Ukrainian Institute of Agricultural Radiology (UIAR) of
National University of Life and Environmental Sciences of Ukraine
(NUBiP of Ukraine)
Mashinobudivnykiv Str. 7, Chabany, Kyiv-Svjatoshin distr., Kyiv reg., 08162 UKRAINE
phone: (38044) 526 1246, fax: (38044) 526 0790, e-mail: vak@uiar.kiev.ua, www.uiar.org.ua

.

Report

Chernobyl: 30 Years of Radioactive Contamination Legacy

Lead writer and coordination of report
Professor Valerii Kashparov

Kyiv - 2016

Analysis by

Prof. Valerii Kashparov	Director of UIAR of NUBiP of Ukraine
Dr Sviatoslav Levchuk	Head of the Laboratory of UIAR of NUBiP of Ukraine
Prof. Iuryi Khomutynyn	Head of the Laboratory of UIAR of NUBiP of Ukraine
Dr Valeriia Morozova	Researcher of UIAR of NUBiP of Ukraine
Marina Zhurba	Researcher of UIAR of NUBiP of Ukraine

Commissioned by Greenpeace Belgium

This report, publications discussed, and conclusions made are solely the responsibility of the authors

Acknowledgements

We gratefully acknowledge James Peter McAllister, Elena Anastopoulos and Iryna Labunska, UK, for their valuable help in editing the English translation of the document!

Table of Contents

Summary

Title: “**Chernobyl: 30 Years of Radioactive Contamination Legacy**”

Lead writer and coordination of report: **Prof. Valerii Kashparov**

The consequences of the Chernobyl accident – the largest radiation accident in the world - including data accumulated during the last 30 years are observed in this report. It is noted that until now there has been no reliable information on the dynamics of the radionuclides release during the accident and the long-term behaviour of the radionuclides in the environment, which have fallen out in the content of the particles of the exposed nuclear fuel. The fuel particles are a specific form of Chernobyl radioactive fallout.

The results of the use of protective measures after the accident and changes to Protective Action Levels caused by these measures were analyzed.

The possibility of changes in the zone division of the radioactively contaminated territories was considered. The possibility of re-evacuation of the population and use of the Chernobyl Exclusion Zone in economic activity were also considered.

Analysis of the current radiological situation outside the Exclusion Zone was conducted, and methods leading to the improvement of this situation are proposed.

Keywords*: Cesium, Strontium; Plutonium; Americium; Chernobyl, Chernobyl accident; Chernobyl NPP; Terrestrial density of contamination; Chernobyl Exclusion Zone; Radioactive fallout; Fuel particles; Countermeasures; Ionizing radiation, Rehabilitation, Remediation*

List of conventional signs and abbreviations

AED	Annual effective dose
Bq; kBq	Activity unit — Becquerel, c^{-1}; 1 kilo Becquerel=1000 Bq
$Bq \cdot l^{-1}$; $Bq \cdot kg^{-1}$	Volume or mass specific activity
BSS	Basic Safety Standards
BY	Belarus
ChBRR	Chernobyl Biosphere Radiological Reserve
ChEZ	Chernobyl Exclusion Zone
ChNPP	Chernobyl Nuclear Power Plant
Ci	Activity unit — Curie, $1\ Ci=3.7 \cdot 10^{10}$ Bq
$Ci \cdot km^{-2}$	Terrestrial contamination density unit, $1\ Ci \cdot km^{-2}=37\ kBq \cdot m^{-2}$
EDR	Equivalent and effective dose rate, units $mSv \cdot h^{-1}$; $\mu Sv \cdot h^{-1}$ $mSv \cdot y^{-1}$
EU	European Union
FP	Fuel particles
EPIC	Environmental Protection from Ionizing Contaminants
Gy	Absorbed dose unit — Grey
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
INES	International Nuclear Event Scale
$kBq \cdot m^{-2}$	Terrestrial contamination density unit
Kg	Unit of mass — kilogram
L	Unit volume — liter
$mGy \cdot d^{-1}$	Absorbed dose rate unit, milliGrey per day,
$mR \cdot h^{-1}$	Exposure dose rate unit, milliRoentgen per hour, $1\ mR \cdot h^{-1}$ is about $10\ \mu Sv \cdot h^{-1}$
NPP	Nuclear Power Plant
NUBiP of Ukraine	National University of Life and Environmental Sciences of Ukraine
PL	Permissible levels
PNEDR	Predicted no effect dose rate
RNG	Radioactive noble gases
RSSU-97	Radiation Safety Standards of Ukraine
RU	Russia
SZRD	Special Zone of Radiation Danger
Sv; mSv; μSv	Equivalent and effective dose unit — Sievert; 1 milliSievert=0.001 Sv; 1 microSievert=0.000 001 Sv
SZRD	Special Zone of Radiation Danger
$T_{1/2}$	Half-life of the radionuclide
TPL	Temporary Permissible Levels
TUE	Transuranic elements
UA	Ukraine
UIAR	Ukrainian Institute of Agricultural Radiology
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USSR	Soviet Union

1. Introduction: The Chernobyl Accident

The Chernobyl accident which took place on April 26, 1986 is the largest radiation catastrophe in history (INES Level 7: Major accident). As a result of the Chernobyl accident, a considerable territory of Belarus, Russia and Ukraine, as well as of Western Europe, primarily the Scandinavian countries and Alpine region, was the most severely contaminated. Until now there has been no consensus on the dynamics and values of the radionuclides release (especially for volatile radionuclides) during the Chernobyl accident.

The first official announcement of the accident at Chernobyl Nuclear Power Plant (ChNPP) was made on television on April 28, 1986. In a rather scholastic report the fact of the accident was communicated, including the deaths of two people. Later, the actual scale of the accident started to be communicated. Concerns for prevention of panic amongst the population were given as an argument for the accident's secure classification. However, the fast and well-organized evacuations of the residents of Pripyat and Chernobyl (April 27, 1986 and May 06, 1986 respectively) promptly became known to the population of Ukraine, Belarus and Russia. At the same time, by the middle of May 1986, doctors of the Ministry of Health, scientists and mass media were forbidden to inform citizens of the USSR about the activities carried out to minimize the impact and consequences of the accident, protection methods, and scale of the accident. It resulted in a large part of the population, particularly those living in rural areas, using garden and farm products, particularly milk. This led to increased exposure, with particular effect on the thyroid gland. Maps of radiation contamination and radiation levels were classified until 1990. (Ministry of Ukraine of Emergencies, 2011).

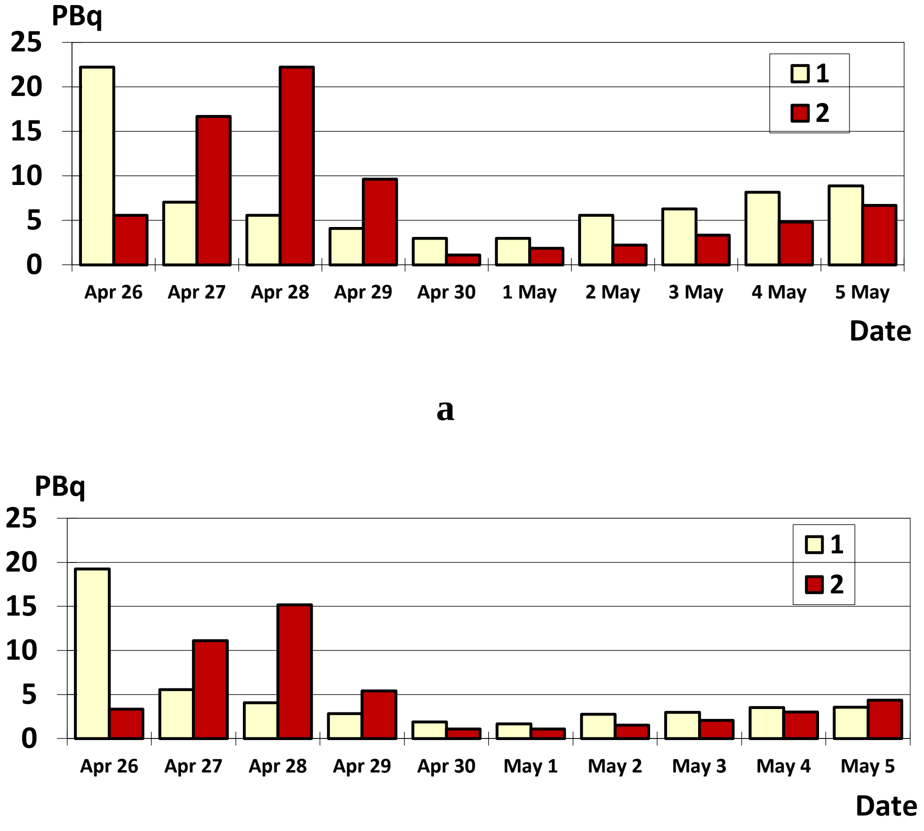
For the purposes of strategic planning of radiation exposure protection of the population a temporary annual effective dose limit of 100 mSv for the period from April 26, 1986 to April 25, 1987 was set by the USSR Ministry of Health. The population resettlement after the Chernobyl accident was carried out at the levels of terrestrial contamination by radionuclides and the radiation doses of population that were lower than that ones used according to the current Radiation Safety Standards of Ukraine.

In the later phase of the Chernobyl accident in the settlements the effective dose of external and internal exposure for a representative person is respectively 1.8 times and 3 times higher than the average dose for population in the settlement (IAEA, 2006). Therefore, the limit adopted in Ukraine of an average annual effective dose for population radiation exposure of 1 $mSv \cdot y^{-1}$ corresponds to an annual effective dose to the representative person of 2–3 mSv. Using the reference level of an annual effective dose to the representative person of 1 $mSv \cdot y^{-1}$ the average annual effective dose for the population in a settlement will be of 0.3–0.5 mSv. Therefore, the use of reference level of an annual effective dose to a representative person of 1 mSv will result in a significant increase of the zone size according to the Law of Ukraine.

There were no standards of environmental radiation protection when the Chernobyl accident occurred.

1.1. Timing and scale of radioactive releases

Durable (for 10 days) dynamics of radioactive substances released from the Chernobyl reactor during the accident (Fig.1.1), as well as the change of meteorological conditions (Fig. 1.2) (Chernobyl, 1996) provided a complex picture of contamination of the vast territories (Fig. 1.3).



a

b

Fig. 1.1: Dynamics of ^{131}I (a) and ^{137}Cs (b) release from Chernobyl reactor in April 26 - May 5, 1986: 1- Abahyan, et al.1986 and 2 – Izrael, et al., 1987

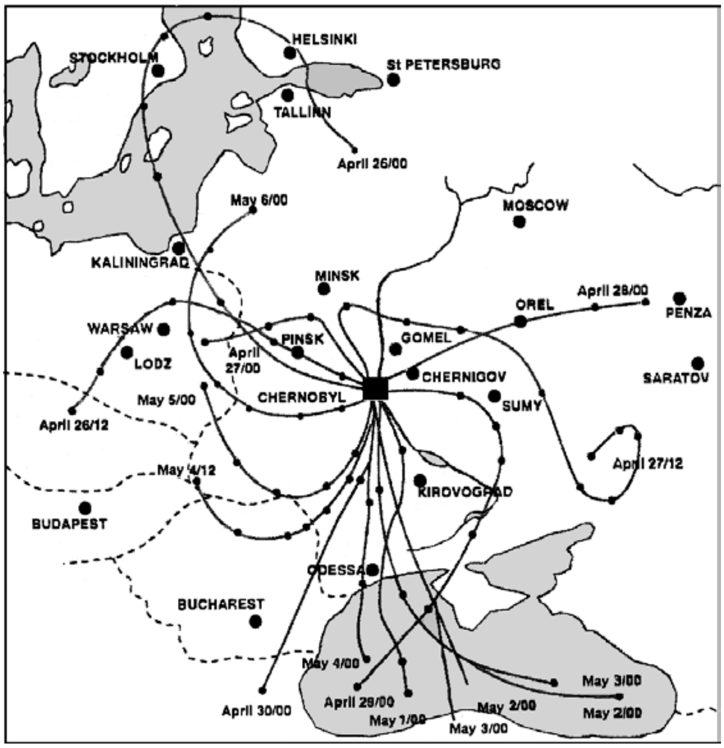
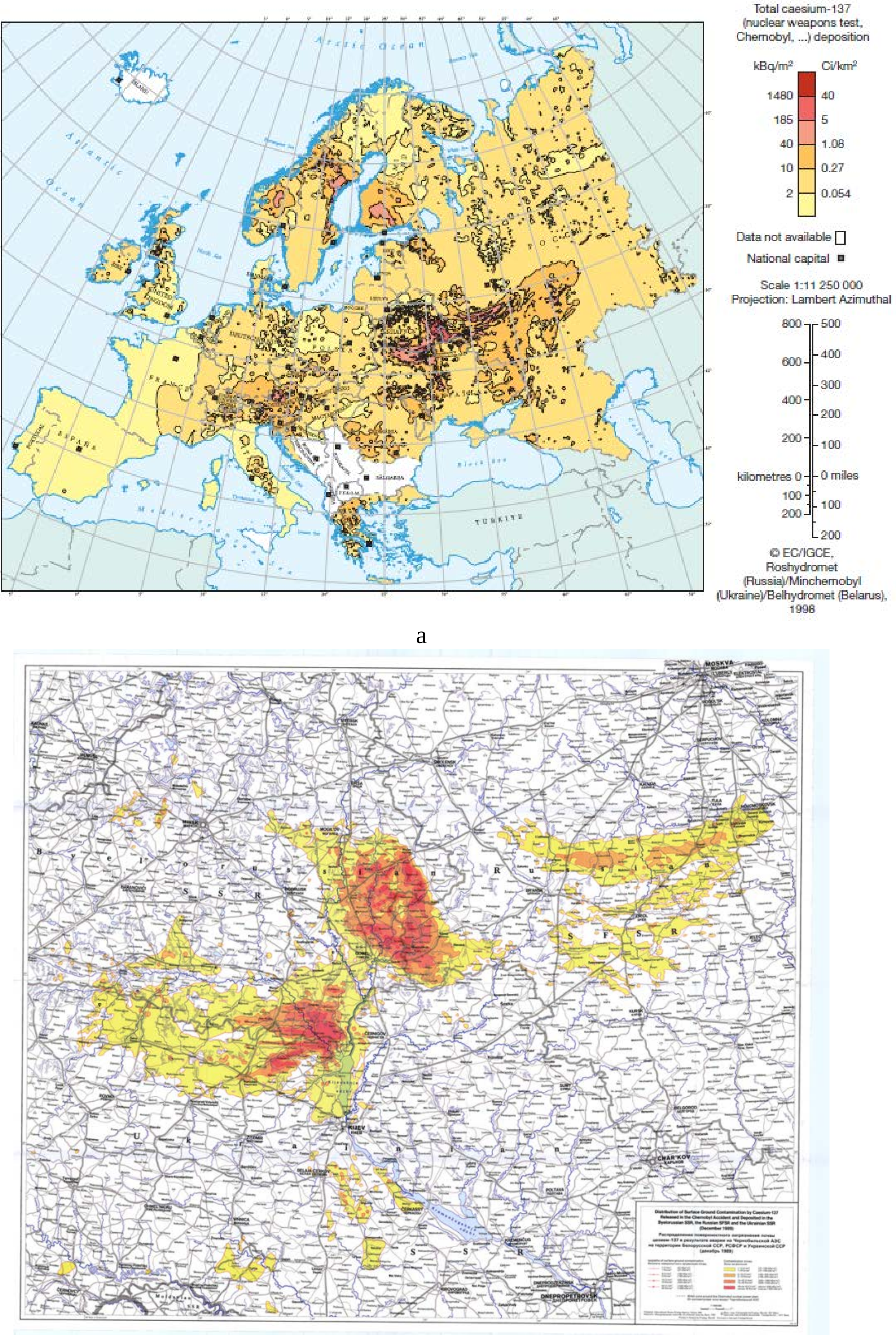


Fig. 1.2: The trajectories of radioactive contamination of the territory (Chernobyl, 1996).



a

b

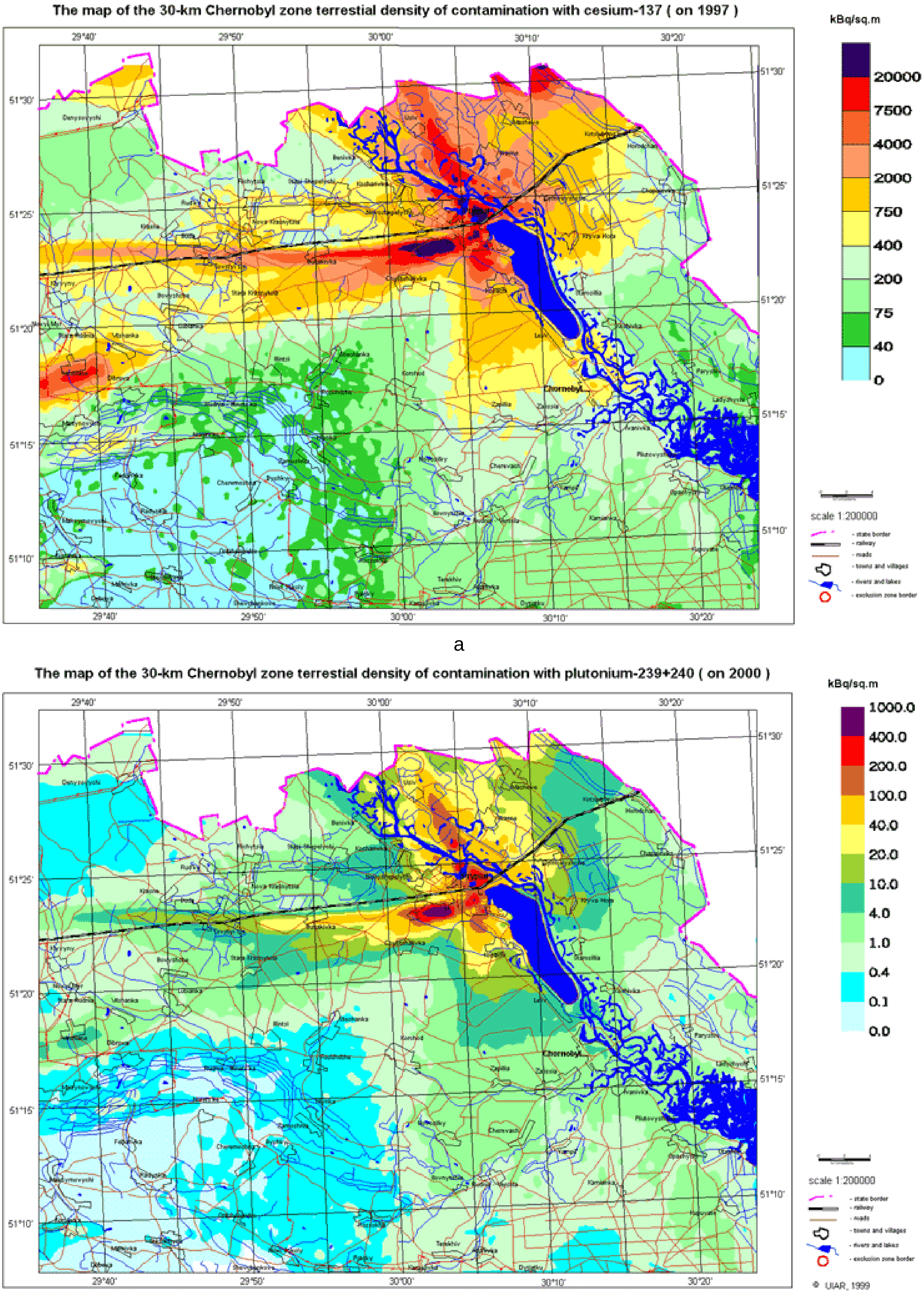
Fig. 1.3: Density of ^{137}Cs contamination of Europe (a) (De Cort, et al., 1998) and SIC (b) (IAEA, 1991)

As a result of the initial explosion on April 26, 1986 a very narrow (100 km long and up to 1 km wide) straight western fuel trace of radioactive fallout was formed (in the direction of Tolsty Les village). The trace of the contamination is characterized mainly by finely dispersed nuclear fuel (Fig. 1.4). This trace of fallout could have been formed only by short-term release of fuel particles (FP) with overheated vapour to a low height at night time with stable atmosphere. It is considered that at the moment of the accident surface winds were weak with no particular direction, and only at a height of 1500 m there was south-western wind with a velocity of 8–10 $m \cdot s^{-1}$ (IAEA, 1992). Cooling of the release cloud resulted in the decrease of its volume, water condensation and wet deposition of radionuclides (moist radioactive fallout). The western fuel trace contains only about 10–15 % of the fuel particles that have been released outside the Chernobyl Nuclear Power Plant (ChNPP) industrial site during the accident. Later, the main mechanism of the fuel particles' (FP) formation was the oxidation of the nuclear fuel (Kashparov, et al., 1996). The absence of experimental data on meteorological conditions in the area of the ChNPP (the closest observations were carried out only at a distance of more than 100 km (Izrael, et al., 1990; Talerko, 1990), as well as the absence of the information about source of the radionuclide release including data on the dispersion composition of radioactive fallout, did not allow an efficient prediction of the nearest zone contamination to be made.

Up to this point, the nature and timing of the formation of the cesium southwest trace of radioactive fallout in the area of the settlements "Vesnyanoe - Poliske - Bober" are still unclear (Fig. 1.3, 1.4). Probably, this trace was formed on the first day of the accident on April 26, 1986 after the destruction of the reactor and fuel heating due to the remaining heat generation that caused the increase of the volatile fission products leakage such as radioactive noble gases (RNG) and the iodine and cesium radioisotopes. Until now there has been no consensus on the dynamics progress, (Fig. 1.1) nor the values of the radionuclides release (especially for volatile radionuclides) during the Chernobyl accident (Table 1.1). The increase of the iodine and cesium radionuclides release during the first days after the accident seems more reliable than the decrease of it. But the decrease of radionuclides release after the reactor destruction is generally accepted (Fig. 1.1) (Izrael, et al., 1990). Usually describing the radionuclides release during the Chernobyl accident instead of radionuclides activity the activity of the so-called radioactive materials is used (these materials are often associated with nuclear fuel) (IAEA, 2006; Ministry of Ukraine of Emergencies, 2011).

For the integral value of the release, most reliable data were obtained only for long-lived cesium radioisotopes and for radionuclides contained in the fuel component of the radioactive fallout. These values were obtained years after the accident on the basis of mapping of radionuclides contamination over vast territories.

The relative release of fission products of uranium (IV) oxide at high temperatures decreases with the increase of them binding energy with oxygen in the following sequence: Kr> Xe> I> Ag> Cs> Te> Sr> Ru> Ba> Zr> Ce (Andriesse & Tanke, 1984). Information about the dynamics of the iodine radioisotopes release is the most controversial, because during the high-temperature annealing of the irradiated nuclear fuel the relative release of the iodine radioisotopes is much higher than the relative release of the radioactive cesium. Thus the relative release of the iodine radioisotopes and the relative release of the radioactive cesium cannot be equal, as it is shown in Fig. 1.1. At the same time the ratio of $^{131}I/^{137}Cs$ activity in the radioactive fallout was changing during the first days of the accident. For this reason the reconstruction of the terrestrial contamination density of ^{131}I according to the later obtained maps of the terrestrial contamination of ^{137}Cs was not fully correct. The main part of the radioiodine release should have occurred during the first 3 days of the accident (on April 26–28, 1986) in the western, northern and eastern directions, but not in the southern route, when there was no more iodine in the fuel (Fig. 1.2) (The Atlas, 2009). The reconstruction of the terrestrial contamination of iodine radioisotopes depending on the release dynamics and the direction of their transfer with the air flow was extremely important for the reconstruction of the radiation doses for the population in the acute period of the accident.



