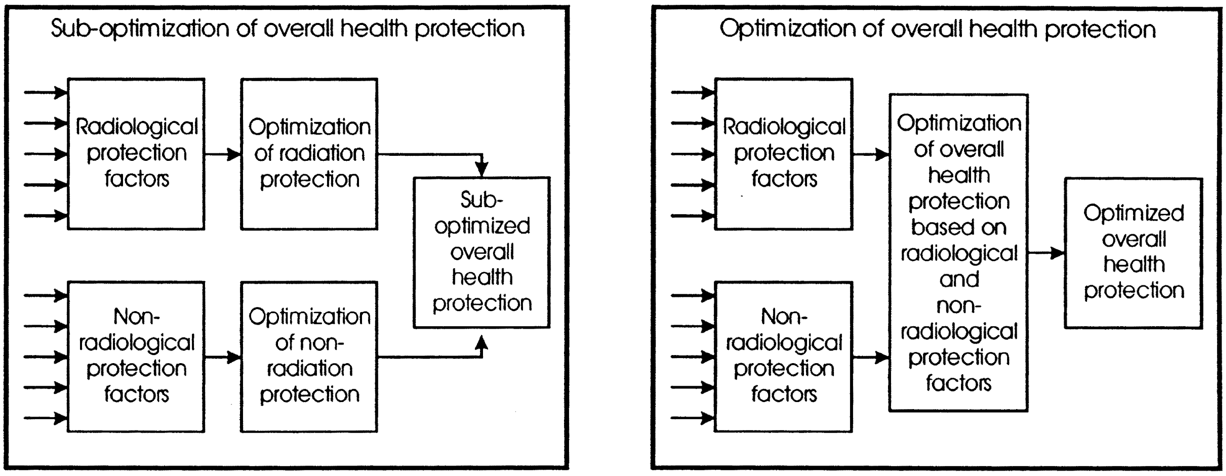


Fig. II–4. Sub-optimization of overall health protection where radiological protection and non-radiological protection factors each are used for separate optimizations leading to a sub-optimized overall health protection (left) and optimization of overall health protection where radiological and non-radiological protection factors are included simultaneously in the optimization process (right).

REFERENCES TO ANNEX II

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford (1990).

[2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Principles for Intervention for Protection of the Public in a Radiological Emergency, Publication 63, Pergamon Press, Oxford (1993).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Intervention Criteria in a Nuclear or Radiation Emergency, Safety Series No. 109, IAEA, Vienna (1994).

[4] CODEX ALIMENTARIUS COMMISSION, Joint FAO/WHO Food Standards Programme. Proposed FAO/WHO Levels for Radionuclide Contamination of Food in International Trade, CX/FAC 89/17 (1989).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Public in the Event of Major Radiation Accidents: Principles for Planning, Publication 40, Pergamon Press, Oxford, New York (1984).
[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Principles for Establishing Intervention Levels for Protection of the Public in the Event of a Nuclear Accident or Radiological Emergency, Safety Series No. 72, IAEA, Vienna (1985).
[7] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection Against Ionising Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

CONTRIBUTORS TO DRAFTING AND REVIEW

Alexakhin, R.	Institute of Agricultural Radiology and Agroecology, Russian Federation
Balonov, M.	International Atomic Energy Agency
Barraclough, I.	International Atomic Energy Agency
Bennett, B.G. *(PRC)*	United Nations Scientific Committee on the Effects of Atomic Radiation
Bogdevich,I.M.	Soils and Agrochemistry Research Institute, Belarus
Bouville, A. *(PRC)*	National Cancer Institute, United States of America
Brenot, J.	Institute of Protection and Nuclear Safety, France
Calmon, P.	Institute of Protection and Nuclear Safety, France
Crick, M.J.	International Atomic Energy Agency
Dreicer, M. *(PRC)*	Environmental Assessments, United States of America
Fry, F.A. *(PRC)*	National Radiological Protection Board, United Kingdom
González, A.J.	International Atomic Energy Agency
Gustafsson, M.	International Atomic Energy Agency
Hedemann Jensen, P. *(PSC)*	Risø National Laboratory, Denmark
Ilyin, L.A. *(PSC)*	Institute of Biophysics, Russian Federation
Jouve, A.	Institute of Protection and Nuclear Safety, France
Kenik, I.A.	Minister for the Consequences of the Chernobyl Accident, Belarus
Kholosha, V. *(PSC)*	Minister, Minchernobyl, Ukraine
Konoplya, E.F.	Radiobiology Institute, Belarus
Korkach, V.	Minchernobyl, Ukraine
Linge, I.I.	Institute of Nuclear Safety, Russian Federation
Los, I.	Ukrainian Research Centre of Radiation Medicine, Ukraine
Nenot, J.-C. *(PSC)*	Institute of Protection and Nuclear Safety, France
Peres, J.-M.	Institute of Protection and Nuclear Safety, France

Poiarkov, V.	Ukrainian Radiation Training Centre, Ukraine
Proskura, N.	Administration of Exclusion Zone, Ukraine
Renaud, P.	Institute of Protection and Nuclear Safety, France
Robeau, D.	Institute of Protection and Nuclear Safety, France
Rolevich,I.V. *(PSC)*	Minister for the Consequences of the Chernobyl Accident, Belarus
Rutschkowski, N.	Institute of Protection and Nuclear Safety, France
Savkin, M.N.	Institute of Biophysics, Russian Federation
Shutov, V.N.	Institute of Radiation Hygiene, Russian Federation
Skurat, V.V.	Radioecological Problems Institute, Belarus
Stozarov, A.N.	Radiation Medicine Institute, Belarus
Sztanyik, L.B. *(PRC)*	F.J. Curie National Research Institute for Radiobiology & Radiohygiene, Hungary
Tabachny, L.	Minchernobyl, Ukraine
Turai, I.	International Atomic Energy Agency
Waight, P.J.	Radiation Protection Bureau, Canada
Webb, G.A.M.	International Atomic Energy Agency
Wozniak, V.Y.	EMERCOM, Russian Federation

PSC = Project Supervisory Committee
PRC = Peer Review Committee

Meetings of the Project Supervisory Committee

Vienna, Austria: 16 June 1995, 20–21 September 1995, 6–7 November 1995, 31 January–2 February 1996, 25–26 March 1996

Scientific Review Meetings

Paris, France: 11–15 December 1995, 28 February–1 March 1996

Consultants Meeting

Vienna, Austria: 16–20 December 1996