The map of the 30-km Chernobyl zone terrestial density of contamination with cesium-137 (on 1997)

a

The map of the 30-km Chernobyl zone terrestial density of contamination with plutonium-239+240 (on 2000)

b

Fig. 1.4: Density of ^{137}Cs (a) and $^{239–240}$Pu (b) contamination of ChEZ (Kashparov, et al., 2001; Kashparov, et al., 2003)

As a result of the clustered fuel heatup during April 26–30, 1986, highly mobile volatile fission products (radioactive noble gases, iodine, tellurium, and cesium) were released from nuclear fuel and raised in the convective flow to a height above 1 km on April 26, 1986, and to 600 m in the following days (IAEA, 1992; Izrael, et al., 1990). The highest release of the radioactive cesium occurred at maximum heating of the fuel on April 27–28, 1986. (Fig. 1.1). This caused the formation of the south-western (the settlements "Poliske - Bober"), north-western (spreading to Sweden), western and north-eastern condensed radioactive traces with insignificant decreasing portion of oxidised fuel particles, that had been formed at a temperature below 1200 K on the periphery of the heating areas. Cesium spots outside the ChEZ were formed at the rate of ^{137}Cs fallout with precipitation. When the temperature in the reactor decreased (April 30–May 03, 1986), and thus, the release of volatile fission products from the fuel became less (Izrael, et al., 1990), the dispersion of nuclear fuel at the rate of its oxidation in the air became more important (this process is the most intensive at the temperature 600–1200K). This provided the formation of the southern fuel trace of radioactive fallout in the direction of Kiev and Tarashcha. After the covering of the reactor, heat exchange of fuel deteriorated. Bad heat exchange of fuel caused the rise in temperature (May 03–06, 1986), increase of the release of volatile fission products and melting of materials, which covered the fuel. Aluminosilicates form thermally stable compounds with many fission products and bind cesium and strontium very well at high temperatures (Hilpert & Nurberg, 1983). It caused a sharp reduction of the release from the destroyed reactor due to the formation of fuel-containing lava on May 06, 1986.

The changes of the nuclear fuel annealing temperature during the accident had a strong effect on both the release ratio of different volatile fission products (migratory properties of Xe, Kr, I, Te, Cs increase with the temperature rise and may differ significantly in the presence of UO_2), as well as on the destruction rate of the nuclear fuel during its oxidation with the formation of micronic fuel particles (Kashparov, et al., 1996). Mainly the area near the accident was contaminated by the radionuclides (^{90}Sr, $^{238–241}$Pu, ^{241}Am, etc.) of the fuel component of the Chernobyl radioactive fallout. This area was the Exclusion Zone and the adjacent territories in the north of the Kiev region and west of the Chernihiv region, and also Bragin and Hoyniki districts of Gomel region (Belarus). The contamination of the near area only occurred due to the following reason. In the atmosphere the rate of the dry gravitational sedimentation of the fuel particles is higher, because of their high density (about 10 $g \cdot cm^{-3}$), than the sedimentation of lightweight condensation particles containing iodine and cesium radioisotopes.

Low activity and sensitivity of the available equipment did not allow to detect ^{110m}Ag, in most cases, in the soil after the Chernobyl accident. However, it has been detected in the liver of cattle at levels frequently exceeding ^{134,137}Cs content in it (Kashparov, 1987).

One of the characteristics of the accident at ChNPP is the presence in the fallout of fuel hot particles with the matrix of uranium oxides with various admixtures. Radionuclide composition of fuel particles is similar to the composition of irradiated nuclear fuel from Unit 4 during the accident (Table 1.1), but it is characterised by the fractionation of volatile highly mobile fission products (Kuriny, et al., 1993). Fuel particles were found in the radioactive fallout both in close proximity to the reactor (Kuriny et al., 1993; Krivokhatsky, et al., 1991; Salbu, et al., 1994) and at a considerable distance from it in European countries: Finland, Sweden, Norway, Lithuania, Poland, Germany, Czech Republic, Austria, Switzerland, Hungary, Romania, Bulgaria, Greece, etc. (Jost, et al., 1986; Kauppinen, et al., 1986; Kolb, 1986; Mattsson & Hatakka, 1986).

According to various estimates (IAEA, 1996a; Kashparov, et al., 2003; The Atlas, 2009; UNSCEAR, 2008) 100% of noble radioactive gases, 20–60% of iodine isotopes, 12–40% of ^{134,137}Cs and 1.4–4% of less volatile radionuclides (^{95}Zr, ^{99}Mo, ^{89,90}Sr, ^{103,106} Ru, ^{141,144}Ce, ^{154,155}Eu, $^{238–241}$Pu etc.) in the reactor at the moment of the accident were released to the atmosphere during the accident (Table 1.1).

Dynamics of the release, and dispersion composition of aerosol and meteorological parameters (including precipitation) determined the formation of radioactive contamination of the territory during the accident at ChNPP.

Table 1.1: Radionuclides activities in the ChNPP Unit 4 (on May 06, 1986) and their relative release outside the ChNPP industrial site during the accident (the value printed after ± indicates an error of estimation – data from Kashparov, et al., 2003; UNSCEAR, 2008).

Radionuclide	Radionuclide activity in the ChNPP Unit 4 (Bq)	Radionuclide relative release, %	
		previous estimate*	present estimate
^{3}H	$1.4 \cdot 10^{15}$	-	-
^{85}Kr	$3.0 \cdot 10^{16}$	~100	~100
^{90}Sr	$2.3 \cdot 10^{17}$	4.0±2.0	1.8±0.6
^{95}Zr	$5.8 \cdot 10^{18}$	3.2±1.6	1.4±0.5
^{106}Ru	$8.6 \cdot 10^{17}$	2.9±1.5	1.4±0.5
^{125}Sb	$1.5 \cdot 10^{16}$	-	1.4±0.5
^{129}I	$8.0 \cdot 10^{10}$	20±10	50–60
^{131}I	$3.1 \cdot 10^{18}$	20±10	50–60
^{133}Xe	$7.0 \cdot 10^{18}$	~100	~100
^{134}Cs	$1.7 \cdot 10^{17}$	10±5	33±10
^{137}Cs	$2.6 \cdot 10^{17}$	13±7	33±10
^{144}Ce	$3.9 \cdot 10^{18}$	2.8±1.4	1.4±0.5
^{154}Eu	$8.5 \cdot 10^{15}$	3.0±1.5	1.4±0.5
^{238}Pu	$1.3 \cdot 10^{15}$	3.0±1.5	1.4±0.5
^{239}Pu	$9.2 \cdot 10^{14}$	3.0±1.5	1.4±0.5
^{240}Pu	$1.5 \cdot 10^{15}$	3.0±1.5	1.4±0.5
^{241}Pu	$1.8 \cdot 10^{17}$	3.0±1.5	1.4±0.5
^{241}Am	$1.6 \cdot 10^{14}$	3.0±1.5	1.4±0.5

*- Reported by USSR State Committee on the Utilization of Atomic Energy (1986)

As the result of the Chernobyl accident the south-western part of the East-European plain and the Ukrainian and Belorussian Polessye were the most contaminated areas (Fig. 1.3).

During the first month after the Chernobyl accident the short-lived ^{131}I with a half-life $T_{1/2}$=8 days (Table 1.2) was the most dangerous (caused the highest health risk for the population). The surface contamination of vegetation by ^{131}I (effective ecological half-life is about 5 days) was the cause of milk contamination and rural population intake of iodine radioisotopes, which has led to high radiation doses and later to thyroid cancer (Ministry of Ukraine of Emergencies, 2011). 35 Days after the accident, the ^{131}I activity had decreased to the value of the ^{137}Cs activity, and by the end of 1987 there was not one atom of ^{131}I released during the accident in the environment. One month after the accident, the biggest radiological danger was posed by the cesium radioisotopes (^{134,137}Cs) throughout the radioactively contaminated area and strontium-90 (^{90}Sr) in the 30-km Chernobyl Exclusion Zone (ChEZ). Now, 30 years after the accident, the activity of ^{137}Cs and ^{90}Sr has decreased by a factor of 2 because of radioactive decay ($T_{1/2}$=30 years and 29 years, respectively). The radioactive contamination of the ChEZ by the long-lived radionuclides ^{239}Pu ($T_{1/2}$= 24100 years) and ^{240}Pu ($T_{1/2}$=6563 years) will persist for millennia.

The ratio of ^{131}I/^{137}Cs activity in the radioactive fallout, that was calculated for a single timepoint in order to register the radioactive decay, was changing during the first days of the Chernobyl accident. For this reason the reconstruction of the terrestrial contamination density of ^{131}I according to the later obtained maps of the terrestrial contamination of ^{137}Cs was not fully correct. The reconstruction of the terrestrial contamination of iodine radioisotopes depending on the release dynamics and the direction of its transfer with the air flow was extremely important for the reconstruction of the radiation dose for the population in the acute period of the accident.

It is believed that the release of iodine radioisotopes during the Chernobyl accident was much higher than the release during the accident at the Fukushima-1 NPP (Table 1.2). However its absolute value depends on the date according to which the ^{131}I activity was calculated. It is also very difficult to evaluate the injection of iodine and cesium radioisotopes into the ocean. According to calculations (Stohl, A., et al., 2012) the release of noble gases (^{85}Kr and ^{133}Xe) during the accident at the Fukushima NPP (Table 1.2) was higher than for the Chernobyl accident (Steinhauser et al., 2014). This indicates that the addition and correct estimation of the release of iodine and cesium radionuclides during the Fukushima Dai-ichi nuclear power plant accident is necessary.

Before the Chernobyl accident, information about the radionuclides behaviour in the environment and the extent of the radiological risk of contamination by the radionuclides of fuel hot particles was absent. It resulted in erroneous forecasts during estimation of the changes in the radiological situation, such as overestimating the content of strontium radioisotopes in water and food products, and alpha-emitting radionuclide content in the air.

Table 1.2: Comparison of the atmospheric release estimates of radiological important radionuclides for the nuclear accidents at Chernobyl and Fukushima NPPs (Kashparov, et al., 2003; UNSCEAR, 2008; Steinhauser, et al., 2014; Aliyu, et al., 2015).

Radionuclide	$T_{1/2}$	Release, PBq	
		Chernobyl	Fukushima
^{85}Kr	10.75 y	33	44
^{133}Xe	5.25 d	6500	14000
^{131}I*	8.03 d	1760**	150
^{134}Cs	2.07 y	47	12
^{137}Cs	30.1 y	85	12 (*6.1–62.5*)
^{90}Sr	28.9 y	4	0.02
$^{239+240}$Pu	24100 y and 6560 y	0.03	$(1\text{-}2)\cdot10^{-6}$
Total (excluding noble gases)		**~5300**	**~520**

*- the lower threshold of an INES 7 accident is tens PBq

** - two levels of magnitude larger than the lower threshold of an INES 7 accident

1.2. Background on Radioactive Contamination and Evacuation

The accident at the ChNPP is the largest radiation catastrophe in the history of humanity and resulted in the industrial radioactive contamination of all European countries (Fig. 1. 5). Primarily, the Chernobyl accident had a negative impact on the rural population and agricultural production of the three most affected countries: Belarus, Russia and Ukraine (Fig. 1.3). More than 150,000 km^2 of these three countries has been designated to various zones of radioactive contamination (Table 1.3). In general, 70% of released cesium and almost all ^{90}Sr and transuranic elements (TUE) in the fuel particle forms were deposited in these three countries. About one third of the contaminated territory was agricultural land. This extensive contamination of agricultural and semi-natural land had a significant effect on humans via contaminated food consumption. Over time, the impact of forest ecosystems (accounted for about a third of the contaminated area) on the radionuclides human intake has increased.

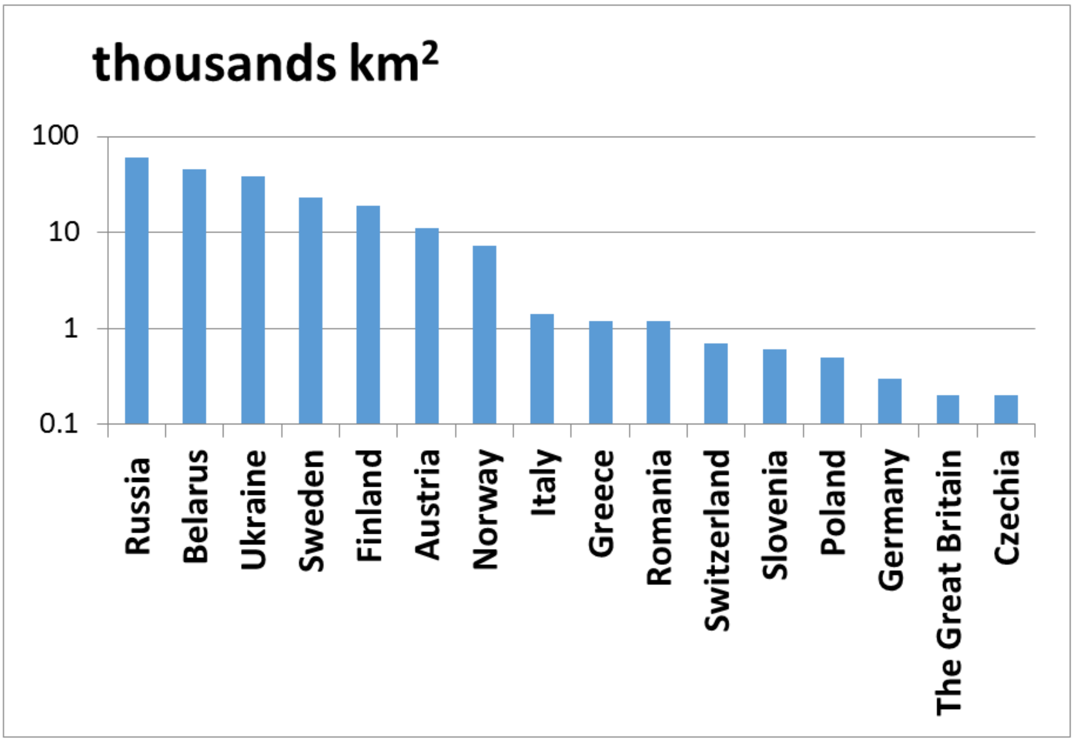


Fig. 1.5: Terrestrial contamination density of ^{137}Cs in Europe exceeding 40 kBq·m^{-2}, thousands km^2 (De Cort, et al., 1998).

Population was resettled from the most contaminated areas (6200 km^2 in Belarus (Ministry for Emergency Situations of the Republic of Belarus, 1994), 193 km^2 in Russia, 4200 km^2 in Ukraine, including 2000 km^2 outside the Chernobyl Exclusion Zone (Radiological state, 2008). Also, traditional economic activity was stopped or largely limited in these territories.

Table 1.3: The area of the territories in Belarus, Russia and Ukraine contaminated with ^{137}Cs after the Chernobyl accident on 10.05.1986 (estimated in 1998) (Ministry of Ukraine of Emergencies, 2011; De Cort, et al., 1998; The Atlas, 2009), thous. km^2

Country	Total area, thous. km^2	Contamination density, kBq·m^{-2}					Total	
		40–100	100–185	185–555	555–1480	>1480		
Russia (European part)	3800	44	7.2	5.9	2.2	0.46	59.8[a]	31.1[b]
Belarus	210	21	8.7	9.4	4.4	2.6	46.1	
Ukraine	600	29	4.3	3.6	0.73	0.56	38.2[c]	21.5[d]

The regime of secrecy of the true extent and consequences of the accident, the disadvantages of the management system and the limits of material resources made it impossible to use stable iodine drugs (iodine prophylaxis) operatively for the radiation protection of personnel and the general population during and after the Chernobyl accident. The evacuation of the population around the ChNPP was carried out quite quickly and in an orderly way.

In the period from April 26 to May 6, 1986 when the main part of the release occurred and radioactive contamination of the territory was arisen, the evacuation of population was being carried out for the prevention of acute radiation injuries among the population and to avoid exceeding the

---

[a] 65.1 thous. km^2 according to the estimation provided in 2006

[b] on 2006

[c] 42.8 thous. km^2 according to the National report in 2011

[d] on 2011

set "Criteria of Decisions to Be Taken on Measures for People Protection in Case of a Reactor Accident" (Ill`in & Avetisov, 1983):

External gamma exposure	0.75 Sv
Thyroid exposure in the result of radioactive iodine intake	2.5 Sv
Integrated concentration of iodine-131 in the air, MBq·s·l^{-1}:	
for children	14.8
for adults	25.9
Total intake of iodine-131 with food, MBq·day^{-1}	0.555
Maximum contamination by iodine-131 of fresh milk, MBq·l^{-1}, or a day ration, MBq·day^{-1}	0.037
The initial density of the iodine-131 fallout on the pasture, MBq·m^{-2}	0.259

The initial evacuation zone was formed as a result of arbitrary decisions made on the basis of geographical indication, forming a circle around the Chernobyl nuclear power plant with a radius of 30 km. In the initial phase of the accident (until May 7, 1986) 99,195 people were evacuated from 113 settlements including 11,358 people from 51 villages in Belarus and 87,837 people from 62 settlements in Ukraine (including about 45,000 people evacuated at 14.00–17.00 on April 27, 1986 from the town of Pripyat located 4 km from the ChNPP).

In the acute period after the accident, it was not possible to differentiate the levels of contamination in animals (live monitoring and clean feeding of animals) and in the period of May-July 1986, the total number of slaughtered animals reached 95,500 cattle and 23,000 pigs evacuated from ChEZ. A technique for *in vivo* measurements of ^{137}Cs in animals (live monitoring of animals) that effectively reduced the production of contaminated meat was developed and used since 1987. Before the introduction of this method, in light of a lack of clean forage for the evacuated animals, difficulties in managing large numbers of animals, they could die that would cause a panic among the population. And in order to prevent the psychological influence of possible death of animals on the population, more than 100,000 agricultural animals were slaughtered. The ^{134,137}Cs content in the meat of these animals exceeded the permissible levels (3700 Bq·kg^{-1}). Taking into account the deficiency of meat products in the USSR, it was decided to mix this meat with clean meat for the production of meat products that satisfied hygiene standards, decision which angered society. As a result, meat from the ChEZ was not used and was stored in refrigerators in various regions of the USSR for several years, and eventually it was buried in the Exclusion Zone.

The analysis of live data on the radiation situation conducted in May 1986 revealed that the territory of the radioactive contamination where comprehensive measures for population protection were required extended far beyond the ChEZ 30-km zone. For the purposes of strategic planning of radiation exposure protection of the population, a temporary annual effective dose limit of 100 mSv for the period from 26 April 1986 to 25 April 1987 (50 mSv from external and 50 mSv from internal dose) had been set by the USSR Ministry of Health. For the practical implementation of the concept of the emergency division of zones the derivative levels were introduced. These levels corresponded to the basic dose criteria and the appropriate dose quotas.

For the division of zones according to external dose rate it was proposed that the average value of the dose rate of gamma radiation in an open air area cited on May 10, 1986 be used. In this case, on May 10, 1986 the annual external dose rate for the critical group of the population of 11 mSv corresponded to the value of the exposure dose rate of 1 mR·h^{-1} (about the equivalent dose rate (EDR) of gamma radiation of 10 µSv·h^{-1}).

The following zones were established:

> 20 mR·h^{-1}– (>200 µSv·h^{-1}) — Exclusion Zone, it is the territory where the population was evacuated forever;

5–20 mR·h^{-1}– (50–200 µSv·h^{-1}) — the Temporary Evacuation Zone, residents were supposed to return to this territory after the normalization of radiation situation;

3–5 mR·h^{-1} – (30–50 µSv·h^{-1}) — Strict Controlled Zone, it is the territory, where the organized resettlement of children and pregnant women to clean areas for summer period in 1986 was conducted.

For the zone division according to the internal dose rate it was proposed at the end of May 1986 to use the average density of long-lived biologically significant radionuclides ^{137}Cs, ^{90}Sr, ^{239,240}Pu present in the surface contamination of the soil in the settlement . The numerical values of the criteria by the surface contamination density amounted to 15 Ci·km^{-2} (555 kBq·m^{-2}) of ^{137}Cs, 3 Ci·km^{-2} (111 kBq·m^{-2}) of ^{90}Sr and 0.1 Ci·km^{-2} (3,7 kBq·m^{-2}) of ^{239,240}Pu. Official information support of such division of zones was carried out at the beginning of July 1986 by the USSR State Committee for Hydrometeorology after the approval of maps of radioactive contamination (Izrael, et al., 1990).

According to initial assessments, the values of the internal radiation doses from ^{134}Cs и ^{137}Cs in the first year after the accident in areas with terrestrial contamination density of ^{137}Cs of 1 Ci·km^{-2} (37 kBq·m^{-2}) accounted for 6.2 mSv·y^{-1} for permanent residents and 2.8 mSv·y^{-1} for residents temporarily resettled to clean territories in a period from May 5 to September 1, 1986. Thus, internal radiation doses of about 100 mSv·y^{-1} for permanent residents and 50 mSv·y^{-1} for temporary resettled persons corresponded to the density of the contamination of 15 Ci·km^{-2} (555 kBq·m^{-2}).

The selection of the limit of 3 Ci·km^{-2} (111 kBq·m^{-2}) of ^{90}Sr was determined based on the experience of the accident at the Mayak Production Association (1957), where the value of the density of the soil contamination of 2 Ci·km^{-2} (74 kBq·m^{-2}) was used as a limit value for the population habitation without any restrictions.

In evaluating the dose from plutonium, the gross simplification was accepted that the resuspension factor by the wind at 10^{-7} m^{-1} was constant over the course of a year, except in winter . In this case at the contamination density of 0.1 Ci·km^{-2} (3.7 kBq·m^{-2}) of ^{239,240}Pu the equivalent dose in the lung in 50 years after the accident would amount to 0.3 mSv·y^{-1}.

In reality the main criterion for evacuation was the exposure dose rate (Roentgen per hour - R·h^{-1}). The evacuated population from the territories where the exposure dose rate exceeded 5 mR·h^{-1} (the equivalent dose rate (EDR) about 50 μSv·h^{-1}) did not return.

In Russia, in regions further from the Chernobyl Nuclear Power Plant, mass evacuation wasn't performed. In 1988 the individual dose limit of 350 mSv per 70 years or 5 mSv·y^{-1} was accepted as a criterion for safe habitation (National Committee on Radiation Protection, 1988). This limit encompassed the dose received during the course of a life from the total external and internal radiation. Therefore, in 1986, the population have not been evacuated from settlements in Russia where the contamination density was over 1.5 MBq·m^{-2}, which, obviously, was a big mistake. It caused additional impact on the increase of the social and psychological stress on the population in the following years.

A consolidated list of evacuated settlements in the three countries is represented in Table 1.4.

Table 1.4: Summarized data on the resettled in 1986 territories and evacuated settlements (Ministry of Ukraine of Emergencies, 2011; The Atlas, 2009)

Evacuation/Exclusion Zone	Square, km^2	Number of the settlements	Number of people
Belarus	1542	108	24725
Russia	193	4	186
Ukraine	2157	75	91406
Total	**3699**	**187**	**116317**

In Ukraine the population of 62 settlements was evacuated in May 1986. In addition, the population from 7 settlements in the Kyiv region and 7 settlements in the Zhytomyr region were evacuated. In Russia the evacuation was performed only in 1988: 186 people were resettled from 4 settlements.

Thus, in 1986 the boundary of the population evacuation zone was designated by the level of equivalent dose rate of 5 mR·h^{-1} (EDR about 50 μSv·h^{-1}). At this level of the EDR, the ratio between short-lived gamma-emitting radionuclides (^{95}Zr, ^{95}Nb, ^{103,106}Ru, ^{141,144}Ce), which precipitated with fuel particles, and long-lived condensed ^{137}Cs was different in different parts of the Exclusion Zone. Therefore, after the disintegration of the short-lived radionuclides the contamination density of the Exclusion Zone by the long-lived ^{137}Cs is very different in different parts of the territory, especially in the fuel and condensation traces (Fig. 1.4).

Two years after the accident with the improvement of the radiation situation the dose limits of population radiation were reduced respectively to 30 mSv·y^{-1} and 20 mSv·y^{-1} in the 3rd and 4th year after the accident.

In 1988 the National Commission on Radiation Protection (NCRP) of the Ministry of Health of the USSR proposed the concept of the limit on the received life-dose of 350 mSv per 70 years as a regulatory framework for the long-term habitation of population. As a result of this limit the restrictions were cancelled for a number of the contaminated areas (National Committee on Radiation Protection, 1988).

The purpose of this Concept (Verkhovna Rada of Ukraine. On the Concept, 1991) was the formulation of principles and justification of practical measures that were aimed at reducing the consequences of the accident for human health, the reduction of received damage through the decrease of the permissible radiation level received during a life-span from 350 to 70 mSv, and guarantee of the mass evacuation of people in case of exceeding of this level.

Based on the concept (Verkhovna Rada of Ukraine. On the Concept, 1991) laws about the legal regime of the areas affected by the Chernobyl accident were accepted in the three countries. According to these laws the division of zones by radiation level and additional resettlement of population were provided in 1991–1994 (Table 1.5) (Levonevsky, 1991; Legislation of Russia, 1991; Verkhovna Rada of Ukraine. On the Legal, 1991; Verkhovna Rada of Ukraine. On the Status, 1991).

Table 1.5: Criteria to establish the zones of radioactive contamination in Ukraine (Verkhovna Rada of Ukraine. On the Legal, 1991)

Zones	Criteria to establish the zones
1. Exclusion zone	Area where the population was evacuated in 1986 (includes 30 km zone around ChNPP)
2. Zone of an Unconditional (Obligatory) Resettlement	Where D_{eff}>5 mSv·y^{-1} *or* *^{137}Cs > 555 kBq·m^{-2} or* *^{90}Sr > 111 kBq·m^{-2} or* *Pu> 3.7 kBq·m^{-2}*
3. The Zone of a Guaranteed voluntary resettlement	Where D_{eff}>1 mSv·y^{-1} *or* *185 < ^{137}Cs <555 kBq·m^{-2} or* *5.5< ^{90}Sr < 111 kBq·m^{-2} or* *0.37 < Pu < 3.7 kBq·m^{-2}*
4. The Zone of an Enhanced Radioecological Monitoring	Where D_{eff} >0.5 mSv·y^{-1} *37<^{137}Cs< 185 kBq·m^{-2},* *0.74 <^{90}Sr< kBq·m^{-2},* *0.185 <Pu< 0.37 kBq·m^{-2}*

Zone of Subsequent Evacuation and Zone of Primary Evacuation in Belarus, Zone of Evacuation in Russia and Zone of Unconditional (Mandatory) Resettlement in Ukraine were the areas where the average annual effective dose could exceed 5 mSv and the contamination density of cesium radioisotopes was higher than 555 kBq·m^{-2} or of ^{90}Sr was higher than 111 kBq·m^{-2} or of Pu radioisotopes was higher than 3.7 kBq·m^{-2}.

Zone with the Right to Evacuation in Belarus and Zone of Guaranteed Voluntary Resettlement in Ukraine (Table 1.5) were the areas where the average annual effective dose was 1–5 mSv per year and the contamination density of the cesium radionuclides was 185–555 kBq·m^{-2} or of ^{90}Sr it was 5.55–111 $kBq \cdot m^{-2}$ or of Pu it was 3.7 $kBq \cdot m^{-2}$. Russia Living Zone with the Right to Resettle was the territory with contamination density of ^{137}Cs of 185–555 $kBq \cdot m^{-2}$.

Nowadays more than 9000 settlements in Belarus (2402 settlements, Table 1.6), Russia (4413 settlements) and Ukraine (2293 settlements, the 4th Zone has been abolished in 1290 settlements on 28 December 2014, Table 1.6) have been assigned to the zones of radioactive contamination (Table 1.5), where about 5 million people reside.

Now the main criterion of the possibility of safe residence of population in the territory contaminated after the Chernobyl accident is the limit of the average annual effective dose of 1 mSv (Levonevsky, 1991; Legislation of Russia, 1991; Verkhovna Rada of Ukraine. On the Legal, 1991).

Because of the acceptance of international principles and recommendations, the limit of the annual average effective dose (permissible dose) of 1 mSv was adopted in 1991 in the USSR. After the collapse of the USSR this concept was adopted in the three republics. In addition, new Radiation Safety Standards in 2000 in Belarus (RSS-2000, 2000), in 1996, 1999 and 2009 in Russia (RSS-99/2009, 2009) and in 1997 in Ukraine were enacted (RSSU-97, 1998).

Table 1.6: Distribution of the settlements/number of residents among radioactively contaminated zones in the Republic of Belarus as of Jan 01, 2014; in the Russian Federation as for April 7, 2005; in the Ukraine Jan 01, 2008

Zone name	Number of the settlements/ Number of people, thous. people		
	Belarus (BY)	Russia (RU)	Ukraine (UA)
Exclusion Zone (BY, RU, UA) and Zone of Primary Evacuation (BY)	126/0	4/0	76/0.12
Zone of Subsequent Evacuation (BY), Zone of the Resettlement (RU), Zone of an Unconditional (Obligatory) Resettlement (UA)	17/1.8	202/75.7	86/9.0
Zone with the Right to Evacuation (BY) Zone of Residence with the Right to Evacuation (RU), Zone of a Guaranteed Voluntary Resettlement (UA)	464/112.6	492/169.2	841/637.2
Zone of Residence with Periodic Radiation Control (BY), Zone of Residence with Privileged Socioeconomic status (RU), Zone of an Enhanced Radioecological Monitoring (UA)[e]	1849/1028.2	3715/1372.9	1290/1645.5
Total	**2402/1142.6**	**4413/1617.5**	**2293/2291.9**

In the early phase, ^{131}I was the main contributor to the internal dose through the pasture–cow–milk pathway. Peak concentrations occurred rapidly (within about 1 day) after deposition (in late April or early May 1986, depending on when deposition happened in certain places). In late April/early May 1986 in Ukraine dairy cows were already grazing outdoors and there were significant levels of the activity concentration of ^{131}I in cow milk exceeding acceptable levels, which ranged from a few hundred to a few tens of thousands Becquerel per litre. The activity concentration of ^{131}I in milk decreased with an effective half-life of 4–5 days owing to its short physical half-life and the processes that removed it from pasture grass. Consumption of leafy vegetables onto which radionuclides had been deposited also contributed to the intake of radionuclides by humans.

---

[e] This zone was eliminated in Ukraine December 28, 2014 (On Amendments, 2015)

In order to decrease the internal radiation doses of the population, the first Temporary Permissible Levels (TPL) (4104–88) were approved by the USSR Ministry of Health only on May 6, 1986. These levels concerned the ^{131}I activity concentrations in some foodstuffs, which were decreasing with the improving radiological situation (Table 1.7). The next TPLs adopted on 30 May 1986 (TPL 129–252) concerned the content of all beta-emitters in food products caused by surface contamination but were primary focused on the ecologically mobile and long-lived cesium radionuclides. The latter TPLs put in force since 1988 (TPL-88) and 1991 (TPL-91) referred to the sum of ^{134}Cs and ^{137}Cs activities. TPL-91, for the first time included TPLs for both cesium radionuclides and ^{90}Sr.

Before the Chernobyl accident there were not any permissible levels (PL) for radionuclides in foodstuff in the USSR. Permissible levels for ^{131}I in milk (370 Bq·l^{-1}) that were ten times lower than the previous ones were already accepted in Austria on May 02, 1986. And it was recommended to use milk below 185 Bq·l^{-1} for drinking purposes. The permissible level of ^{137}Cs in baby food of 11 Bq·kg^{-1} was accepted in Austria on May 23, 1986 (IAEA, 1994.).

In the USSR including time of the Chernobly accident, the food production system could be divided into two groups: large collective farms and small private farms. Collective farms routinely used land rotation combined with ploughing and fertilisation to improve productivity. Traditionally small private farms had one or several cows producing milk mainly for personal consumption.

Table 1.7: Temporary permissible levels (TPL)/action levels for radionuclides in foodstuff after the Chernobyl accident in the USSR (IAEA, 2006), Bq·kg^{-1}

FOODSTUFF	Date				
	May 06, 1986 for ^{131}I	May 30, 1986 for total beta activity	Dec 15, 1987 for $^{134+137}$Cs	Oct 06, 1988 for $^{134+137}$Cs	Jan 22, 1991 for $^{134+137}$Cs and ^{90}Sr
Drinking water	3700	370	20	20	20
Bread and bakery products, cereals		370	370	370	370
Milk	3700	370	370	370	370
Condensed milk		18500	1110	1110	1110
Sour cream	18500	3700	370	370	370
Cheese	74000	7400	370	370	370
Butter	74000	7400	1110	1110	370
Meat and meat products		3700	1850	1850	740
Fish	37000	3700	1850		740
Vegetables		3700	740	740	600
Leaf vegetables	37000	3700	740	740	600
Fresh fruit and berries		3700	740	740	600
Dried fruits and berries		3700	11100	1110	2900
Fresh mushrooms and wild berries		18500	1850		1480
Dried mushrooms			11100		7400
Baby food			370	370	185

Radiation monitoring of the agricultural production contamination at large milk plants and in collective farms was arranged in 1–2weeks after of the accident had occurred:

- urban population was mainly protected against consumption of radioactive contaminated agricultural products, especially milk, through the distribution network (foodstuffs were delivered from clean regions);
- rural population that had cows in private farms was not informed about contamination of milk with ^{131}I, that resulted in high doses to the thyroid gland and increase of thyroid cancer morbidity in children after the accident.

In the first few days after the accident, countermeasures were largely directed towards collective milk and few private farmers were involved. Information on countermeasures for milk was confined to managers and local authorities and was not distributed to the private farming system of the rural population. This resulted in limited application of the countermeasures with some delay, especially in rural settlements for privately produced milk, resulting in a low effectiveness in some areas (Ministry of Ukraine of Emergencies, 2011).

In the first weeks after the accident the main aim of the application of countermeasures in the USSR was to decrease the ^{131}I activity concentrations in milk or to prevent contaminated milk entering into the food chain. To achieve this the following measures were recommended (IAEA, 1994):

- radiation monitoring and subsequent rejection of collective milk at processing plants in which ^{131}I activity concentrations were above action levels (3700 Bq·l^{-1} at that time).
- processing rejected milk (mainly converting milk to storable products such as condensed or dried milk, cheese or butter) in order to decrease the ^{131}I activity due to its radioactive decay ($T_{1/2}$=8 day).
- exclusion of contaminated pasture grasses from animals diet by changing from pasture to indoor feeding with uncontaminated feed.

Table 1.8: Current non-emergency permissible levels of specific activity (Bq kg^{-1}) of cesium radionuclides in food products adopted after the Chernobyl accident (IAEA, 2006) and after the Fukushima accident.

Country	**Codex Alimentarius Commission (international trade)**	**EU**	**Belarus**	**Russia**	**Ukraine**	**Japan**
Year of adoption	*1989*	*1986*	*1999*	*2001*	*1997 and 2006*	*2012*
Milk	1000	370	100	100	100	50
Infant food			37	40–60	40	
Bread, flour, cereals		600	40	40–60	20–50	100
Meat and meat products			180–500	160	200	
Dairy products			50–200	100–500	100	
Fish			150	130	150	
Vegetables, fruits, potato, root-crops			40–100	40–120	40–70	
Fresh wild berries and mushrooms			185–370	160–500	500	
Dried wild berries and mushrooms			2500	2500	2500	

Due to the feeding of animals with "clean" fodder the ^{137}Cs content in cattle meat would reduce to permissible levels 1–2 months after the beginning of the countermeasure implementation. However, this countermeasure was not in widespread use at this stage, partly due to a lack of uncontaminated feed at this early time in the growing season (there was no additional reserve of the clean fodder) (Ministry of Ukraine of Emergencies, 2011).

Current non-emergency national Permissible Levels for foodstuffs, drinking water and wood in Belarus, Russia and Ukraine are comparable and all of them are substantially lower than the EU maximum permissible levels (except for dried wild berries and mushrooms) (Table 1.8). Higher permissible levels in the EU are caused by a small (insignificant) part of products from Belarus, Russia and Ukraine in the ration of Europeans.

The Permissible Levels of ^{90}Sr in foodstuffs in Belarus, Russia and Ukraine are lower than those for ^{137}Cs: 3.7–25 $Bq \cdot l^{-1}$ for milk, 11–40 $Bq \cdot kg^{-1}$ food grain, 1.85–5 $Bq \cdot kg^{-1}$ for bread, 1.85–5 $Bq \cdot kg^{-1}$ for infant food etc.

After the Chernobyl accident non-emergency permissible levels were accepted only 11 years after the accident. In Japan they were accepted after 1 year. The reason for this was that these two accidents differ in their extent, levels of radioactive contamination of products, dynamics of the decrease of radioactive contamination of vegetation in the conditions of different soils and climate, and also by the countermeasures that have been used, or not. The main reason for high levels of radioactive contamination of products in Belarus, Russia and Ukraine was the extensive system of agricultural production. In Japan the radioactive cesium content in local animal products had not already exceeded the permissible levels just in a year after the accident because of the intensive system of agricultural production and the use of imported feed for animals from other countries. For example, in Ukraine after the Chernobyl accident the level of internal exposure to the population was higher than the level of external exposure due to consumption of radioactively contaminated food products (Likhtarev, et al., 2012, 2013). In contrast, in Japan the level of external exposure to the population after the accident at the Fukushima NPP was higher than the level of internal exposure because of the low content of radionuclides in food products.

1.3. Overview of Protective Action Levels after the nuclear disasters

Different radionuclides are especially relevant from a health perspective. After the Chernobyl accident, radiation levels were dominated by ^{137}Cs and ^{90}Sr which are both beta-emitters, ^{137m}Ba - a gamma-emitter, and ^{238,239,240}Pu with ^{241}Am, which are alpha-emitters. External dose rate depends on the density of the contamination of territory with ^{137}Cs. Internal dose is formed by the consumption of ^{137}Cs and ^{90}Sr with food and water. Inhalation of alpha-emitting radionuclides (^{238,239,240}Pu and ^{241}Am) with contaminated air is the main source of internal radiation dose.

To protect human health from radiation exposure, actions need to be taken to reduce or shield people from exposure, remove them from exposure or limit the period of their exposure. Depending on the radionuclide, different protective measures are needed at different times. Protective Action Levels refer to the exposure levels used to trigger the deployment of an emergency measures.

On the basis of the Basic Safety Standards (IAEA, 1996b), based on the experience of the Chernobyl accident (IAEA, 1992), ten years after the accident Radiation Safety Standards were developed and enacted in the three most affected countries (RSS-2000, 2000; RSS-99/2009, 2009; RSSU-97, 1998).

According to the Radiation Safety Standards of Ukraine (RSSU-97, 1998) any intervention (countermeasures) after a radiation accident may be qualified as unjustified, justified and unconditionally justified.

The intervention is not justified if the benefit for people health from the countermeasure is equal to or less than the amount of damage caused by this intervention.

The interventions are qualified as unconditionally justified if the averted dose value is so much that the benefit to health from such intervention is definitely higher than the amount of damage which this action causes. Certainly such urgent interventions should be qualified as justified if by the implementation of these interventions it is possible to avoid the threat of acute clinical manifestations of radiation damage: radiation sickness, radiation skin burns, radiation-induced thyroiditis, etc., and other deterministic (tissue) effects (> 100 mSv).

Between the border of justified interventions on one side and unconditionally justified interventions on another there is a range of values of averted doses which imply that countermeasures must be optimized before the implementation.

At the initial (acute) phase of the accident the main and most effective urgent and immediate countermeasures are: shelter, evacuation, iodine prophylaxis, limiting of population outdoor activity (Table 1.10), and temporary ban on the consumption of certain locally produced foods and on the use of water from local sources (RSSU-97, 1998). After the Chernobyl accident the mandatory evacuation of population was carried out when the expected dose was higher than 100 mSv in the first year. According to the current Radiation Safety Standards of Ukraine (RSSU-97) a mandatory evacuation must be carried out when the averted dose in the first 2 weeks after the accident is higher than 500 mSv (Table 1.10). Thus, after the Chernobyl accident the regulations for the evacuation of population were not significantly tightened in case of nuclear and radiation accidents.

The long-term countermeasures that can be performed in the early and late phases of the accident are (Table 1.11):

- temporary evacuation;
- resettlement (for permanent residence);
- limiting of the consumption of radioactively contaminated water and foods;
- decontamination of the territories;
- different agricultural countermeasures;
- other countermeasures (hydrological, including flood control, limitations related to forest management, hunting, fishing, etc.).

Any long-term countermeasures must be stopped when the dose estimates indicate that further continuation of these countermeasures is unjustified because the residual dose level is lower than the acceptable level. The population resettlement after the Chernobyl accident was carried out under the levels of terrestrial contamination with radionuclides and radiation doses to the population which were lower than that ones used according to the current Radiation Safety Standards of Ukraine (RSSU-97, 1998) — Table 1.11.

Table 1.10: The values of averted doses used for the classification of urgent countermeasures as justified and unconditionally justified (RSSU-97, 1998)

Countermeasures	Averted dose per the first 2 weeks after the accident for					
	Justified countermeasures			unconditionally justified countermeasures		
	mSv	mGy		mSv	mGy	
	For whole body	For thyroid	For skin	For whole body	For thyroid	For skin
Shelter	5	50	100	50	300	500
Evacuation	50	300	500	500	1000	3000
Iodine prophylaxis: children	-	50[f]	-	-	200[f]	-
adults	1	200[f]	-	-	500[f]	-
Limiting of population outdoor activity: children	1	20	50	10	100	300
adults	2	100	200	20	300	1000

---

[f] The expected dose of the internal exposure by iodine radioisotopes received by the organism during the first two weeks after the accident.

Table 1.11: The lower limits of criteria used for the qualification of countermeasures as justified, and levels of these criteria used for the qualification of countermeasures (including resettlement) as unconditionally justified **right after the Chernobyl accident** / and now (RSSU-97, 1998) - Table 1.5 (Verkhovna Rada of Ukraine. On the Legal, 1991)

Criteria for decision	Lower limits of the justification	Unconditionally justified intervention levels and action levels
Averted dose for the whole period of the resettlement[g], mSv	**70**/200	**350**/1000
Averted dose per the first year (12 month) after the accident[g], mSv	50	**100**/500
Summarized averted dose per whole period of the temporary resettlement[g], mSv	100	1000
Radionuclide contamination density by long-lived radionuclides, kBq·m^2		
^{137}Cs	**185**/400	**555**/4000
^{90}Sr	**5.5**/80	**111**/400
α- emitting (^{238,239,240}Pu, ^{241}Am, and others)	**0.37**/0.5	**3.7**/4

According to the RSSU-97 the following summarized levels of external and internal radiation are acceptable (RSSU-97, 1998):

- 1 mSv per year for chronic exposure of more than 10 years;
- 5 mSv in total for the first two years;
- 15 mSv in total for the first 10 years.

These values must be taken into account when the measure (boundary) of the communal accident is being determined.

Temporary resettlement and evacuation implies population displacement from the accident area for a limited period of time. The evacuation is carried out as an emergency countermeasure in the early phase of the accident. At the same time temporary resettlement is carried out only after a detailed study of the radiation environment (usually in the middle and even later phase).

The criterion for evacuation after the Chernobyl accident was an expected effective dose during the first year after the accident (from April 26, 1986 until April 25, 1987) of 100 mSv (see paragraph 1.2 above). Since 1991 the criterion for the resettlement was the average annual effective dose of 1–5 mSv (Table 1.5). Now according to the RSSU-97 the lower limit of the justified evacuation corresponds to higher levels of radiation exposure, and it is more than the averted dose of 50 mSv in the first 2 weeks after the accident (Table 1.10). Therefore, the level of the unconditionally justified evacuation corresponds to the averted dose of 500 mSv in the first 2 weeks after the accident. According to the RSSU-97 the criteria for resettlement of population is the averted dose of 50–500 mSv during the first year (12 months) after the accident (Table 1.11). In 1986 the averted dose in Chernobyl due to resettlement was in this range (100 mSv). In 1991 the values of the permitted average annual effective dose of 5 mSv for an obligatory resettlement and 1 mSv for a voluntary resettlement were enacted in the three countries. These values were significantly lower than the limits established by the RSSU-97 (Table 1.9, 1.10). At the same time the permitted contamination densities of ^{137}Cs (of 555 and 185 kBq·m^{-2}), ^{90}Sr (of 111 and 5.5 kBq·m^{-2}) and $^{238–240}$Pu (of 3.7 and 0.37 kBq·m^{-2}) (Table 1.5) which were used as criteria for the

---

[g] It needs for the forecast of the changes in the radiation situation

resettlement in 1991 and also for the division of radiation zones do not correspond to levels of the justified intervention according to RSSU-97 (Table 1.11).

In the case of a radiation accident the limitations on food and water consumption may be accepted in order to reduce the internal dose (Table 1.12). Action levels (Bq·kg^{-1}) for radionuclides in food products adopted in Europe, by IAEA, in Ukraine and in Japan after the accident are rather close. In response to the accident of Fukushima Daiichi NPP, the government of Japan has set provisional regulation values of radionuclides in foods. The temporary permissible level for ^{131}I in milk in the USSR after the Chernobyl accident was 10 times higher. Based on the Chernobyl experience of the application of countermeasures, two action levels are specified for the radiation accident situations in Ukraine.

Table 1.12: Action levels (Bq·kg^{-1}) for radionuclides in food products adopted after nuclear and radiological accidents in Europe (EC, 1986), by IAEA[h] (IAEA, 1994), in Ukraine (RSSU-97, 1998 and after Chernobyl in 1986 — Table 1.7) and in Japan after the accident of Fukushima Daiichi NPP

Radionuclide group	Activity concentration (Bq·kg^{-1}or Bq·l^{-1})		
	baby foods	dairy produce	other foodstuffs
Isotopes of I, especially ^{131}I			
EC	150	500	2000
IAEA	100	100	1000
Ukraine (RSSU-97)	100–200	400–1000	800–2000
Ukraine (after Chernobyl)		3700[i]	37000
Japan (after Fukushima)		300[i]	2000
All other nuclides with half-life greater than 10 days, especially ^{134}Cs and ^{137}Cs			
EC	400	1000	1250
IAEA	1000	1000	1000
Ukraine (RSSU -97)		100–400	200–800
Ukraine (after Chernobyl)		370	370–3700
Japan (after Fukushima)		200	500
Isotopes of Sr, especially ^{90}Sr			
EC	75	125	750
IAEA	100	100	100
Ukraine (RSSU -97)	5–50	20–200	40–400
Alpha emitting isotopes, especially ^{239}Pu and ^{241}Am			
EC	1	20	80
IAEA	1	1	10

1.4. Proposed changes to Protective Action Levels and analysis of those changes

According to the latest International Basic Safety Standards (IAEA, 2011) for optimization of protection and safety in emergency exposure situations and in existing exposure situations

---

[h] These levels apply to national control where alternative food supplied are available: if this is not the case, higher levels may applied

[i] and for drinking water

reference levels of doses are used, for avoiding deterministic effects (>100 mSv) and reducing the likelihood of stochastic effects (<100 mSv) due to public exposure.

The reference levels are not dose limits and they are established or approved by the government, the regulatory body or another relevant authority.

Any situation that results in a dose of greater than **100 mSv** being incurred acutely or in one year would be considered unacceptable, except under circumstances relating to exposure of emergency workers. Reference levels of **20–100 mSv** would be used for the residual dose after a nuclear or radiation emergency to reduce the risk of stochastic effects (Table 1.13).

Reference levels of **1–20 mSv** would be used for optimization of radiation protection of population in existing exposure situations (for Chernobyl now) to levels that are as low as reasonably achievable, as well as economic, societal and environmental factors being taken into account. The minimum value of the reference level of 1 mSv is lower than the annual dose received from natural sources (the worldwide average annual radiation dose from natural sources, including radon, is 2.4 mSv (UNSCEAR, 2000)). While this optimization process is intended to provide optimized protection for all individuals subject to exposure, priority shall be given to those groups for whom residual dose exceeds the reference level. All reasonable steps shall be taken to prevent doses remaining above the reference levels. Reference levels shall typically be expressed as an annual effective dose to the **representative person** in the range of 1–20 mSv.

Table: 1.13: Generic criteria for protective actions and other response actions in emergency exposure situations to reduce the risk of stochastic effects (IAEA, 2011)

Generic criteria	**Examples of protective actions and other response actions**
Projected dose that exceeds the following generic criteria: Take urgent protective actions and other response actions	
50 mSv for *Thyroid* in the first 7 days	Iodine thyroid blocking
100 mSv in the first 7 days	Sheltering; evacuation; decontamination; restriction of consumption of food, milk and water; contamination control; public reassurance
Projected dose that exceeds the following generic criteria: Take protective actions and other response actions at early stage	
100 mSv per annum 100 mSv for *Fetus* for the full period of in utero development	Temporary relocation; decontamination; replacement of food, milk and water; public reassurance

The annual effective dose for a representative person (a critical group) is the average dose for 10 % of the most exposed people who have received the highest doses of external and internal exposure. In the later phase of the liquidation of the Chernobyl accident in the settlements, the effective dose of external and internal exposure for a representative person was respectively 1.8 times and 3 times (IAEA, 2006) higher than the average dose for the population of the settlement. Therefore, the limit of average annual effective dose adopted in Ukraine for population radiation exposure (AAED) of 1 $mSv \cdot y^{-1}$ for the third Zone of a guaranteed voluntary resettlement (Verkhovna Rada of Ukraine. On the Legal, 1991) corresponds to an annual effective dose to **the representative person** of 2–3 mSv. Using the reference levels of an annual effective dose to the representative person of 1 $mSv \cdot y^{-1}$ the average annual effective dose for the population in a settlement will be 0.3–0.5 mSv;is equal to or even lower than the dose in the 4th Zone of an enhanced radioecological monitoring, which was liquidated on 28.12.15 (Verkhovna Rada of Ukraine. On Amendments, 2015).

According to the dosimetry certification in 2011-2012 only in 25 settlements the AAED was higher than 1 mSv, in 60-101 settlements the AAED was 0.5-1 mSv and in less than 370 settlements the AAED was 0.3-0.5 mSv (Lihtarov, et al., 2012; Lihtarov, et al., 2013). Therefore, the use of reference levels of an annual effective dose for the representative person of 1 mSv will result in the significant increase of the area of the contaminated territories according to the Law of Ukraine: *"..., in Ukraine, the territories radioactively contaminated as a result of the Chernobyl accident, are the areas with persistent contamination of the environment by radioactive substances with levels above those existed before the accident and which can result in population exposure dose more than 1.0 mSv per year, taking into account climatic and complex ecological characteristics of these territories; and where the level of contamination requires implementation of measures to protect the population from radiation, in addition to other special interventions aimed to limit additional population exposure caused by the Chernobyl accident, as well as to ensure normal economic activity of population"* (Verkhovna Rada of Ukraine. On the Legal, 1991).

1.5. Radiation protection of environment

Recently the risk assessment of the exposure not only for humans but also for other organisms has become very relevant. The main paradigm of radioecology is based on the statement: "If humana are protected, other biological objects are protected too", but the question of the legality of this paradigm is being raised (ICRP 103, 2007).

The general conclusion from the Environmental Protection from Ionizing Contaminants (EPIC) database is that the threshold for deterministic radiation effects in wildlife lies somewhere in the range of absorbed dose rate 0.5–1 $mGy{\cdot}d^{-1}$ (the predicted no effect dose rate –PNEDR) for chronic low linear energy transfer radiation (IAEA, 2006). Quantitative dose rate/effect correlations were established for morphological and cytogenetic changes in Scots pine trees exposed to chronic irradiation (Yoschenko, et al., 2011; Watanabe, et al., 2015). Dose rate of 0.02 $mGy{\cdot}d^{-1}$ and 1 $mGy{\cdot}d^{-1}$ caused disappearance of the apical dominance in 10% and 50% of the sampled trees, respectively (Fig. 1.6). This morphological effect and related suppression of development can, to a certain extent, affect evolution of specific ecosystems in the Chernobyl Exclusion Zone, which possibly has to be taken into consideration for establishment of the PNEDR values and similar values for terrestrial ecosystems.

Different biological effects and changes in species richness of insects and animals in the ChEZ have also been found (Møller and Mousseaue, 2007, 2009, 2011; Møller, et al., 2005, 2013; Mousseaue and Møller, 2014). These effects and changes were caused by both the radiation influence and changes in the environment because of the population evacuation, and the termination of traditional economic activities in the ChEZ (Smith, 2008), and it requires further research.

The danger of the revealed radiobiological effects at the population level is still unclear, and at the present time this question requires further research.

There were no standards of radiation protection of the environment when the Chernobyl accident occurred. Now Biota Working Group of IAEA Environmental Modelling for Radiation Safety and ICRP Committee 5 task group are developing such standards for the reference species of organisms.

a

b

Fig.1.6: The morphological changes (the apical dominance) in Scots pine trees References on ”Red forest” site (the absorbed dose up to 10 Gy per year now) (Ministry of Ukraine of Emergencies, 2011; Yoschenko, et al., 2011) in ChEZ (a) and Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant (Watanabe, et al., 2015) (b)

1.6. Proposed changes to Protective Action Levels

During the regional Workshop on Transition of Areas Affected by the Chernobyl Accident to Normal Radiological Conditions and Resumption of Economic activities in Abandoned Areas (Vienna, October 7–8, 2015) Ukrainian national experts recommended the following changes to Protective Action Levels in Ukraine for the existing exposure situation in order to improve radiation protection of the population (Kashparov, V.A. 2015):

1. *From the experience and according to the current situation and to the recommendations of the BSS to use the level of 1 mSv·y*$^{-1}$ *as a reference level of the representative person exposure for the post-Chernobyl situation and existing exposure.*
2. *Use the reference level of the representative person exposure of 1 mSv·y*$^{-1}$ *as a basic criterion of the radiological classification of the territory instead of the terrestrial contamination density with radionuclides for the post-Chernobyl situation.*
3. *The measures on radiation protection of population and other special interventions aimed to limit the additional exposure of population of more than 1 mSv·y*$^{-1}$ *caused by the Chernobyl accident and interventions aimed to ensure a normal economic activity should be considered priorities.*
4. *Optimize permissible levels/action levels for radionuclides in foodstuff/commodities and the system of radiation monitoring.*

2. Chernobyl’s Contamination 30 years later with sections on food, environment (ground and wildlife) and water

Thirty years after the Chernobyl accident the activity of ^{90}Sr and ^{137}Cs decreased by a factor of 2. By 2016 (when about one half-life of ^{137}Cs had elapsed) the total area with a contamination density of ^{137}Cs above 1 Ci·km^{-2} (37 kBq ·m^{-2}) in Belarus, Russia and Ukraine will be respectively 1.6, 2.9 and 2.7 times smaller. In 2046 (when 2 half-lives of ^{137}Cs have elapsed) the areas with a contamination density of ^{137}Cs above 37 kBq·m^{-2} (it is a legally defined bottom criterion of the radioactive terrestrial contamination after the Chernobyl accident) in the three countries in proportion to 1986 will be respectively 2.4, 5 and 7 times smaller (The Atlas, 2009; CD, ATLAS, 2008; Ministry of Ukraine of Emergencies. 2011).

At the present time the contamination with ^{137}Cs of agricultural products has decreased by factors of tens and hundreds due to fixing of the different soils, but herewith the content of radioactive cesium in the non-wood forest products (mushrooms, berries, meat of wild animals) is several times greater than it was earlier. The exceeding of the permissible content of ^{137}Cs is observed in milk and meat from cattle (PL-2006) grazed on peat soils and non-wood forest products (Kashparov, et al., 2011; UIAR, 2015; Maloshtan, et al., 2015).

Throughout the period following the accident the increase of ^{90}Sr bioavailability is occurring due to the leaching of ^{90}Sr from fuel particles, and now it has achieved its maximum value (half-life of fuel particles in soils are 2–14 years). As a result of this the ^{90}Sr content in an alimentary grain and firewood in the near 60 km zone of the accident has been increasing during the last 15 years. Now this parameter has achieved its maximum value and exceeds hygiene standards (Kashparov, et al., 2013; Otreshko, L.N., et al., 2015).

During the time period after the accident, as a result of radioactive decay the activity of the ^{238}Pu ($T_{1/2}$=87.7 year) alpha-emitting radionuclides has decreased by 20%, and the activity of ^{239}Pu ($T_{1/2}$=24100 year) and ^{240}Pu ($T_{1/2}$=6563 year) have barely changed. As a result of the radioactive decay of the beta-emitting ^{241}Pu ($T_{1/2}$=14.4 year) and the ^{241}Am ($T_{1/2}$=432.8 year) radionuclides have been accumulated and their activity has been increasing. At the present time the activity of ^{241}Am is higher than the activity of $^{238+239+240}$Pu by 33% and it will be increasing during the next 50 years by 16%. After this the activity of ^{241}Am with a half-life of 432.8 years will slowly decrease.

The increase of the radioactive contamination of ^{241}Am in the environment due to the radioactive decay of ^{241}Pu has no significant effect on the radiological situation (total alpha-emitted radionuclides activity) because of future insignificant increase (<20%) and simultaneous decrease of ^{238}Pu ($T_{1/2}$=87.7 year) activity (Fig. 2.3).

High levels of contamination of the 10 km Exclusion Zone by the long-lived ^{239}Pu ($T_{1/2}$=24100 year), ^{240}Pu ($T_{1/2}$=6563 year) and the presence of dangerous radiological objects (including radioactive waste disposal, processing of radioactive waste, storage of nuclear fuel, Unit 4 of the ChNPP) make the returning of population and inhabitation of these areas impossible for tens of thousands of years (Kashparov, et al., 2015a). In the Chernobyl Exclusion Zone numerous morphological, cytogenetic and biochemical changes in plants, insects and animals are observed even at relatively low dose loads (from 0.02 mGy·d^{-1}) (Geraskin, et al., 2003; Ministry of Ukraine of Emergencies, 2011; Yoschenko, et al., 2011; Kashparov, et al., 2012; Møller and Mousseaue, 2007, 2009, 2011; Møller, et al., 2005, 2013; Mousseaue and Møller, 2014).

The results of active experiments and mathematical modelling show that fires in the Chernobyl Exclusion Zone don’t significantly increase the secondary contamination of the territories outside the ChEZ and the exposure doses to population, see paragraph 2.3 (Kashparov, et al., 2000;Yoschenko, et al. 2006a; Yoschenko, et al., 2006b; Khomutinin, et al., 2007; Kashparov, et al., 2015b).

For everywhere outside the ChEZ the content of radionuclides in the groundwater and surface water is within the hygiene standards for drinking water (Ministry of Ukraine of Emergencies, 2011). In the Exclusion Zone around the places of temporary localization of radioactive wastes the migration of ^{90}Sr and plutonium radionuclides to groundwater from landfills was found (Bugai, et al., 2012; Levchuk, et al., 2012). After the reduction of the water level in the cooling pond of the Chernobyl Nuclear Power Plant by 3.5 m during the past year (pumps for filling the cooling pond have not worked since September 2014) the content of ^{90}Sr and ^{137}Cs in the water of this pond is a few Bq·l^{-1}. There is a risk of catching fish containing ^{90}Sr and ^{137}Cs above the permissible level (150 Bq·kg^{-1} and 35 Bq·kg^{-1}) in the Kiev reservoir near the borders of the ChEZ, but only 5 from 100 caught fishes will be contaminated.

There is no such danger in the rest of Ukraine with the exception of certain closed water bodies with low potassium content in the water, where the content of ^{137}Cs in fish can be several times higher than the Permissible Level -2006 (Khomutinin, et al., 2011; Khomutinin, et al., 2013; Khomutinin, 2014).

At the present time there are no official proposals to lift the Exclusion Zone around Chernobyl Nuclear Power Plant.

There are different opinions about the future of the Exclusion Zone in Ukraine (SAUEZ, 2015a.): not to change anything; to create a Biosphere Radiological Reserve; and to create a Special Zone of Radiation Danger of the ChNPP (a zone of special industrial use with the exceptional "lifelong" status of the unfitness for population inhabitation).

2.1. Evacuation Zones Around Chernobyl and general evacuation policies

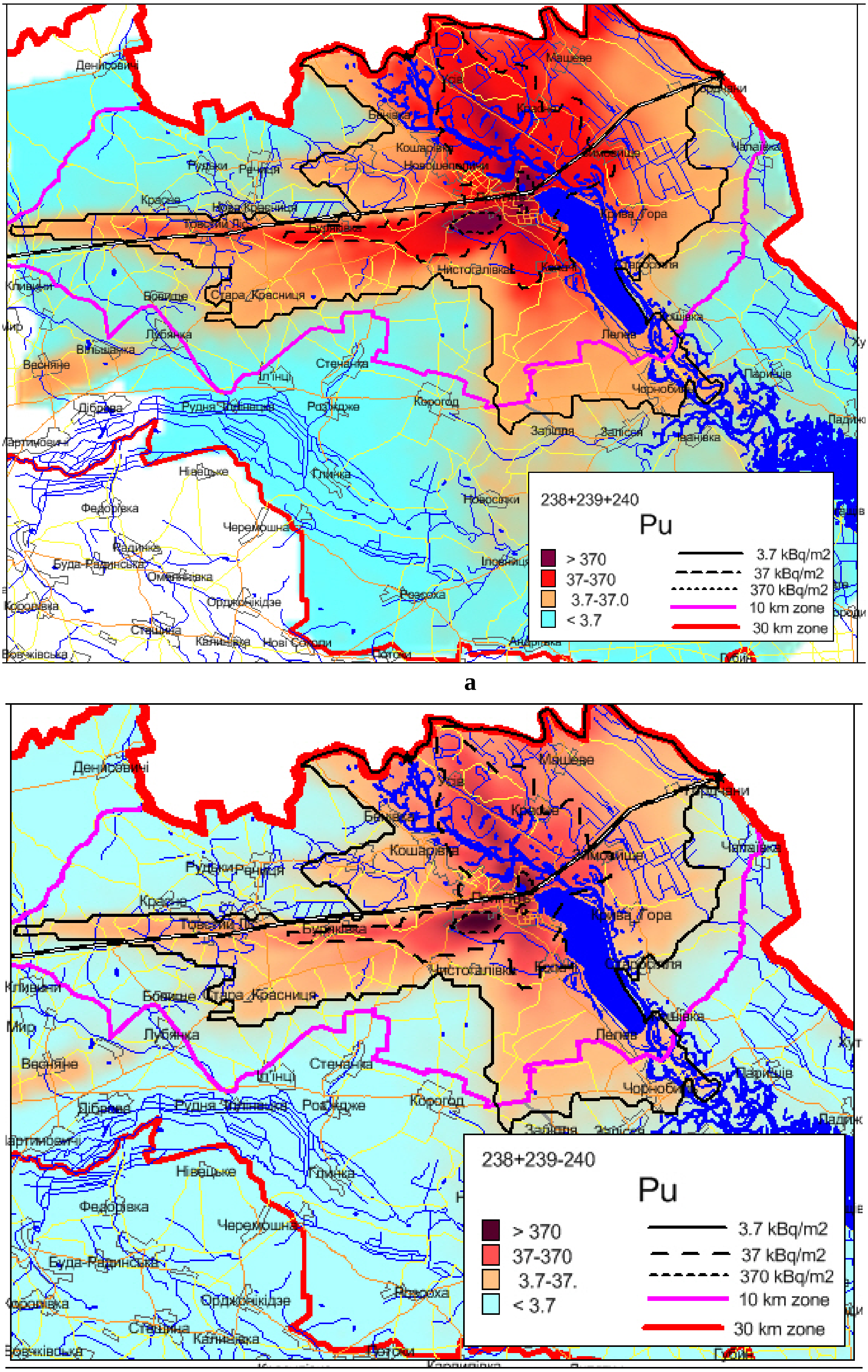
At the present time and over the next ten years in the Chernobyl Exclusion Zone the radiological threat will be posed mainly by medium-lived and long-lived radionuclides: ^{90}Sr ($T_{1/2}$=29 y), ^{137}Cs ($T_{1/2}$=30.2 y), ^{238}Pu ($T_{1/2}$=87.7 y), ^{239}Pu ($T_{1/2}$=24100 y), ^{240}Pu ($T_{1/2}$=6563 y), ^{241}Am ($T_{1/2}$=432.8 y).

The ChEZ is also called the «30-km zone». The most contaminated areas around the Chernobyl nuclear power plant with a special mode of the admission (fenced, with additional checkpoint) is also called the 10-km zone or Zone No.1, however its shape is not round but elongated along the spread of the radioactive contamination in the western direction (Fig. 2.1)..

According to the Laws of Belarus, Russia and Ukraine (see chap. 1) the areas rendered hazardous due to radiation are territories where the average annual effective dose of population radiation exposure is greater than 5 mSv or the contamination density of ^{137}Cs > 555 kBq·m^{-2}, ^{90}Sr > 111 kBq·m^{-2}, plutonium isotopes > 3.7 kBq·m^{-2}. Habitation by humans and production of agricultural and other products is forbidden in these areas. By the Law of Ukraine (Verkhovna Rada of Ukraine. On the Legal, 1991) it is not indicated exactly what plutonium isotopes should be considered (alpha-emitting $^{239–240}$Pu isotopes have been assumed). It causes contradictions in the interpretation of boundaries in the radioactive zones, because now the activity of beta-emitting ^{241}Pu ($T_{1/2}$=14 y) is more than 10 times higher than the activity of $^{238–240}$Pu and the contour line of the territory where contamination density of ^{241}Pu>3.7 kBq·m^{-2} extends beyond the ChEZ territory (Ministry of Ukraine of Emergencies, 2011).

The analysis of the border of the hazardous areas due to the radionuclides contamination (Table 1.5) shows that after 500 years the contamination density of $^{238-240}$Pu will be higher than 3.7 kBq·m^{-2} in the 10-km zone around the ChNPP (about 450 km^2) and therefore the 10-km zone will not be habitable- Fig. 2.1 (Kashparov, et al., 2015a).

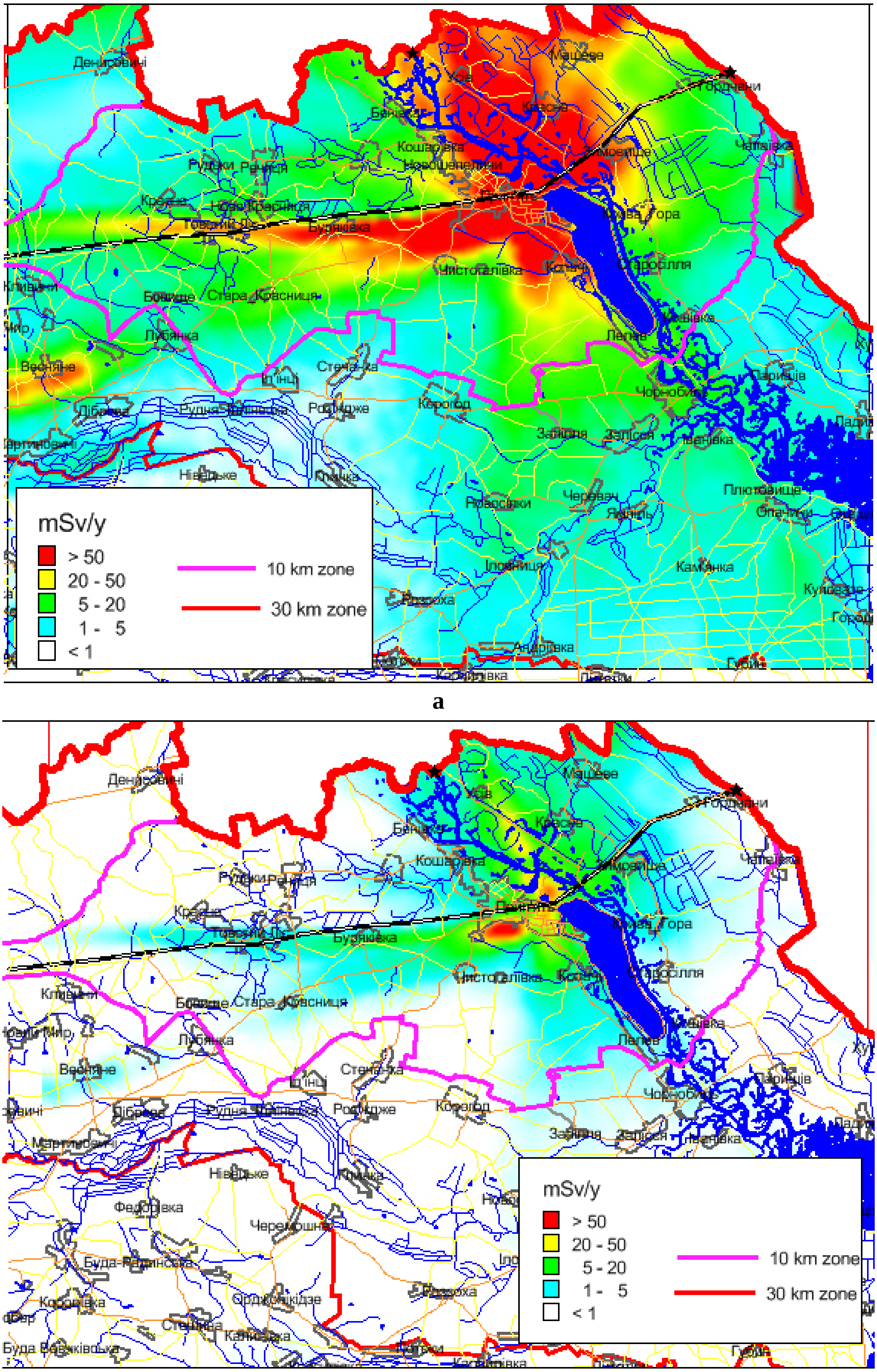
The maps with the expected effective radiation doses for the representative person in 2016 and 2516 show that levels of radiation higher than 1 and 5 mSv·y^{-1} are now beyond the borders of the 30-km and 10-km ChEZ, respectively (Fig. 2.2). Probably, even in 500 years in the south direction the effective dose will be higher than the dose limit of 1 mSv·y^{-1} (Fig. 2.2) because of possible ingestion of $^{239–240}$Pu and ^{241}Am with contaminated soil (unwashed vegetables, hands, etc.). Even in 500 years within the area of 500 km^2 the radiation level may be higher than the dose limits for the representative person.



a

b

Fig. 2.1: The terrestrial contamination density of $^{238-240}$Pu in the ChEZ: a – in 2016 and b – in 2516.

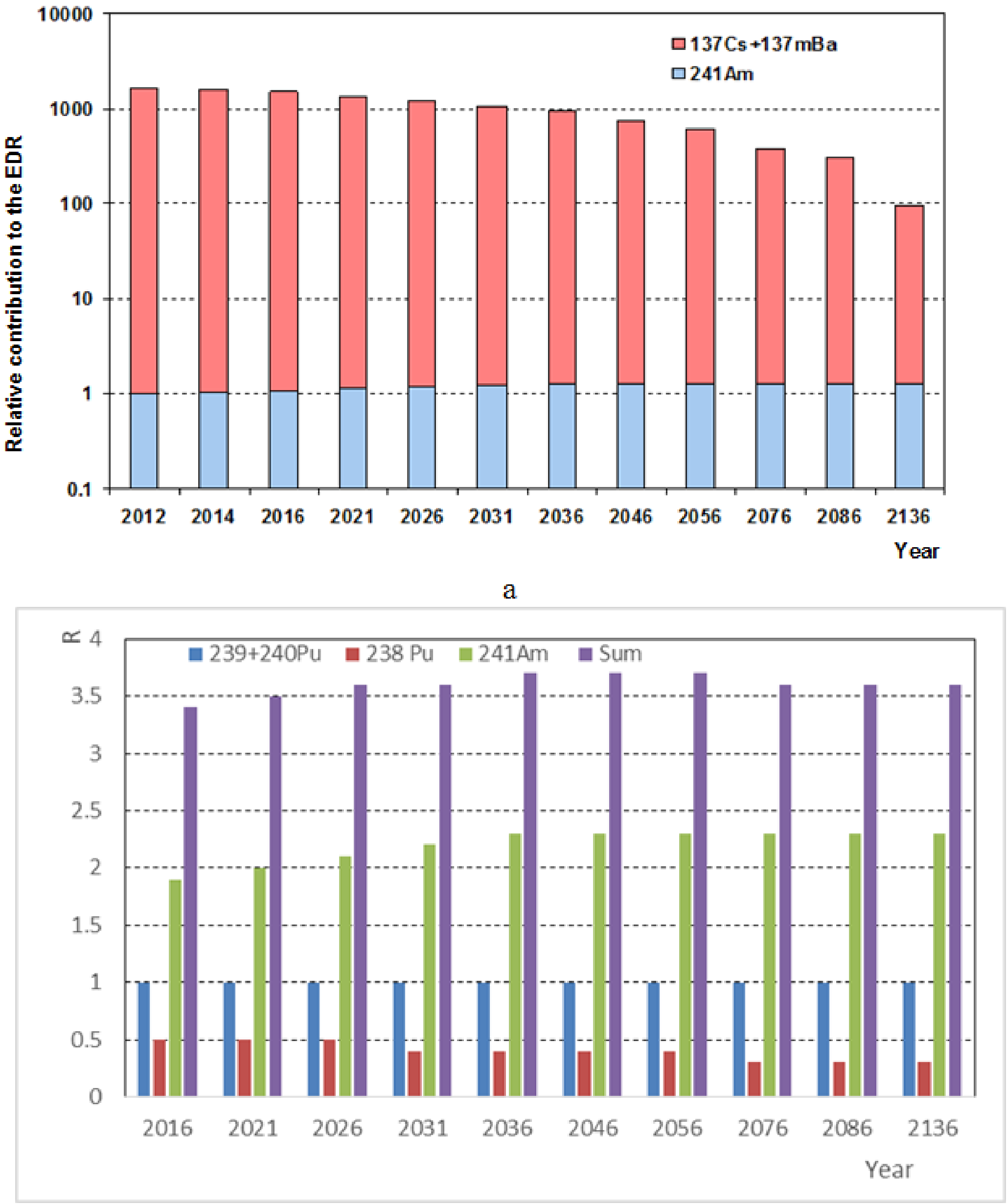


a

b

Fig. 2.2: Expected effective doses for the representative person in 2016 (a) and 2516 (b)

In the future the increase of ^{241}Am activity due to the radioactive decay of ^{241}Pu will not increase the Equivalent Dose Rate and inhalation threat significantly in the ChEZ territory (Fig. 2.3).



a

b

Fig. 2.3: The relative contribution to:
a – the formation of the equivalent dose of ^{137}Cs and ^{241}Am (the contribution of ^{241}Am to the EDR formation at present time is accepted as 1 unit);
b – the relative activity of alpha-emitting radionuclides (in proportion to the activity of the long-lived $^{239 + 240}$Pu radionuclides) in the fuel component of the Chernobyl radioactive fallout

At present time almost throughout the ChEZ territory the ^{137}Cs content in wild mushrooms and berries may exceed the PL-2006 standards (500 Bq·kg^{-1} for fresh and 2500 Bq·kg^{-1} for dry weight) (PL-2006, 2006). In the 10-km Zone and “Cesium spot” beyond the Zone near the Vesnyanoe settlement (Fig.1.4a) the ^{137}Cs content in milk and beef may also exceed the standards in an area of about 440 km^2. Nowadays the ^{90}Sr content in grain may exceed the hygiene standards for alimentary grain (20 Bq·kg^{-1}) throughout the ChEZ territory and outside the CheZ in adjacent regions (Kashparov, et al., 2013; Otreshko, L.N., et al., 2015). In 100 years in 2116 the contamination by ^{137}Cs above the PL-2006 standards will be observed only within the 10-km Zone in an area of about 460 km^2, and the ^{90}Sr content may exceed permissible levels in grain outside this zone on the total area of about 800 km^2 (Fig. 2.4).

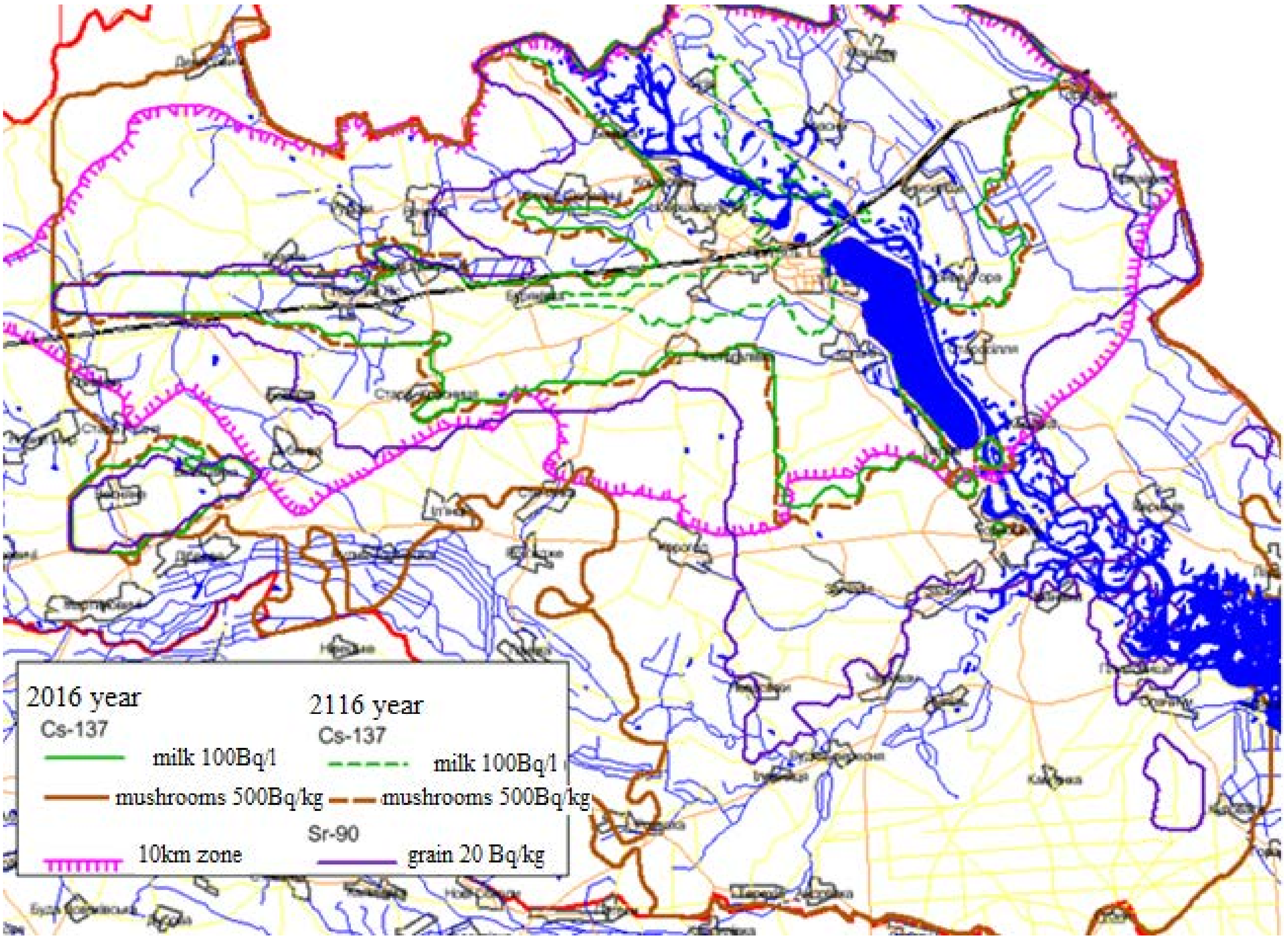
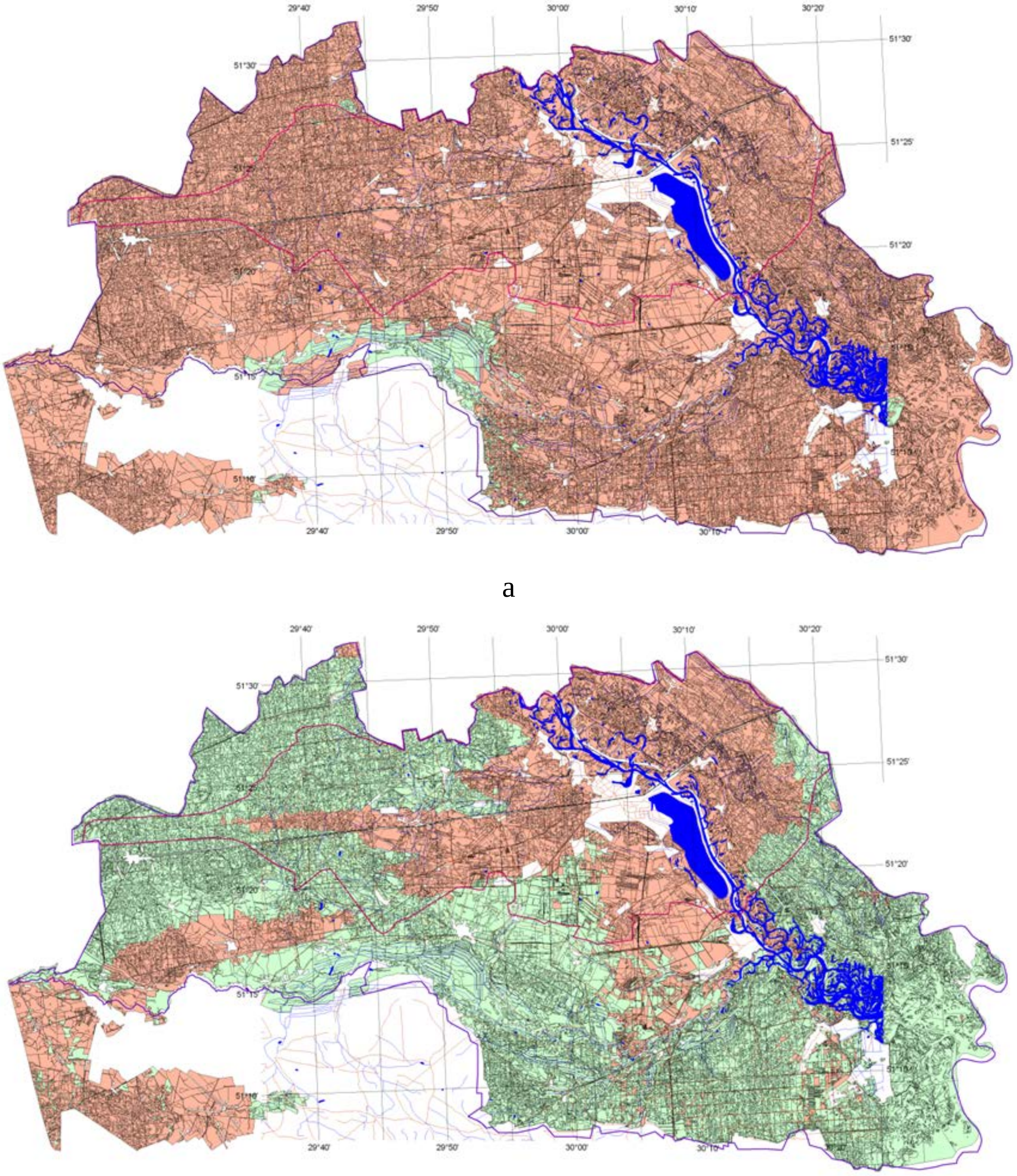


Fig. 2.4: Levels of ^{137}Cs specific activity in milk (100 Bq·l^{-1}) and mushrooms (500 Bq·kg^{-1}), and ^{90}Sr (20 Bq·kg^{-1}) in grain in the ChEZ in 2016 and 2116

The strictest requirements on the content of radionuclides in wood were established in Ukraine for the specific activity of ^{90}Sr in wood and brushwood (it is 60 Bq·kg^{-1}) (SSSAR-2005, 2005). At the present time throughout the ChEZ territory the long-term production of firewood is impossible (Fig. 2.5).

2.1.1. Special Zone of Radiation Danger (SZRD) of the ChNPP

Thus, around the ChNPP in the 10-km ChEZ long-term stable contamination with long-lived alpha-emitting radionuclides has occurred. These conditions will not allow population to live there in the foreseeable future. Taking into account the existing legislative framework of Ukraine with the international safety standards and documents of the European Union it is being planned to create a Special Zone of Radiation Danger (SZRD) of ChNPP (a zone of special industrial use with the exceptional "lifelong" status of unfitness for habitation) on this territory. The rest of the ChEZ where the return of population and the maintaining of traditional economic activities are not planned should be a buffer zone between the SZRD of ChNPP and the territory where habitation begins again (Kashparov, et al., 2015a). This is the official position of the ChNPP administration in light of the results of the analysis of the radiation situation in the ChEZ. The possibility of the creation of a radio-ecological biosphere reserve in this buffer zone, as in Belarus, and other variants are also considered. The future status of this territory has not been determined yet.



a

b

Fig. 2.5: The ^{90}Sr content in the wood in 2016 (a) and in 2116 (b)

🟥 >60 Bq·kg^{-1} 🟩 <60 Bq·kg^{-1}

The results of the analysis of radionuclides terrestrial contamination (Fig. 2.1), contamination of products (Fig. 2.4, 2.5) and dose assessment (Fig. 2.2) show that the main criteria for the SZRD location is the contamination density of the long-lived alpha-emitting radionuclides of $^{239\text{-}240}$Pu and ^{241}Am (more than 3.7 kBq·m^{-2}) and the expected average annual doses of radiation exposure for the representative person caused by these radionuclides (more than 5 mSv) - Fig. 2.1, 2.2. These criteria are also used for the planning of the sites of placement of radiation-dangerous objects (including, radioactive waste disposal, processing of radioactive waste, storage of nuclear fuel, and 4th of ChNPP) and sites of the potential location of a deep geological storage of radioactive wastes in the southern and western part of the ChEZ. In this regard the borderline of the SZRD should lie within the contour line of the terrestrial density of the contamination by $^{238+239+240}$Pu at the level of 3.7 kBq·m^{-2} (with a probability of 90%) and within existing boundaries of the ChEZ (Fig. 2.6) (Kashparov, et al., 2015a).

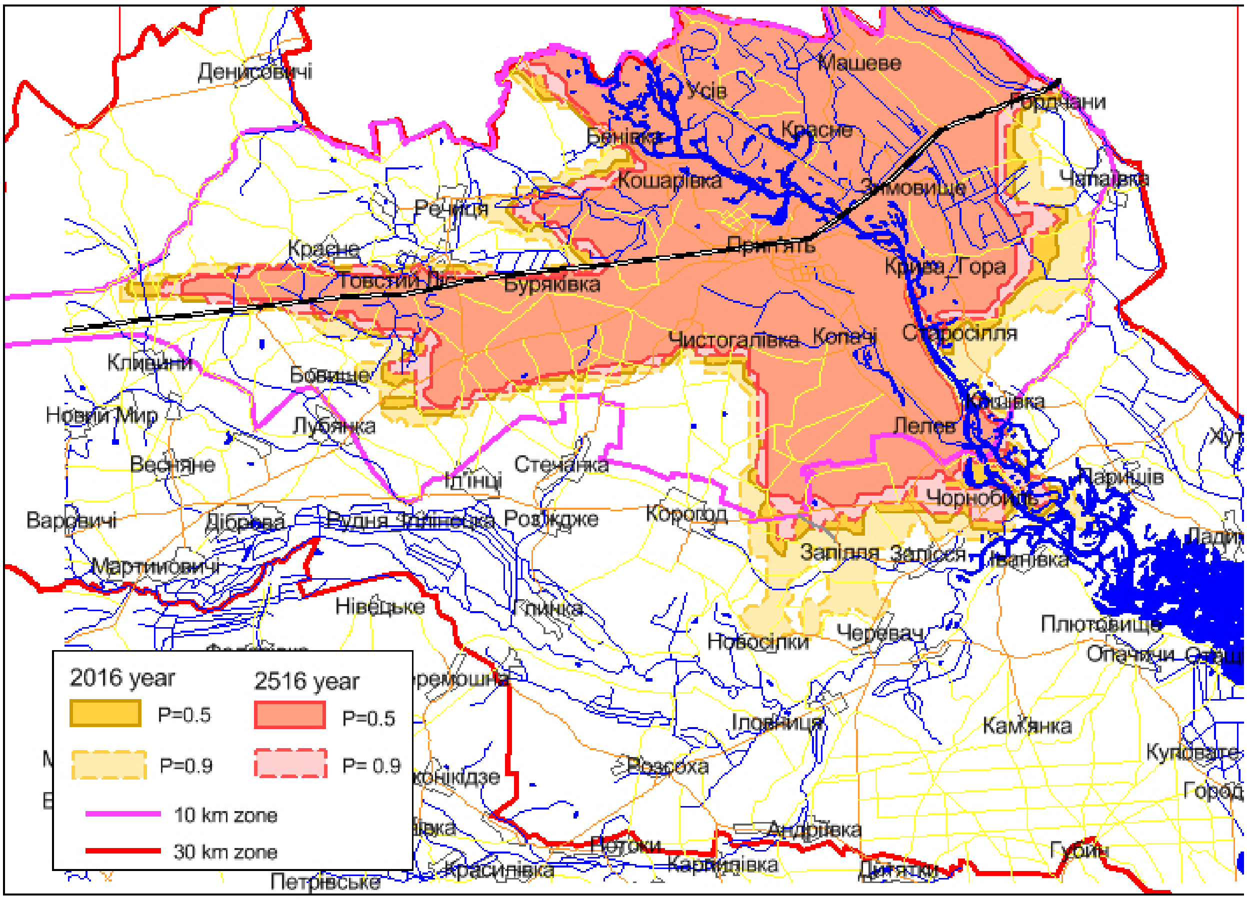
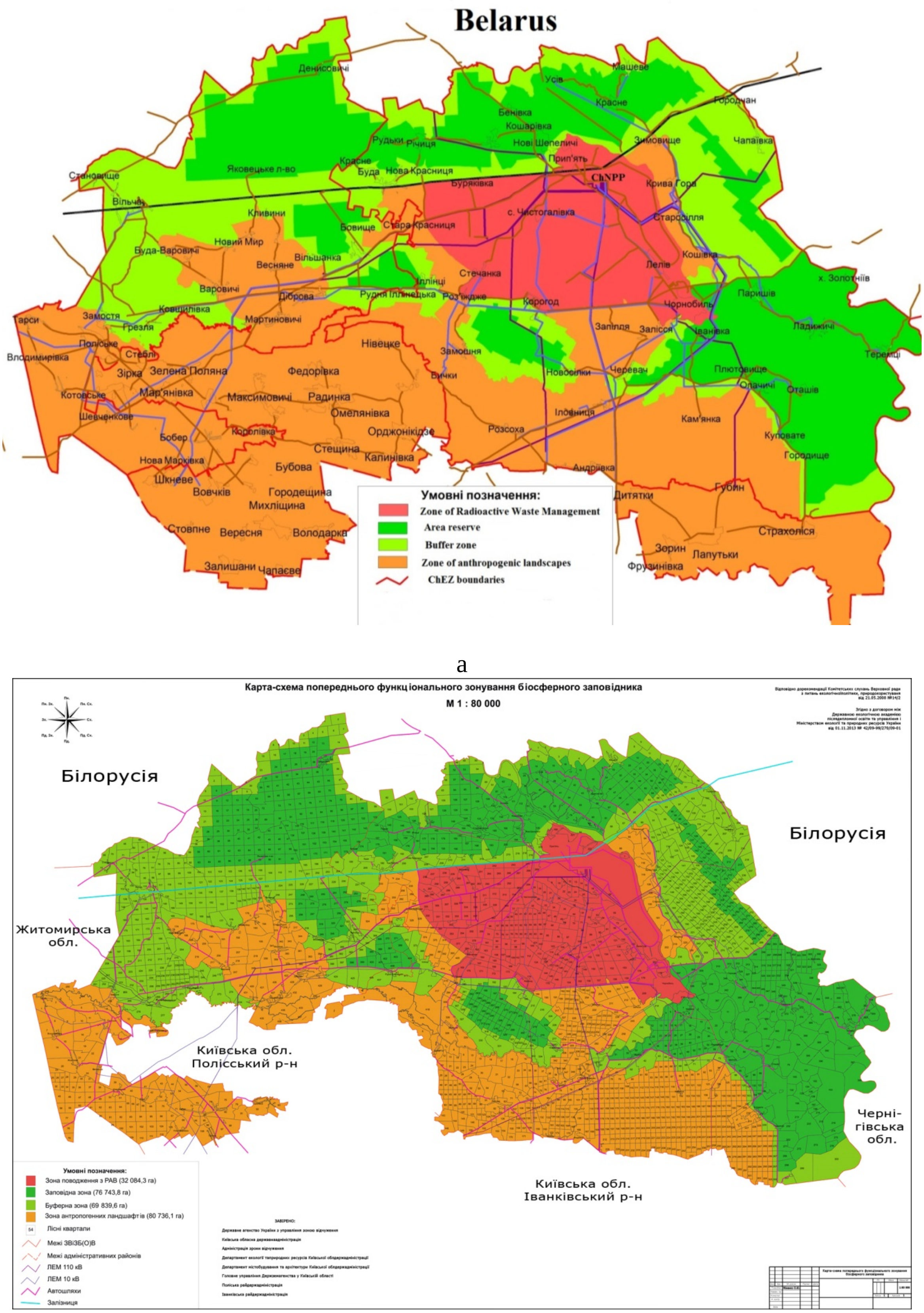


Fig. 2.6: The boundaries of the contamination density of $^{238+239+240}$Pu on the level of 3.7 kBq m^2 in the ChEZ in 2016 and 2516 as the main criteria for the SZRD location.

2.1.2. Biosphere Radiological Reserve in ChEZ

There are different opinions about the future of the Exclusion Zone in Ukraine (SAUEZ, 2015a.): not to change anything; to create a Biosphere Radiological Reserve (Fig.2.7); to create a Special Zone of Radiation Danger of the ChNPP (a zone of special industrial use with the exceptional "lifelong" status of the unfitness for population inhabitation). In order to prepare documents needed for the establishing of the Chernobyl Biosphere Radiological Reserve (ChBRR) a special group within the Ministry of Environment was created. It was proposed by this group that the boundary of the ChBRR beyond the ChEZ in the South direction should be extended (fig.2.7a) ((Bondar, et al., 2013). Currently, the Ministry of Environment of Ukraine has proposed to reduce the area of anthropogenic impact and combine the borders of the ChBRR and ChEZ (fig.2.7b) (Ivanenko, 2015).



a

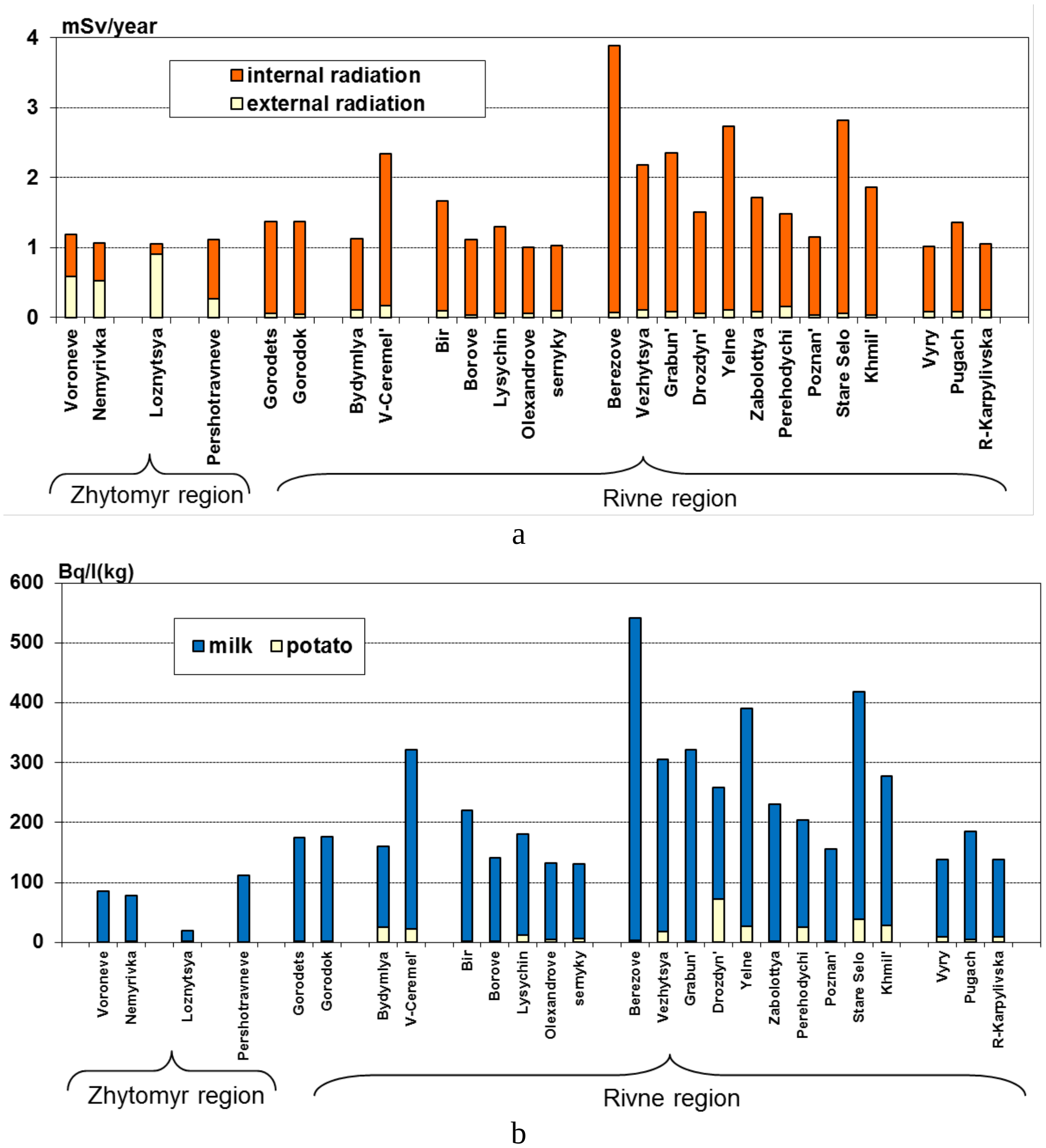
b

Fig.2.7: The previous proposals for functional zoning of the ChBRR: a – proposal of Bondar et al., 2013 and b – official proposal of the Ministry of Ecology and Natural Resources of Ukraine (Ivanenko, 2015)

2.2. Proposals to lift evacuation zones around Chernobyl

At the present time there are no official proposals to lift ChEZ around Chernobyl.

According to the data of the dosimetry certification of Ukraine in 2011 and 2012 the average annual effective dose was higher than 1 mSv only in 25 settlements (Fig. 2.8) (Lihtarov, I.A., et al. 2012; Lihtarov, I.A., et al. 2013). According to the Law only these residential settlements should be designated to the radioactively contaminated areas and protective measures to reduce radiation exposure to the population must be carried out in these settlements. In these critical settlements where the average annual effective dose (AED) is higher than 1 mSv internal exposure is caused mainly by the consumption of local milk (Fig. 2.8b). The application of protective measures/countermeasures such as the radical improvement (creating highly productive artificial pastures) of fields or the use of a special sorbent for cows (ferrocyn) with a reduction factor (radiological efficiency) of 3 allows the ^{137}Cs content in milk to be reduced below the permissible level (100 Bq·l^{-1}) and the dose of radiation exposure below 1 mSv·y^{-1} in nearly all settlements. Unfortunately, since 2009 the protective measures to reduce radiation exposure to the population have not been applied in Ukraine (Ministry of Ukraine of Emergencies, 2011).



a

b

Fig. 2.7: The previous proposals for functional zoning of the ChBRR: a — proposal of Bondar, et al., 2013 and b — official proposal of the Ministry of Ecology and Natural Resources of Ukraine (Ivanenko, 2015)

On December 28, 2014 in Ukraine the 4th Zone of an Enhanced Radoecological Monitoring that included 1290 settlements was abolished (Verkhovna Rada of Ukraine. On Amendments, 2015), although the criteria of the settlements attribution to other radioactively contaminated zones were not changed. As a result of work of the UIAR in 2014 detailed maps of the contamination with ^{137}Cs and ^{90}Sr of the Ivankov district of Kyiv region were constructed (Fig. 2.9) and the average levels of the radionuclide contamination of the settlements were determined (Table 2.1) (Kashparov, et al. 2014). It was found that more than 10 settlements of the Ivankov district assigned before December 28, 2014 to the 4th Zone of Radioactive Contamination (Table 2.1) had to be redesignated to the 3rd Zone of a Guaranteed Voluntary Resettlement because of the density of the ^{90}Sr contamination (that is higher than 5.5 kBq·m^{-2}) from 1991 (Tabl1 1.5).

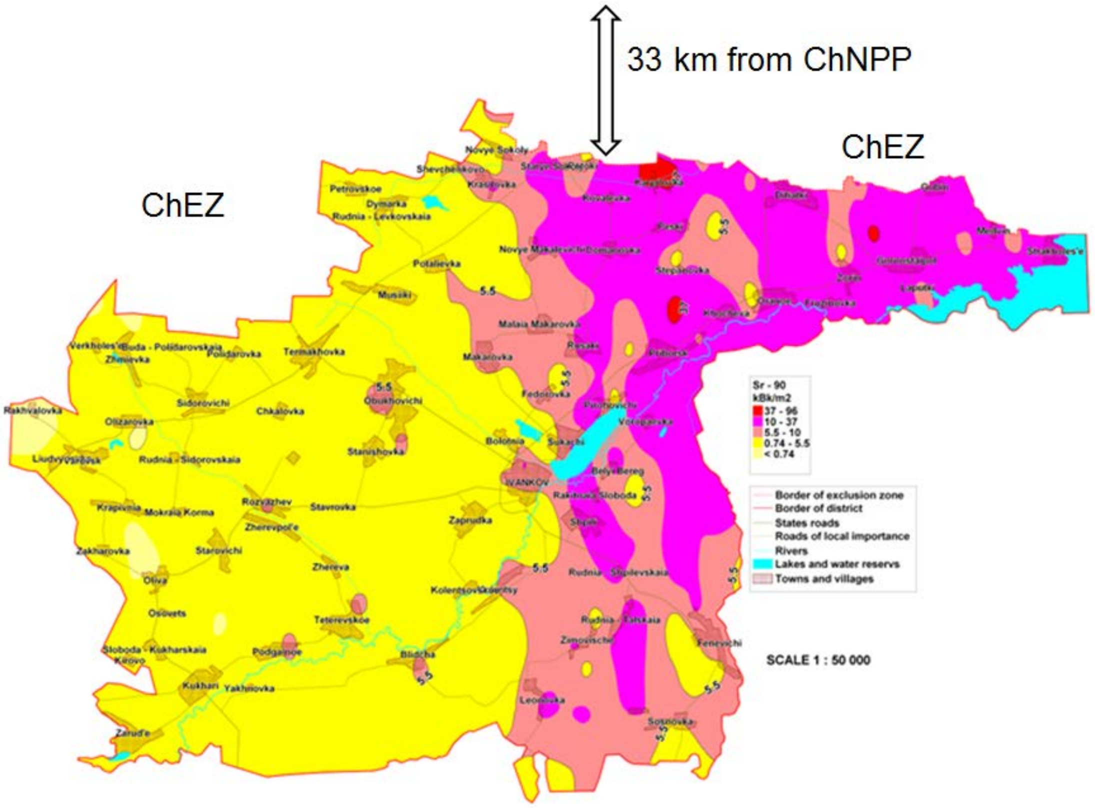


Fig. 2.9: Cartogram for density of soil contamination with ^{90}Sr in Ivankov region near the ChEZ, 2014 (Kashparov, et al., 2014)

During the mapping of the density of the soil contamination with ^{90}Sr and ^{137}Cs in the Ivankov region outside the ChEZ in 2014, separate "hot spots" with a size of several hectares and high dose rate were revealed. In 1986 the military units that took part in the liquidation of the consequences of the Chernobyl accident were situated in these areas. In these areas the dose rate exceeded the background levels by factors of tens and hundreds because of the contamination of the territory in 1986-1987 caused by decontamination of the equipment, etc. - Fig. 2.10 (Kashparov, et al., 2014). At present there are no any restrictions to access such "hot spots" outside the ChEZ, containing highly radioactive material. There are no danger warning signs in these areas, and they can be freely accessed by the population, including children. For protection of the public, it is necessary to identify and mark all of these "hot spots" through dedicated research of the territory outside the ChEZ, where people reside. Danger warning signs should be installed; and decontamination of the territory should be conducted if it is required.

Table 2.1: The terrestrial contamination density of ^{90}Sr in the settlements of the 4th Zone of an Enhanced Radioecological Monitoring abolished on 28.12.14 (Verkhovna Rada of Ukraine. On Amendments, 2015), of Ivankov district of Kyiv region in 2014 (the criterion for the 3rd Zone of a Guaranteed Voluntary Resettlement is ^{90}Sr > 5.5 kBq·m^{-2}) (Kashparov, et al., 2014)

No	Settlement	Number of analyzed samples	Terrestrial contamination density	
			Mean±STD, kBq·m^{-2}	Min–Max, kBq·m^{-2}
1	Domanovka	1	43.3	
2	Zimovische	3	7.5±3.5	4.3–11.3
3	Kovalevka	2	22.1±1.6	21.0–23.3
4	Leonovka	3	9.6±1.8	7.5–10.8
5	Malaia Makarovka	3	8.2±2.0	6.6–10.4
6	Novye Makalevichi	3	12.4±4.6	9.4–17.7
7	Pirogovichi	3	9.5±9.0	2.6–19.6
8	Potoki	1	6.2	
9	Rusaki	4	14.6±7.8	6.5–23.1
10	Sosnovka	4	7.7±3.0	4.5–10.4
11	Teterevskoe	5	4.8±3.4	2.9–10.9
12	Fenevichi	7	8.3±2.9	3.8–11.6
13	Khocheva	2	28.5±10.9	20.9–36.2
14	Shpili	4	12.1±4.0	7.7–16.9

2.3. Risks of recontamination — forest fire

In the period 1993–2013, more than 1100 wildfires of different kinds and scales were officially registered in the ChEZ, including in the most contaminated 10-km zone. The most fire-dangerous periods are April–May and August. The largest fires occurred on August 1992 in a total area of 17 000 ha of meadows and forests, including a crown fire in the area of more than 5 000 ha (Evangeliou, et al., 2015a).

In the absence of the traditional economic activity in the ChEZ during the last 30 years, dangerous fuel material in the forests and meadows has accumulated intensively. Excessively high density of plants in the pine forests throughout the ChEZ, a mixture of different tree ages, and the presence of young trees on the edges of forests, all increase the risk of high-intensive, crown, and extensive wildfires. The existing tools, structure and location of fire departments in the ChEZ are insufficient to such a high risk of fire, as they do not guarantee a rapid response nor effective firefighting in critical weather conditions. For example, in the ChEZ a fire department with two or three old fire engines, with a limited amount of fuel and lubricant, and with 5–7 firefighters is responsible for an area of more than 65 000 ha. At the same time outside the ChEZ every fire department is responsible for an area that is about 15–20 times smaller. Besides this, about a third of the territory of the ChEZ is not covered by fire detection (there are no fire lookout towers) and almost 23 000 ha of forest is not reachable for fire engines and fire brigades (Evangeliou, et al., 2015b). All of these factors cause a high risk of large-scale fires in the ChEZ. The largest of the ChEZ fires after 1992 happened in the end of April 2015.

At the time of fire, high-temperature evaporation of radionuclides occurs and small-dispersed radioactive aerosol appears due to ash-formation and radionuclide condensation on various carriers. All these facts are accompanied by a rise of above-ground radionuclide concentration in the air, up to hundreds and thousands of times higher than the normal levels (Kashparov, et al., 2000; Yoschenko, et al., 2006a).

At the present time, large parts of the ChEZ territory are covered with forests, where ordinary pine and birch trees prevail (64% and 23%, respectively). The part of flammable material, which is burnt, depends on the type of fire and fire risk in various weather conditions, and varies from 0% for wood to 97% for needles/leaves. During the forest fires up to 3–4% of the ^{137}Cs and ^{90}Sr and up to 1% of the Pu isotopes can be released from the forest litter. The released fraction of the radionuclides during the forest fires may even be bigger if the source of release is a large-scale and very intensive fire, since in this case a bigger burn-up of the combustible material can be expected (Yoschenko, et al., 2006b). Experimental and calculated data demonstrate that, even under the most unfavorable conditions, radionuclide resuspension during forest fires will not provide a significant contribution to terrestrial contamination. Additional terrestrial contamination due to a forest fire at a distance more than 100 m from the front of the fire can be estimated to be in the range of 10^{-4}–10^{-5} of its background value (Table 2.2, 2.3) (Kashparov, et al., 2000; Khomutinin, et al., 2007; Yoschenko, et al., 2006a).

During the forest fire in the most contaminated areas of the Exclusion Zone (Fig. 2.10) the additional radioactive contamination outside the ChEZ will be not significant and the expected dose for personnel and population of the ChEZ will not exceed a few μSv (Table 2.2–2.4). Thus, the radionuclide release outside the Exclusion Zone will be less than 1 percent of the radionuclide content in the fire area (Table 2.4). The maximum doses of tens of μSv can be received by firefighters (Table 2.3).

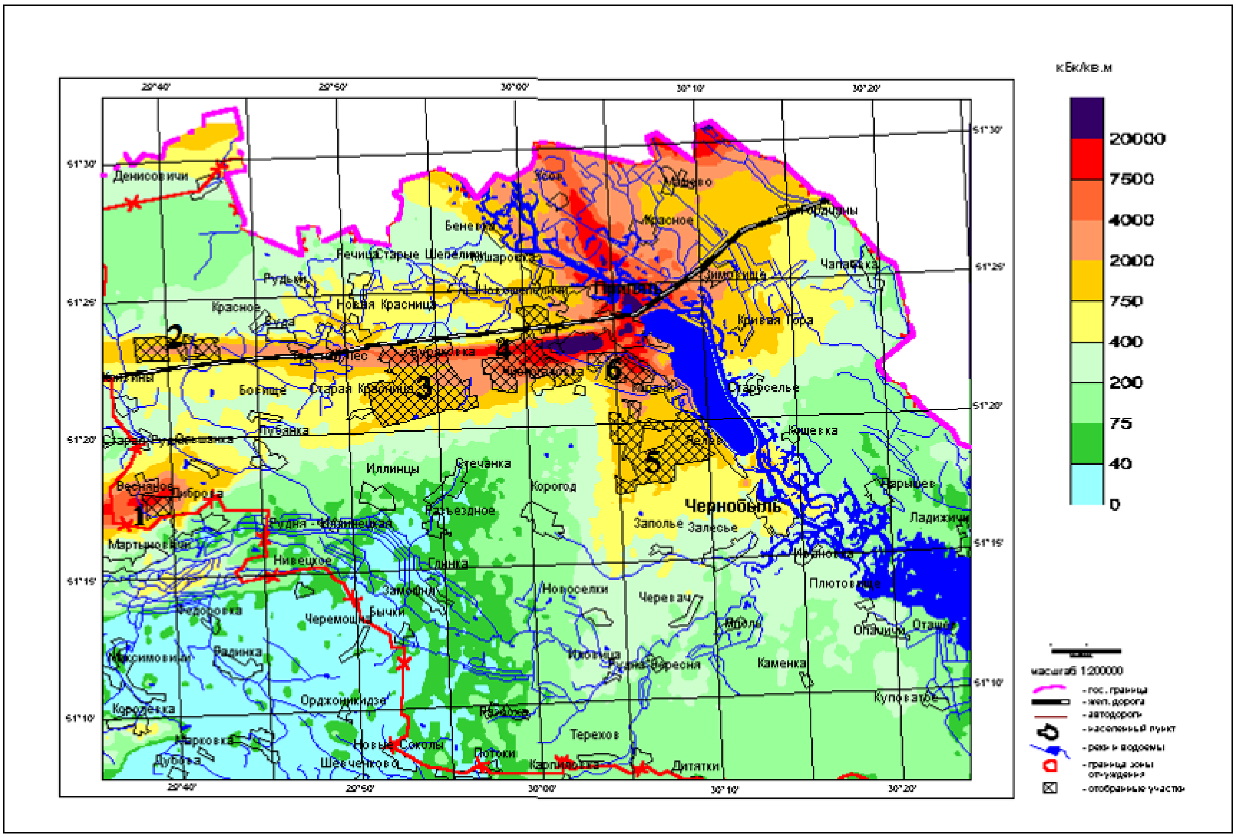


Fig. 2.10: Assessment of the effects of forest fires on the most contaminated areas near the settlements: Vesniane (1), Krasne (2), Buryakivka (3), Chistogalivka (4), Kopachi (5) and Leliv (6)

Table 2.2: Estimates of the maximum radionuclide fallout density and the maximum doses from radionuclide inhalation to the population of the settlements adjacent to the Chernobyl Exclusion Zone (Khomutinin, et al., 2007)

The settlements adjacent to the ChEZ (Distance from the fire)	Additional fallout density, Bq·m^{-2}			Dose, µSv.
	^{137}Cs	^{90}Sr	$^{239+240}$Pu	
Forest fire near settlement Buryakivka (3)				
Nivetske (17 km)	0.4	0.3	0.00005	1.0
Cheremoshna (18 km)	0.6	0.3	0.00004	0.9
Forest fire near settlement Chistoalivka (4)				
Cheremoshna (24 km)	0.4	0.2	0.00003	0.6
Nivetske (22 km)	0.5	0.2	0.00004	0.8
Forest fire near settlement Leliv (6)				
Dytiatky (24 km)	0.1	0.1	0.00001	0.3

Table 2.3: Maximum values of terrestrial contamination density of radionuclides and possible maximum values of doses received through the inhalation of radionuclides for personnel in the Chernobyl Exclusion Zone and firefighters in the conditions of forest fire in the ChEZ (Khomutinin, et al., 2007).

Distance from the fire	Additional terrestrial contamination density, Bq·m^{-2}			Dose, µSv
	^{137}Cs	^{90}Sr	$^{239+240}$Pu	
Forest fire near settlement Buryakivka (3)				
Chernobyl (24 km)	0.2	0.01	0.00001	0.4
ChNPP (14 km)	1	0.5	0.0001	1.6
“Vector” (2 km)	2	1	0.0001	2.6
Firemen	–	–	–	22
Forest fire near settlement Chistoalivka (4)				
Chernobyl (19 km)	1	0.4	0.00008	1.3
ChNPP (8 km)	4	2	0.0003	4.6
“Vector” (6 km)	3	1	0.0003	3.9
Firemen	–	–	–	40
Forest fire near settlement Kopachi (5)				
Chernobyl (14 km)	1	0.6	0.0001	1.4
ChNPP (3 km)	4	3	0.0005	5.6
“Vector” (12 km)	1	0.8	0.0001	1.8
Firemen	–	–	–	24

According to the most conservative estimates the transfer of radionuclides outside the Chernobyl Exclusion Zone as a result of large fires in April and August 2015 in the area of about 15 000 ha could cause the additional contamination of European territory outside the Exclusion Zone of less than 10 Bq·m^{-2} for ^{90}Sr and ^{137}Cs (background level of global fallout before the Chernobyl accident — 1–2 kBq·m^{-2}) and 0.1 Bq·m^{-2} for $^{238–239}$Pu and ^{241}Am (background level of global ^{239}Pu fallout is about 50 Bq·m^{-2}) (Evangeliou, et al., 2015b).

The effective dose of radiation for firefighting personnel in the ChEZ is formed of the external irradiation from radionuclides found outside the human body (soil, litter etc.) plus internal irradiation of the organism after radionuclide inhalation through respiratory organs, eyes and mouth.

For a wide range of forest fire scenarios related to the Chernobyl ^{137}Cs radioactive fallout outside ChEZ, the contribution of the inhalation dose to the total external dose (that is proportional to the terrestrial density of the contamination of ^{137}Cs) does not exceed several percent (Kashparov, et al., 2000; Khomutinin, et al., 2007).

Table 2.4: Estimates of the maximum activity flux outside the 30-km zone and the maximum possible dose from radionuclide inhlalation at the closest point of the zone border (Khomutinin, et al., 2007).

Location (distance to the closest point of the 30-km zone border; site number on Fig. 2.10)	Activity fraction transported across the border from the fire area, %.			Doses at the border of the zone, µSv.
	^{137}Cs	^{90}Sr	$^{239+240}$Pu	
Forest fire near Vesniane (1 km; 1)	0.32	0.40	0.004	1.4
Forest fire near Krasne (5 km; 2)	0.26	0.33	0.004	0.3
Forest fire near Buryakivka (14 km; 3)	0.15	0.20	0.002	1.6
Forest fire near Chistogalivka (20 km; 4)	0.11	0.13	0.002	1.1
Forest fire near Kopachi (11 km; 5)	0.20	0.25	0.003	1.8
Forest fire near Leliv (24 km; 6)	0.06	0.08	0.001	0.3

At the present time during forest and field fires the effective dose from the external exposure will be higher than the expected doses from the internal exposure for the participants of firefighting in the ChEZ territory even in the fuel traces of radioactive fallout at the highest levels of contamination with ^{90}Sr, $^{238–241}$Pu and ^{241}Am in proportion to the ^{137}Cs contamination. In a forest fire more than half of the expected effective dose of the internal exposure may be caused by the inhalation of ^{90}Sr. At field fires one third of the value of the expected effective dose of internal radiation exposure of the firefighters can be caused by the inhalation of ^{90}Sr, $^{238–241}$Pu and ^{241}Am with the approximately equal contribution of these radionuclides. The influence of the beta-emitting ^{241}Pu on the expected internal effective dose for the personnel is similar to this one of the alpha-emitting radionuclides $^{238-240}$Pu and must be taken into account (Kashparov, et al., 2015b).

According to analyses of remote sensing data the area of large grass fires, ground and crown forest fires in the Chernobyl Exclusion Zone in April 2015 was 10 127 ha in total: 1735 ha burned on April 27, 5761 ha — on April 28, and 2631 ha — on April 29. (Evangeliou, et al., 2015b). This area is more than 30 times higher than the official data and is consistent with Greenpeace data (Fires, 2015). Grass fire burned 6250 ha, while ground and crown forest fires burned 2737 ha and 1140 ha, respectively. The maximum terrestrial density of the radionuclide contamination inside the perimeter of the forest surface fire in the areas number 306–308 of Lubyanka forest ranger district was ^{137}Cs: 1040 kBq·m^{-2}; ^{90}Sr: 368 kBq·m^{-2}; $^{238-240}$Pu: 11.4 kBq·m^{-2} and ^{241}Am: 14.4 kBq·m^{-2} (Evangeliou, et al., 2015b). The expected effective doses for the firefighters were estimated on the basis of data on the area and type of the largest wildfire since 1992 in the Chernobyl Exclusion Zone on April 27–29, 2015 to levels of radionuclide contamination and fuel material. These doses did not exceed 0.64 mSv for external and 0.37 mSv for internal exposure per work hour (Fig. 2.11; Kashparov, et al., 2015b). On April 26–29, 2015 in a ten-hour working day the total expected effective dose from Chernobyl radionuclides for firefighters is estimated at maximum 42 µSv, which is lower than the reference levels of the individual doses for the ChEZ personnel of 3000 µSv per year (RSSU-97, 1998).

The external dose of radiation for firefighters can be reduced by minimizing the time of personnel staying in the area with high density of ^{137}Cs contamination, shielding gamma radiation by material of car cabins (down to a tenth), using remote-controlled tools (cars, tractors, etc.), and by aviation used for forest freighting keeping a safe distance.

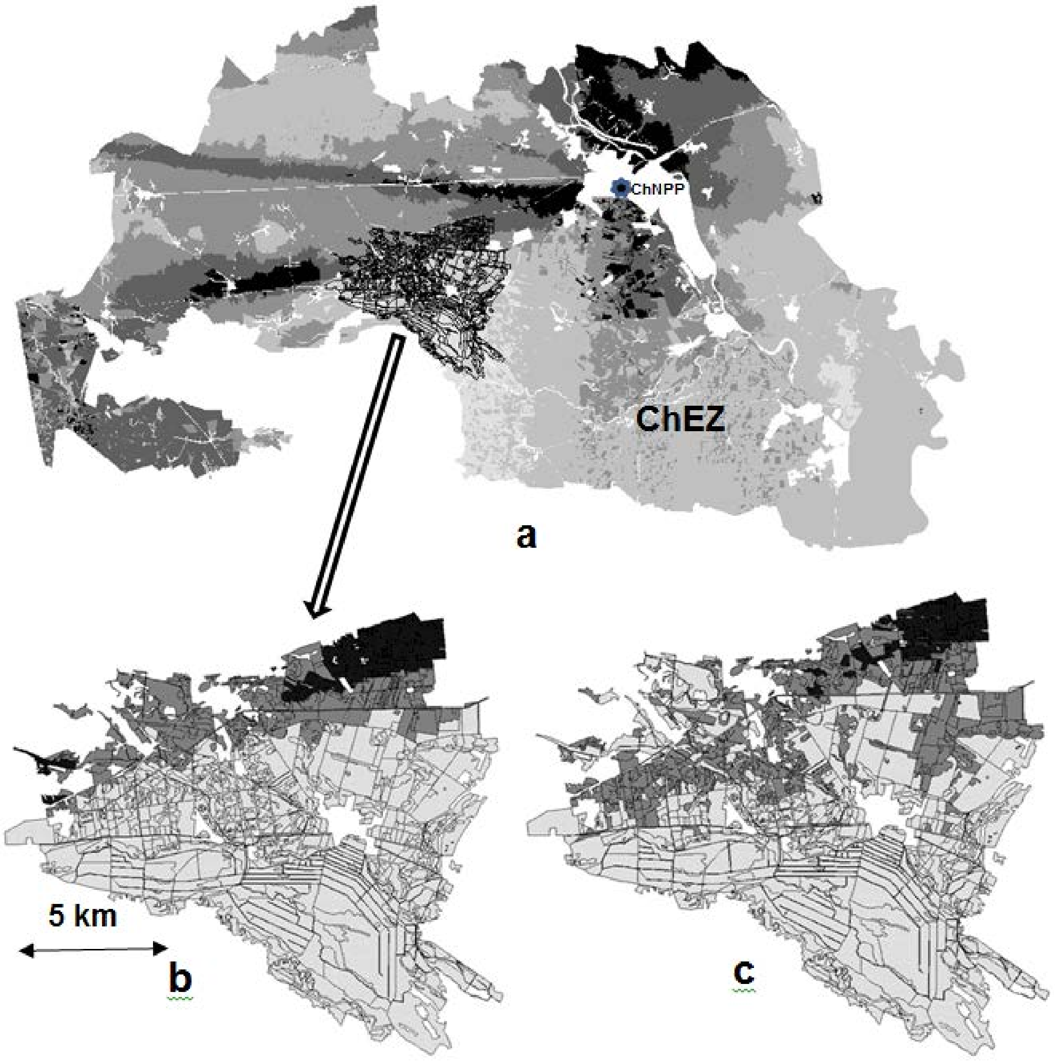


Fig. 2.11: Maps of the terrestrial contamination density of ^{137}Cs in the ChEZ (a):

⬜ <40 kBq/m^2; ▒ 40-185 kBq/m^2; ▓ 185-555 kBq/m^2; ⬛ >555 kBq/m^2

and expected effective radiation doses for the participants of firefighting for one hour of work near the fire frontline in 26–29 April 2015 (Kashparov et al., 2015b):

b – external dose ⬜ <0.1 µSv ▓ 0.1-0.3 µSv ⬛ 0.3-0.64 µSv
c – internal dose ⬜ <0.01 µSv ▓ 0.01-0.1 µSv ⬛ 0.1-0.37 µSv

Inhalation of radionuclides can be reduced by factors of tens and hundreds by the use of respirators etc. In cases of meadow and forest fires, radioactive aerosols of micron and submicron sizes are found in the air. The retention efficiency of these particles by Petrjanov cloth, used in respirators, exceeds 98%. Therefore, in order to protect the respiratory tract during firefighting, it seems expedient to apply various types of respirators and other individual protective tools for respiratory organs, and also to use of sealed car cabins and, if it is necessary, shielded car cabins.

The contamination of skin and clothes of the firefighters due to radioactive aerosol deposition is estimated as much lower than the permitted levels of surface contamination (Kashparov, et al., 2015b).

Taking into account the sharp decrease of the airborne radionuclide concentration with the distance from the source of release in case of forest fires, it can be stated that the inhalation component of the total dose (as well as the external irradiation from radionuclides in air) does not give a significant contribution to radiation exposure for people in the Exclusion Zone which are not involved in firefighting and for the population outside of the Exclusion Zone (Yoschenko, et al. 2006a; Khomutinin, et al., 2007).

Besides of the radiological risk of fires for the participants of firefighting, personnel of the ChEZ and population in the contaminated areas, providing information on fires in the Chernobyl Exclusion Zone is socially and psychologically important for the population of both Ukraine and other countries. In this connection, special attention should be focused on the firefighting capacity in the ChEZ and also on the creation of modern systems of fire detection and firefighting (Evangeliou, et al., 2014, 2015a,b).

2.4. Radiological situation outside the ChEZ

2.4.1. ^{137}Cs

The milk, cattle meat and non-wood forest products (mushrooms, berries and bushmeat) current exceed the permissible content of ^{137}Cs.

In the settlements of the northern regions of Ukraine, where the average dose is more than 1 mSv·y^{-1}, the main contribution to the total dose formation is provided by internal exposure due to the consumption of milk and non-wood forest products (Fig. 2.8). At this point there are about 10 settlements (Fig. 2.8) where the specific activity of ^{137}Cs in milk and cattle meat is always 3–4 times greater than PL-2006 standards. Also there are 50 settlements where the content of radioactive cesium in milk may exceed the permissible levels (Likhtarev et al., 2012, 2013; UIAR, 2015; Ministry of Ukraine of Emergencies, 2011). The reason for such high levels of ^{137}Cs in plants and animal products is abnormally high bioavailability of the cesium on peat soils with a relatively low contamination density of the soil with ^{137}Cs (about 100 kBq·m^{-2}) (Maloshtan et al., 2015).

Beside the waterlogged peats, abnormal high bioavailability of radioactive cesium that slowly changes in time (Fig. 2.12) (Maloshtan et al., 2015; UIAR, 2015) is also known for arctic and alpine ecosystems due to the low rate of decay of soil organic matter at high moisture content and low temperature. As a result, such soils are characterized by high acidity of soil solution, high concentration of ammonia and nutritional deficiency. High ^{137}Cs transfer factors (TF) are also caused by the species composition, low productivity and quality of the natural meadows, and by the soil properties: high content of organic matter (> 70 %) in peat-bog soils formed at sands and low contents of clay minerals, phosphorus, exchangeable potassium and calcium.

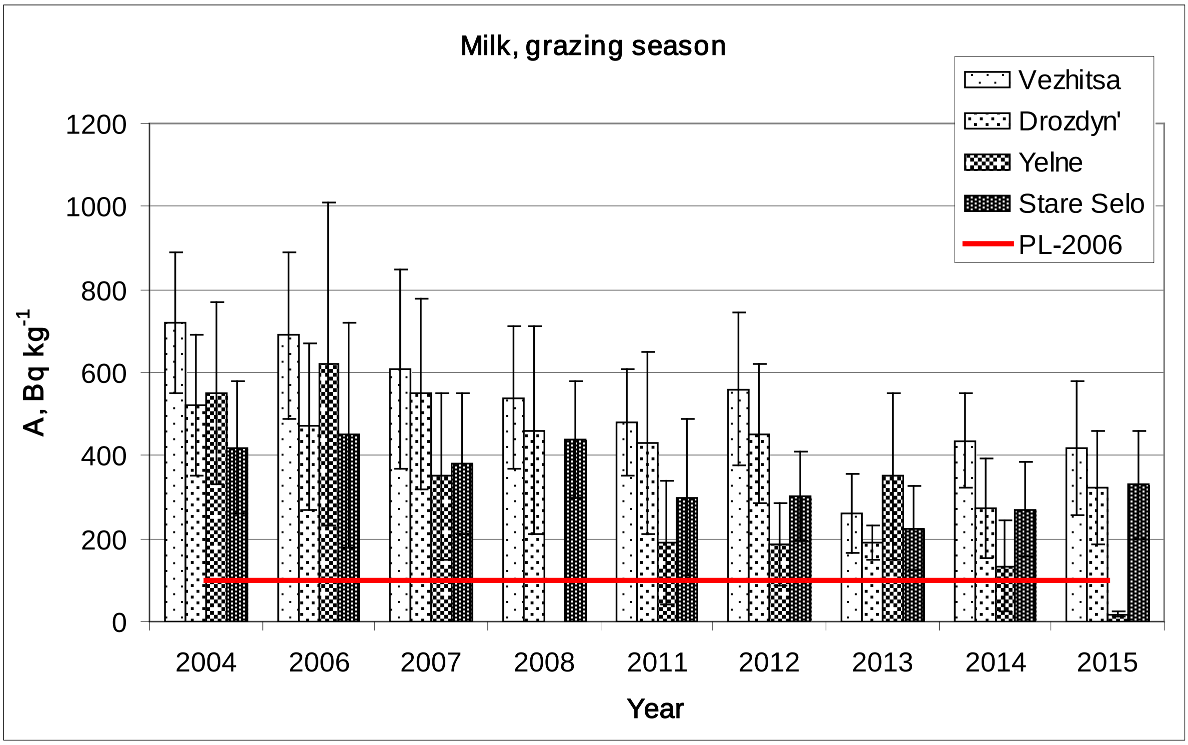


Fig. 2.12: The dynamics of the milk contamination by ^{137}Cs which is produced in the private farms of the most critical settlements during the grazing period (arithmetic mean, standard deviation, n > 20) (Maloshtan et al., 2015; UIAR, 2015: Current radiation situation at the agricultural areas in Ukraine)

2.4.1.1. Milk

The data of the last dosimetry certification of the settlements in 2012 for radiation protection of population on the average specific activity of ^{137}Cs in cattle milk (the arithmetic mean of five samples) (Lihtarov, I.A., et al. 2013) and the results of the monitoring of the UIAR of the National University of Life and Environmental Sciences of Ukraine indicate that most of the milk with ^{137}Cs content above the permissible hygiene state standards PL-2006 (100 Bq·l^{-1}) and also most of the beef with ^{137}Cs content of over 200 Bq·kg^{-1} are produced in the private farms of Rivne and Zhytomyr regions. The most critical villages, where the specific activity of ^{137}Cs in cattle is several times greater than the PL-2006 standards, are located only in Rokytne district of Rivne region.

The network of the monitoring investigations of the UIAR covers the most critical settlements of Rokytne, Sarny and Dubrovytsia districts of Rivne region (Table 2.5). The contamination density by ^{137}Cs of the monitored territory varies from 20 to 100 kBq·m^{-2}. The samples of the whole milk were collected during the grazing period in the most critical settlements of the region that were contributed to the third Zone of a Guaranteed Voluntary Resettlement.

The analysis of the obtained results revealed that the situation in these settlements of the monitoring network (Rokytne district) has not changed significantly for the last five years, taking into account the variability of the values due to different factors (Fig. 2.12, Table 2.5). In all settlements of the monitoring network the ^{137}Cs content in the collected milk samples was several times higher than the permissible limits. During 2015 the highest average values of the ^{137}Cs content in milk were recorded in the Perehodychi village of Rokytne district (870 Bq·kg^{-1}, in May).

The contamination of milk in a separate settlement depends on pastures where the cattle are grazed because the contamination density of ^{137}Cs of pastures can vary significantly even within the area of this village. Besides it, the pastures are located on soils with the different agrochemical properties and different mode of moisture and hence different transfer coefficients of ^{137}Cs in plants.

The results of the monitoring confirm that in the near future the radiation situation will not become significantly better, because the possibilities of the natural autorehabilitation (the fixing of radioactive cesium in the soil) without the use of countermeasures are almost exhausted. In the critical settlements where the measures to reduce the radioactive cesium intake in milk are not applied the decrease of the contamination of milk products will occur only through the decay of this radionuclide that is observed during the recent years (Fig. 2.12).

Table 2.5: The average values of the ^{137}Cs content in samples of whole milk (Bq·kg^{-1}) produced in the private farms of the critical settlements of Rokytne district according to the results of the monitoring during 2011–2015 (UIAR, 2015: Current radiation situation at the agricultural areas in Ukraine) and the data of the certification in 2012 (Lihtarov, I.A., et al. 2013).

Settlement	Data of the the monitoring during 2011–2015, Bq·l^{-1} (Mean±SD n>20)					Data of the certification in 2012, Bq·l^{-1}
	2011	2012	2013	2014	2015	2012
Stare Selo	303±193	303±107	225±100	270±110	330±130	381
Drozdyn	434±215	453±169	186±41	270±120	323±135	186
Vezhytsya	482±128	560±183	258±94	440±120	418±160	288
Perehodychi	346±197	285±187	137±22	240±100	470±230	179
Berezovo	124±43		104±75	80±40	80±40	538
Yelne	193±147	185±99	350±200	134±111	18±5	364

2.4.1.2. Wild mushrooms and berries

Among all components of the forest ecosystems the largest accumulation of the radioactive cesium from the soil is in mushrooms and berries (blueberries, cranberries, blackberries, etc.). In the case of the organized procurement for export or sales in markets the radionuclide content in mushrooms and berries is always controlled. But most of mushrooms and berries consumed by the population are not controlled at all.

The transfer of cesium in wild mushrooms varies significantly between mushroom species and depends on growing conditions (forest type) within each of them. In later years mushroom sampling focused on the areas with highest ^{137}Cs deposition in Ukraine. Mushroom species sampled include commonly consumed mushrooms. Currently, ^{137}Cs concentrations in Ukrainian mushrooms (outside the Chernobyl Exclusion Zone) vary from <10 Bq·kg^{-1} (fresh weight) up to >10 kBq·kg^{-1} according to species and sampling sites. The maximum contamination level of dried mushrooms can reach hundreds of kBq·kg^{-1} (Ministry of Ukraine of Emergencies, 2011).

About 50% of all samples of mushrooms (n = 77) that were collected in different regions of Ukraine during the monitoring in the UIAR in 2013–2014 did not comply with the requirements of the PL-2006. Today, the probability of exceeding the permissible content of ^{137}Cs (500 Bq·kg^{-1}) in types of mushrooms that are characterized by a strong accumulation of radionuclides is quite high throughout the Ukrainian Polissia territory (at the contamination density of more than 20 kBq·m^{-2}) (IAEA, 2006).

In Ukraine blueberries are the most widespread wild berries which are stored by the population for both personal consumption and sale. In contrast to mushrooms the parameters of the ^{137}Cs contamination of blueberries are much better. According to the monitoring results of the contamination of these berries in 2013–2014 samples with the exceeding of the permissible level (500 Bq·kg^{-1}) were not found. The ^{137}Cs content in the collected samples varied within a range of 45 to 210 Bq·kg^{-1} (UIAR, 2015: Current radiation situation at the agricultural areas in Ukraine).

2.4.2. ^{90}Sr

2.4.2.1. Cereal

The ^{137}Cs content in grain products which are now produced in Ukraine usually is not bigger than a few Bq·kg^{-1} and less than the established permissible level of 50 Bq·kg^{-1}. The level of the contamination of these agricultural products with another long-lived radionuclide originating from Chernobyl, ^{90}Sr, differs in some regions. Thirty years after the Chernobyl accident, the Ivankov district of Kyiv region adjacent to the Exclusion Zone (Fig. 2.9) produces grain in which in some cases the ^{90}Sr content reaches 60 Bq·kg^{-1}, exceeding the established in Ukraine permissible levels for food grains (20 Bq·kg^{-1}) (Kashparov, et al, 2013; Otreshko, et al, 2014). The soil contamination density of this critical area with the ^{90}Sr varies within the range of 5–40 kBq·m^{-2}. The monitoring of these products' contamination which was conducted in the UIAR of the NUBiP of Ukraine in 2009–14 revealed that in spite of the long period of time that had passed after the contamination, in general the situation of the grain contamination with ^{90}Sr in this region has not improved, and in some cases it has become worse. During the last three years in some areas the radioactive strontium content in grain samples was significantly higher than the values that were recorded more than ten years ago. In other words the bioavailability of ^{90}Sr has increased in these areas (Fig. 2.13). There are two reasons for this fact. Firstly, the ^{90}Sr was in the matrix of the particles of the exposed nuclear fuel in the content of the emergency fallout and was not available to plants. Over time, these particles were dissolved and transferred into the soil solution and this radionuclide was introduced into the migration processes (the bioavailability was increased). Secondly, in these areas agrotechnical measures are not carried out properly (unbalanced fertilization, absence of the liming of acid soils). Liming of the soil decreases ^{90}Sr content in plants by half.

The dynamics of the contamination of vegetation (grain and wood) with ^{90}Sr is mainly determined by the kinetics of fuel particle dissolution and by changes in the mobile radiostrontium content in the root-layer (Fig. 2.13). Depending on the fuel particle dissolution rate, root contamination of plants with ^{90}Sr is very important for radiating protection of the human and environment after the Chernobyl accident (Kashparov, et al, 2013; Otreshko, et al, 2014).

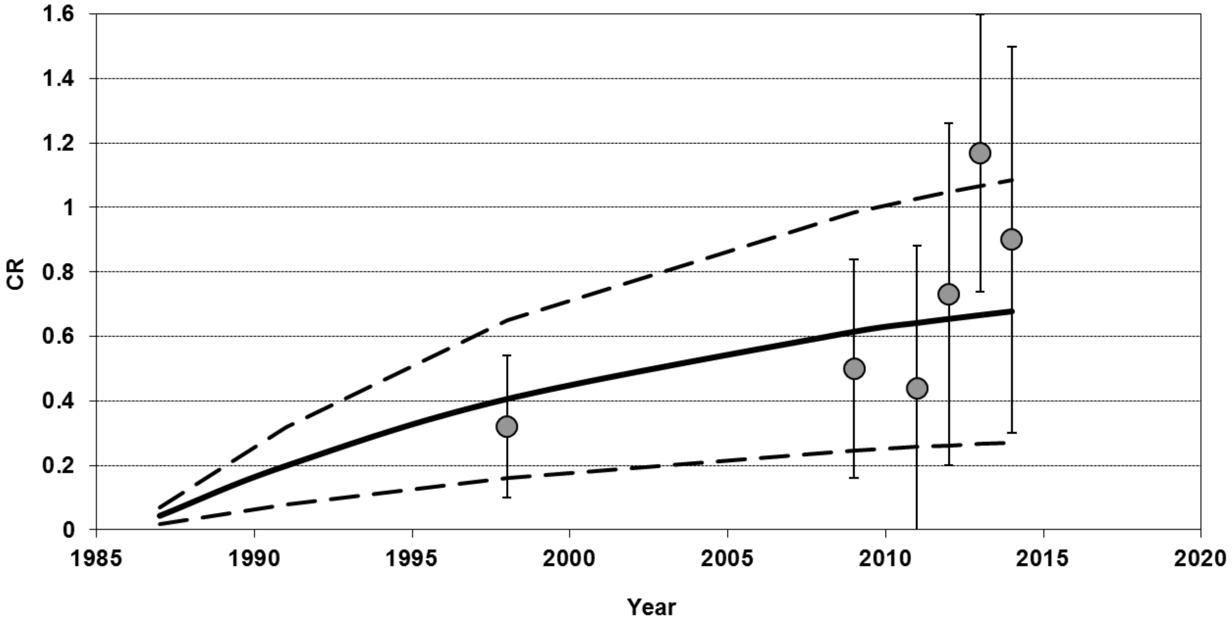


Fig. 2.13: Dynamic of the ^{90}Sr average CR (transfer factor) in grain and theoretical dependence (solid line) for the Zone in Ivankov district of Kyiv region (Kashparov, et al, 2013; Otreshko, et al, 2014).

According to the results of the research the ^{137}Cs content in most samples was greater than 10 Bq·kg^{-1} (the standard value was 50 Bq·kg^{-1}), while the specific activity of ^{90}Sr in grain varied within a range of 5 to 60 $Bq \cdot kg^{-1}$ (standard value was 20 $Bq \cdot kg^{-1}$). Overall, more than 50% of the collected samples of grain did not comply with the established permissible levels of radionuclide content (PL-2006, 2006). The area of these critical agricultural lands is less than 2000 hectares and the gross grain yield is less than 2000 tons.

2.4.2.2. Firewood

Due to price increases of gas and other energy sources, wood is used by the population and local administrations of Ukraine, including Chernobyl, more and more often. On 30 October 2015 the European Union sent a test furnace incinerator to Chernobyl for the burning of radioactive wood and for water heating for the town of Chernobyl in the ChEZ (SAUEZb, 2015). A thermal power plant where about 600 tons of wood a day can be burned has been built near the Ivankov village (Ukrainian, 2014).

According to the hygiene standards the permissible levels of the ^{90}Sr and ^{137}Cs content in firewood are 60 $Bq \cdot kg^{-1}$ and 600 $Bq \cdot kg^{-1}$, respectively.

The ^{90}Sr and ^{137}Cs content in soil and wood was measured along the southern fuel trace of the Chernobyl fallout, in the Ivankov district of Kyiv region in 2012–2013 (Otreshko, et al., 2015). The transfer factor of ^{90}Sr to wood of deciduous trees and pine rose to 34±20 and 61±56 $(Bq \cdot kg^{-1})/(kBq \cdot m^{-2})$, on average, that exceeds the values recommended by IAEA by more than a factor of ten (IAEA, 2010). Among 26 analyzed samples, the ^{90}Sr-specific activity was lower than the permissible level for firewood in only four, and in 20 samples it exceeded 100 $Bq \cdot kg^{-1}$. Burning of this wood can result in the formation of ash with the specific activity corresponding to the level of radioactive waste (10 $kBq \cdot kg^{-1}$).

There is a risk of the exceeding of the hygiene standard of the ^{90}Sr content in firewood and brushwood almost throughout the territory of Ivankov district, where the density contamination by ^{90}Sr is higher than 5.5 $kBq \cdot m^{-2}$, (Fig. 2.9). This raises a concern for the population of the region.

3. Analysis of interplay of current levels of radioactive contamination and Evacuation Policies in Ukraine, Belarus, Russia

As a result of the Chernobyl catastrophe basic Laws of Belarus, Russia and Ukraine «On legal regime of territories affected …» and «On the status and social protection of citizens suffered …» were adopted in the beginning of 1991 before the collapse of the USSR based on the uniform Concept for habitation of population within the territories of higher levels of radioactive contamination. The basic principle of the Concept is that the value of effective dose of additional exposure connected with the Chernobyl catastrophe should not exceed 1.0 mSv per year and 70.0 mSv per all life for the critical group of population (children born in 1986) besides the doses of natural background radiation received by the population during a pre-accident period in the same conditions. Protective measures provided by these laws (resettlement, providing of free residence, special health service, various privileges and compensations such as early retirement, free transport and food, reduced coast of utility bills, etc.) had to be financed by the funds of the general union budget of the USSR. After the collapse of the Soviet Union in the end of 1991, the liquidation of the consequences of the Chernobyl accident had to be financed by the budgets of the independent states. Due to the economic crisis of those years it was impossible to finance all of measures provided by the law.

The function of the state with respect to the Chernobyl catastrophe is represented in the Constitution of Ukraine: «… overcoming of the consequences of the Chernobyl catastrophe — a catastrophe of global scale — and preservation of the gene pool of the Ukrainian people, is the duty of the State» (Article 16). In 1992–98 a special Fund for measures for mitigating Chernobyl accident consequences and for social protection of population was created as part of the Ukrainian Budget. This Chernobyl Fund received fees from enterprises and economic organizations irrespective of subordination and proprietary forms in amount of 10–19% of payroll allocating transferred sums to the costs of works and services. From January 1, 1999, fee allocation to the Fund for Measures on Mitigating Chernobyl Accident Consequences and Social Protection of Population was stopped. The Decree established that financing of the expenditures from the Fund for Measures on Mitigating Chernobyl Accident Consequences and Social Protection of Population is carried out at the expense of State Budget of Ukraine. Notwithstanding the fact that during the years of independence Ukraine spent more than US$10bn on the liquidation of the Chernobyl catastrophe consequences, in price equivalent the laws were not financed by more than 57% (Ministry of Ukraine of Emergencies, 2011).

In Belarus US$19.4bn were spent for the financing of programs providing for the liquidation of the consequences of the accident during the period 1991–2010. In 2011–15 the sum of US$1 726.6bn was divided by the following way: 43.4% were given out for social protection and medical care of the population; 41.9% for the social development of the affected regions; 13.6% for the radiation protection and the targetted application of countermeasures; 1.1% for the scientific and information support (Chernikov, 2014). In recent years the state policy of Belarus was aimed at the redistribution of funds in individual payments to mitigate the potential risk for population health, at the financing of the state programs for social and economic recovery of the regions, and at the addressed health service of citizens.

During the post-accident period the radiation situation in the area radioactively contaminated as the result of the Chernobyl NPP accident was improved significantly because of the radioactive decay of radionuclides, application of countermeasures and autorehabilitation processes. In Belarus the number of settlements officially designated to the different zones of the radioactive contamination (the status is reconsidered by the Government of Belarus every 5 years) decreased by a factor of 1.5 and the number of people who live there decreased by a factor of 1.9 (Fig. 3.1). The application of the countermeasures made it possible to reduce the number of settlements which registered milk contaminated with ^{137}Cs and ^{90}Sr above the permissible levels in private farms by several orders of magnitude (Chernikov, V., 2014.). Also the last made it possible to reduce levels of radionuclide content in products in general.

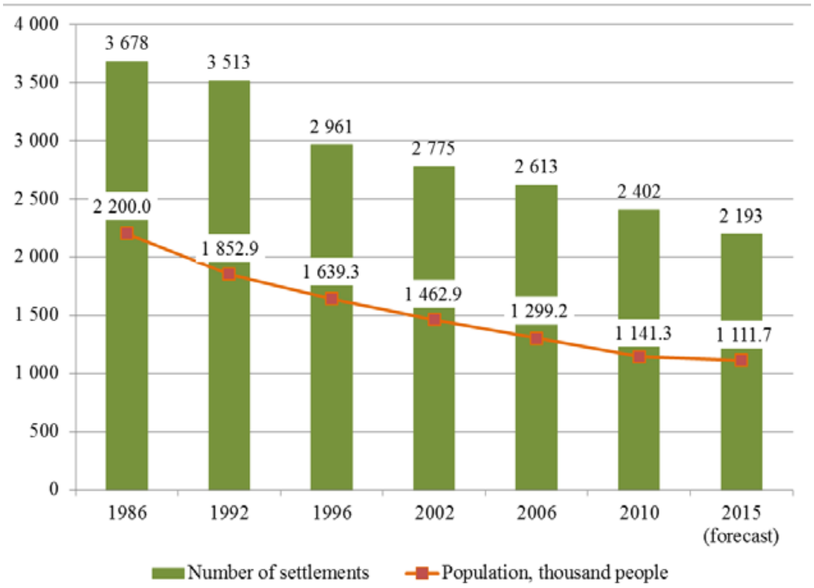


Fig.3.1: Dynamics of the number of settlements and population in the contaminated areas of Belarus (Tsybulko, 2015)

In Russia from 1991 (Government Decree No. 237-p from 28 December 1991) until 2005 the number of settlements in the zones of the radioactive contamination decreased from 7012 to 4413 (Government Decree No. 197 from 7 April 2005). By 2056 a significant reduction of the number of settlements in the areas of the radioactive contamination to 984 is predicted. More than 95% of these settlements will be in the Zone of residence with privileged socioeconomic status (Sanzharova, 2015). The number of settlements situated within the zones of the radioactive contamination was reduced to 3864 settlements according to the Resolution of the Government of the Russian Federation on October 8, 2015 No 1074 “On approval of the list of settlements situated within the zones of the radioactive contamination after the Chernobyl accident” (Cabinet of Ministers of Russia, 2015). At the end of 2015 small villages where now nobody lives and also a part of the settlements of Zone with Preferential Socioeconomic Status with low doses for the population have been excluded from this list (Bruk, et al., 2015).

In Ukraine, since 1991 the status of 2293 settlements designated to the different zones of the radioactive contamination has not been reconsidered. Reasons for this include the difficulty of the boundary-changing procedure of the contaminated zone by the Parliament of Ukraine, which was legally approved in 1996, and the negative attitude of the local government and population to these changes for fear of losing privileges and compensations. Only once in 2004, 6 settlements, where the population was not really resettled, were reattributed from the second Zone of an Unconditional (Obligatory) Resettlement to the third zone by the Decree of the President of Ukraine in order to legalize the state financing of the countermeasure applying in these settlements (Verkhovna Rada of Ukraine. Resolution, 2004). The population was resettled not from all of the settlements of the second Zone of an Unconditional (Obligatory) Resettlement. Nowadays, the process of the resettlement has been stopped and 532 families of the Zhytomyr region are still living in the second zone.

On 28 December 2014 the biggest, fourth Zone of an Enhanced Radioecological Monitoring (1290 settlements), where the most of the affected population live (more than 1.5 million of people) was eliminated as result of the changes in the Laws of Ukraine «On the legal regime of the territories exposed …» and «On the status and social protection of citizens suffered …» (Verkhovna Rada of Ukraine. On Amendments, 2015). To this day there is no decree of the Government of Ukraine for the changes in the list of settlements designated to the zones of the radioactive contamination. The fourth Zone does not exist anymore, but there are 1290 settlements still classified as Zone 4.

The main items of expenditure of the state budget of Ukraine for the liquidation of the consequences of the Chernobyl accident are the compensation and privileges providing to the population for the potential hazard for health, and also the expenses for the ChEZ and ChNPP. In Ukraine as a result of lack of financing of the measures provided for the social protection of the affected population, the legislative social rights and guarantees of the population suffered from the Chernobyl accident are not fully supported.

In 2015 the average annual effective dose of the population exposure in Belarus was equal or higher than 1 mSv·y^{-1} in 82 settlements which amounted 3.5% of the total number of settlements (2396) located in the areas of radioactive contamination. In 9 settlements the dose was higher than 2 mSv·y^{-1} but less than 5 mSv·y^{-1} (The Catalog, 2015).

In Russia from 4413 settlements designated to the zones of radioactive contamination in 276 settlements the average annual effective dose for the critical group of the population (AAED$_{90}$, the ninth decile of the distribution excluding active countermeasures) was greater than or equal to 1 mSv, and in 8 settlements it was higher than 5 mSv·y^{-1} (Bruk, et al. 2015).The maximum AAED$_{90}$ was for the population of Zaborye village in the Bryansk region. At the contamination density of the territory of ^{137}Cs of about 2200 kBq·m^{-2} in 2014 in this settlement the AAED$_{90}$ from external and internal exposure was 3 and 5 mSv, respectively. In Bryansk region 978 settlements have been assigned in 2005 to the zones of radioactive contamination: 4 — Exclusion Zone, 202 — Zone of Evacuation; 237 — Living Zone with the Right to Resettle and 535 — Zone with Preferential Socioeconomic Status (Government Decree No. 197 from 7 April 2005). Now after October 2015 in Bryansk region 749 settlements designated to the zones of radioactive contamination: 4 — Exclusion Zone, 26 — Zone of Evacuation; 191 — Living Zone with the Right to Resettle and 528 — Zone with Preferential Socioeconomic Status (Cabinet of Ministers of Russia, 2015).

In Russia the relatively large doses of the radiation exposure of population are caused by the fact that after the Chernobyl accident the evacuation of population was carried out in the territory at a ^{137}Cs contamination density of above 1480 kBq·m^{-2} (40 Ci·km^{-2}), while in Belarus and Ukraine the threshold was 555 kBq·m^{-2} (15 Ci·km^{-2}). At the present time in Russia in Krasnogorsk districts of Bryansk region the population continues to reside on the territories with contamination densities above 1480 kBq·m^{-2} (40 Ci·km^{-2}): Barsuki — 2165 kBq·m^{-2}, Zaborje — 2198 kBq·m^{-2}, Kovali - 1706 kBq·m^{-2}, Tugani — 1576 kBq·m^{-2}, Nikolaevka — 1650 kBq·m^{-2}, Novoaleksandrovka — 1502 kBq·m^{-2}, etc.) (Bruk, et al., 2015).

In Ukraine from 2293 settlements assigned to the zones of radioactive contamination in 2012 (the last dosimetry certification was carried out) only in 26 settlements the average annual effective dose for the population was equal or higher than 1 mSv·y^{-1}. In 6 settlements the dose was higher than 2 mSv·y^{-1} but less than 5 mSv·y^{-1} (Lihtarov, et al. 2013). The main contribution to the dose is made by the internal radiation as result of the consumption of local foods (milk, meat, mushrooms and berries) with a high content of radionuclides.

In Ukraine, Belarus, and Russia, different officially approved methods of assessment of the effective doses for the population with different degrees of conservatism are used for the management decisions. As a rule, the calculated effective doses for population are 2–10 times higher than the real ones (Bruk, et al., 2015; Lihtarov, et al., 2013). It makes the data on the radiation doses of the population in different countries after the Chernobyl accident difficult to compare (Table 4.1).

Nowadays, 30 years after the Chernobyl accident the resettlement of the population from the contaminated area would be unjustified and not considered in Ukraine.

In Ukraine, Belarus and Russia the average annual effective dose of 1 mSv is accepted as the dose limit. At the exceeding of this limit protective measures (countermeasures) are considered justified. In Belarus protective measures in agriculture are applied when the expected effective dose for the population is higher than 0.1 mSv·y^{-1}.

In the new version of the International Basic Safety Standards (IAEA, 2011) and the European legislation developed on the base of them the definite dose limits are not used for the decision making in the case of a radiation accident (evacuation, resettlement, etc.) and a situation of existing radiation exposure (limiting of the food and water consumption, countermeasures applying, etc.). The reference levels of radiation for the representative person of any values (but the values should be as low as possible) must be established by the leadership of the country depending on the concrete situation and taking into account economic and social factors. For the evacuation and resettlement the IAEA recommends to use the reference level in the range of 20 to 100 mSv and for the applying of the protective measures in the situation of the existing radiation exposure this one may vary within the range of 1 to 20 $mSv \cdot y^{-1}$ (IAEA, 2011).

Since in Ukraine the main contribution to the dose value is provided by the internal radiation exposure, at the present time the use of protective measures in agriculture (radical improvement of grassland and application of ferrocyn to cows) allows people to obtain products with radionuclide content below the permissible level, and to decrease the average annual effective dose for the population to the level below 1 mSv in all settlements of Ukraine (Jacob, et al., 2009). Unfortunately, countermeasures for the radiation protection of the population have not been applied in Ukraine since 2009, due to lack of funds in the state budget of Ukraine for the financing of all programs for the liquidation of the consequences of the Chernobyl accident. Besides this, social payments for the populations (compensations and privileges) are considered more important than the expansion of the radiation protection.

In Russia for a long time in a number of settlements it has been impossible to decrease the average annual effective dose below 1 mSv, because of the big contribution to the total dose is provided by the external radiation exposure under the high contamination densities of the territory with ^{137}Cs and the low decontamination efficiency of the area (the radiological effectiveness is not bigger than a factor of 1.5) (Jacob, et al. 2009).

At the present time the radiological and ecological situation outside the ChEZ changes very slowly and will be dangerous for the population for several decades. Mainly it is connected with a radioactive decay of ^{137}Cs which half-life is about 30 years. High levels of the contamination of the Exclusion Zone by the long-lived ^{239,240}Pu and the presence of nuclear dangerous objects make the returning and inhabitation of the population on these areas impossible for tens or hundreds of thousands of years.

Table 4.1: The amount of settlements in Ukraine, Belarus, Russia where the effective doses are greater than the established dose limits (The Catalog, 2015; Bruk, et al. 2015; Likhtarev, et al., 2013)

Country	Year	Number of settlements		
		Total in zone	1–5 $mSv \cdot y^{-1}$	>5 $mSv \cdot y^{-1}$
Belarus	2015	2396	82	0
Russia	2014	4413	276	8
Ukraine	2012	2293	26	0

Conclusion

In spite of the improvement of the radiation situation 30 years after the Chernobyl accident a whole complex of problems connected with the protection of the population and rehabilitation of the lands still needs to be solved in the contaminated areas of Belarus, Russia and Ukraine. The most important of these problems are presented below:

- About 9000 settlements in Belarus (2396), Russia (4413) and Ukraine (2293) where over 4.5 million people live are assigned to the zones of the radioactive contamination (IAEA, 2006).
- The average annual effective doses for the population exceed 1 mSv in more than 400 settlements.
- More than 10000 km^2 are unusable for economic activity.
- For an indefinite period there will be an Exclusion Zone around the ChNPP in Ukraine and Polesie State Radioecological Reserve in Belarus.
- In the part of the radioactively contaminated area it is impossible to provide the production of agricultural products which comply with radiation and hygiene standards;
- Wood and other forest products will be radioactively contaminated for a long time.
- Different radiobiological effects of non-human organisms are revealed in the ChEZ.

Among the post-Chernobyl problems the rehabilitation of the settlements is the most difficult and important. Because in order to solve this problem it is need to solve not only radiological but also economic, demographic and socio-psychological problems step by step.

For example, nowadays only in Ukraine more than 10000 residents receive the internal dose of more than 1 mSv every year through the consumption of the radioactively contaminated milk in 25 settlements (Likhtarev, et al., 2012, 2013). The collective dose per year for these residents (more than 10 man-Sv) is much higher than the collective dose for all staff of the ChEZ. Also this collective dose will be more significant than the consequences of any hypothetical emergency situations which can occur in the ChEZ such as forest fires (Khomutinin, et al., 2007, Ministry of Ukraine of Emergencies, 2011). However, in recent years the protective measures aimed at the reducing of the radioactive contamination of products and the decrease of the doses for the population are not carried out according to the Law of Ukraine (Verkhovna Rada of Ukraine. On the Legal, 1991).

Thus, at the present time the measures aimed at the radiation protection of the population in the areas affected by the Chernobyl accident are the most important of the Chernobyl tasks.

References

1. Abahyan, A.A., et al.1986. Information about the accident at the Chernobyl Nuclear Power Plant and its consequences prepared for the IAEA. *Atomic Energy* **61**(5): 301–320. (In Russian)
2. Aliyu A.S., Evangeliou N., Mousseau T.A., Wu J.,Ramli A.T. 2015. An overview of current knowledge concerning the health and environmental consequences of the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. *Environment International* **85**: 213–228.
3. Andriesse, C.D. & Tanke, R.H. 1984. Dominant factor in the release of fission products from overheated urania. *Nuclear Technology* **65**: 415–421.
4. Bondar O.I. et al. 2013. REPORT "The development of materials for the project of the Chernobyl Biosphere Reserve", State Environmental Academy of Postgraduate Education and Management, Kiev, Ukraine. (in Ukrainian).
5. Bruk, G.Ja., et al. 2015. The average annual effective doses for the population in the settlements of the russian federation attributed to zones of radioactive contamination due to the chernobyl accident (for zonation purposes), 2014. *Radiation Hygiene* **8**(2): 32–128. http://www.radhyg.ru/index.php/jour/article/view/6/8
6. Bugai D., Skalskyy A., Dzhepo S., et al. 2012. Radionuclide migration at experimental polygon at Red Forest waste site in Chernobyl zone. Part 2: Hydrogeological characterization and groundwater transport modelling . *Applied Geochemistry* **27**(7): 1359–1374
7. Cabinet of Ministers of Russia. Resolution of Cabinet of Ministers of Russia number 1074 on 8 October 2015 «On approval of the list of settlements situated within the zones of the radioactive contamination after the Chernobyl accident» (in Russian).
8. CD, ATLAS, Ukraine, radioactive contamination, MES, “Intelligence Systems GEO”, Ltd., 2008.
9. Chernikov V. 2014. Head of Department in the aftermath of the Chernobyl disaster Ministry of Emergency Situations of the Republic of Belarus. Pers. comm.
10. Chernobyl Nuclear Power Plant and RBMK reactors. 1996. *Bulletin of Ecological Conditions of the Exclusion Zone* **3**: 4–8. (in Ukrainian, French)
11. De Cort, M., et al. 1998. Atlas of Caesium Deposition on Europe after the Chernobyl Accident, Rep. 16733, Office for Official Publications of the European Communities, Luxembourg. ISBN 92–828–3140-X.
12. EC, 1986. EUROPEAN COMMISSION, Council Regulation (EEC) No. 1707/86 OJ No. L 146 of 31 May 1986: 88–90.
13. Evangeliou N., Zibtsev S., Myroniuk V. et al. Resuspension of radionuclides due to wildfires near the Chernobyl Nuclear Power Plant (CNPP) in 2015: An impact assessment. (in press)//. 2015b.
14. Evangeliou, N., Balkanski, Y., Cozic, A. et al. 2014. Wildfires in Chernobyl- contaminated forests and risks to the population and the environment: A new nuclear disaster about to happen? *Environment International* **73**: 346–358.
15. Evangeliou, N., Balkanski, Y., Cozic, A. et al. 2015a. Fire evolution in the radioactive forests of Ukraine and Belarus: future risks for the population and the environment. *Ecological Monographs* **85**(1): 49–72
16. Geraskin S.A., Zimina L.M., Dikarev V.G. et al. 2003. Bioindication of the anthropogenic effects on micropopulations of Pinus sylvestris, L. in the vicinity of a plant for the storage and processing of radioactive waste and in the Chernobyl NPP zone. *Journal of Environmental Radioactivity* **66:** 171–180,
17. Hilpert, K. & Nurberg, H.W. 1983. Mass spectrometric study of the potential of Al_2O_3/SiO_2 additives for the retention of caesium in coated particles. *Nuclear technology* **63**: 71–76.
18. IAEA, 1991. International Chernobyl Project: Technical Report. International Advisory Committee. Vienna.
19. IAEA, 1992. International Chernobyl project, technical report. ISBN 92–0-400192–5.

20. IAEA, 1994. Guidelines for agricultural countermeasures following an accidental release of radionuclides. A joint undertaking by the IAEA and FAO. TRS No.363. ISBN 92–0-100894–5.
21. IAEA, 1996a. One decade after Chernobyl: effect on the environment and further prospectives. IAEA/J1-CN-63, Vienna, Austria.
22. IAEA, 1996b, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources. 1996. *International Atomic Energy Agency*. **Safety series No. 115**, Vienna, 333p. ISSN 0074–1892; STI/PUB/996, ISBN 92–0-104295–7
23. IAEA, 2006. *Environmental consequences of the Chernobyl accident and their remediation: twenty years of experience*. Report of the Chernobyl Forum Expert Group "Environment" (eds. L. Anspaugh and M. Balonov). *Radiological assessment reports series*, IAEA, STI/PUB/1239, 166 pp.
24. IAEA, 2010. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and fresh-water environments. Vienna: IAEA-TRS-472, 194p
25. IAEA, 2011. Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. Interim Edition. General Safety Requirements. 2011. International Atomic Energy Agency. **Safety standards series No. GSR Part 3 (Interim**), Vienna, 303 pp. ISSN 1020–525X; STI/PUB/1531, ISBN 978–92–0–120910–8.
26. ICRP 103, 2007. 2007 Recommendations of the International Commission on Radiological Protection (Users Edition). ICRP Publication 103 (Users Edition). Ann. ICRP 37 (2–4).
27. Ill`in, A.L., Avetisov, G.M. 1983. Criteria of Decisions to Be Taken on Measures for People Protection in Case of a Reactor Accident. *Medical Radiology* **5**: 92. (in Russian).
28. Ivanenko, I. 2015. Director of Department of Protected Areas of the Ministry of Ecology and Natural Resources of Ukraine. Presentation "Chernobyl Radiation and Environmental Biosphere Reserve - the stages of transformation". http://dazv.gov.ua/ofitsijni-dokumenti/derzhavni-zakupivli/808-materiali-kruglogo-stolu-yakij-vidbuvsya-13-listopada-2015-r (in Ukrainian)
29. Izrael, Yu.A., Petrov, V.N., Severs, D.A.1987. Modeling of the radioactive fallout in the neighboring to the accident on Chernobyl NPP zone. *Meteorology and Hydrology* **7**: 5–12. (In Russian).
30. Izrael, Yu.A., Vakulovsky, S.M., Vetrov, V.A., Petrov, V.N., Rovinsky, F.Ya., Stukin, E.D. 1990. *Chernobyl: Radioactive Contamination of the Environment*. Gidrometeoizdat publishers, Leningrad, 223 pp. (in Russian)
31. Jacob, P., et al. 2009. Rural areas affected by the Chernobyl accident: Radiation exposure and remediation strategies. *Science of The Total Environment* **408**(1): 14–25.
32. Jost, D.T., Gaggeler, H.W., Baltensperger, U., Zinder, B., Haller, P. 1986. Chernobyl fallout in size-fractionated aerosol. *Nature* **324**: 22–23.
33. Kashparov, V., Levchuk, S., Protsak, V. et al. 2014. Mapping the contamination of Ivankiv district territory with radionuclides. UIAR final report within the frameworks of contract No.2013–04 from 19/11/2013, Kiev, UIAR, 47 pp.
34. Kashparov, V., Yoschenko, V., Levchuk, S., Bugai, D., Van Meir, N., Simonucci, C., Martin-Garin, A. 2012. Radionuclide migration in the experimental polygon of the Red Forest waste site in the Chernobyl zone — Part 1: Characterization of the waste trench, fuel particle transformation processes in soils, biogenic fluxes and effects on biota. *Applied Geochemistry* **27**(7): 1348–1358.
35. Kashparov, V.A. 1987. Director of Ukrainian Institute of Agricultural Radiology, National University of Life and Environmental Sciences of Ukraine. Pers. comm.
36. Kashparov, V.A. 2015. Director of Ukrainian Institute of Agricultural Radiology, National University of Life and Environmental Sciences of Ukraine. Pers. comm.
37. Kashparov, V.A., Ivanov, Yu.A., Zvarich, S.I. Protsak, V.P., Khomutinin, Yu.V., Kurepin, A.D., Pazukhin, E.M. 1996. Formation of Hot Particles During the Chernobyl Nuclear Power Plant Accident. *Nuclear Technology* **114**: 246–253.

38. Kashparov, V.A., Levtchuk, S.E., Otreshko, L.M., Maloshtan, I.M. 2013. Contamination of agricultural products by ^{90}Sr in Ukraine in the remote period after the Chernobyl accident. *Radiatsionnaya biologiya. Radioekologiya* **53**(6): 639–650. (in Russian)
39. Kashparov, V.A., Lundin, S.M, Kadygrib, A.M., Protsak, V.P., Levtchuk, S.E., Yoschenko, V.I., Kashpur, V.A., Talerko, N.M. 2000. Forest fires in the territory contaminated as a result of the Chernobyl accident: radioactive aerosol resuspension and exposure of fire-fighters. *Journal of Environmental Radioiactivity* **51**: 281–298.
40. Kashparov, V.A., Lundin, S.M., Khomutinin, Yu.V., Kaminsky, S.P., Levtchuk, S.E., Protsak, V.P., Kadygrib, A.M., Zvarich, S.I., Yoschenko, V.I., Tschiersch, J. 2001. Soil contamination with ^{90}Sr in the near zone of the Chernobyl accident. *Journal of Environment Radioactivity* **56**: 285–298.
41. Kashparov, V.A., Lundin, S.M., Zvarich, S.I., Yoschenko ,V.I., Levtchuk, S.E., Khomutinin, Yu.V., Maloshtan, I.N., Protsak, V.P. 2003. Territory contamination with the radionuclides representing the fuel component of Chernobyl fallout. *The Science of The Total Environment* **317**: 105–119.
42. Kashparov, V.A., Protsak, V.P., Khomutinin, Yu.V. 2015a. Report of UIAR of NUBiP of Ukraine "Radio-ecological study of the functional zone division of the exclusion zone to improve the efficiency of the activity of the removal of Chornobyl NPP and transformation the object of "Shelter" into an ecologically safe system". No 1–137–14, State code 015–97, code 1.2.10, 71pp. (in Ukrainian).
43. Kashparov, V.A., Zhurba, M.A., Kireev, S.I., Zibtsev, S.V., Myroniuk, V.V. 2015. Estimates of expected doses of fire brigades in the Chernobyl exclusion zone in April 2015. 2015. *Nuclear Physics and Atomic Energy*, **16**(4): 399 – 407.
44. Kashparov, V.O., Polischuk, S.V., Otreshko, L.M. 2011. Radiological problems of agricultural production on the contaminated as the result of the Chernobyl accident area in Ukraine. *Chernobyl Research Bulletin, Bulletin of Ecological State of the Exclusion Zone and Zone of an Unconditional (Obligatory) Resettlement* **2**(38): 13–30. (in Ukrainian)
45. Kauppinen, E.I., Hillamo, R.E., Aaltonen, S.H., Sinkko, K.T.S. 1986. Radioactivity size distributions of ambient aerosols in Helsinki, Finland, during May 1986 after the Chernobyl accident: preliminary report. *Environmental Science and Technology* **20**: 1257–1259.
46. Khomutinin, Yu.V. 2014. Evaluation of radioecological safety of fresh water reservoirs in Ukraine during late phase of ChNPP accident. *Nuclear Physics and Atomic Energy* **15**(4): 389- 401.
47. Khomutinin, Yu.V., Kashparov, V.A., Kuzmenko, A.V. Pavlyuchenko, V.V. 2013. Forecast of the dynamics and the risk of the exceeding the permissible content of ^{137}Cs and ^{90}Sr in fish in the Kiev reservoir fish during the late phase of the Chernobyl accident. *Radiatsionnaya biologiya. Radioekologiya* **53**(4): 411–427. (in Russian)
48. Khomutinin, Yu.V., Kashparov, V.A., Kuzmenko, A.V. 2011. Dependence of the accumulation coefficients of ^{137}Cs and ^{90}Sr by fish on potassium and calcium content in water of limnetic pond. *Radiatsionnaya biologiya. Radioekologiya* **51**(3): 374–384. (in Russian)
49. Khomutinin, Yu.V., Yoschenko, V.I., Kashparov, V.O., Levchuk, S.E., Glukhovskiy, O.S., Protsak, V.P., Lundin, S.M. 2007. Assessment of radiological danger of hypothetical forestfire in the Chernobyl exclusion zone. *Chernobyl Research Bulletin, Bulletin of Ecological State of the Exclusion Zone and Zone of an Unconditional (Obligatory) Resettlement* **1**(29): 28–33. (in Ukrainian)
50. Kolb, W. 1986. Radionuclide concentration in ground level air from 1984 to mid 1986 in North Germany and North Norway; influence of the Chernobyl accident. *Physikalisch-Technische Bundesanstalt* **PTB-Ra-18**: 53–56.
51. Krivokhatsky, A.S., Dubasov, Y.V., Smirnova, E.A., Skovorodkin, N.V., Savonenkov, V.G., Alexandrov, B.M., Lebedev, E.L. 1991. Actinides in the near release from the Chernobyl NPP accident. *Journal of Radioanalytical Nuclear Chemistry Articles* **147**: 141–151.

52. Kuriny, V.D., Ivanov, Yu.A., Kashparov, V.A., Loschilov, N.A., Protsak, V.P., Yudin, E.B., Zhurba, M.A., Parshakov, A.E. 1993. Particle associated Chernobyl fall-out in the local and intermediate zones. *Annals of Nuclear Energy* **20**: 415–420.
53. Legislation of Russia. Federal Law "On Social Protection of Citizens Exposed to Radiation as a Result of the Chernobyl Accident", 15 May 1991. http://pravo.gov.ru/proxy/ips/?docbody=&nd=102011440&rdk=&backlink=1 (in Russian)
54. Levchuk, S., Kashparov, V., Maloshtan, I., Yoschenko, V., Van Meir N. 2012. Migration of transuranic elements in groundwater from the near-surface radioactive waste site. *Applied Geochemistry* **27**(7): 1339–1347.
55. Levonevsky. On Legal Regime of Territories Affected to Radioactive Contamination as a Result of the Chernobyl Accident, Act of Republic of Belarus, on 12 November, 1991 No 1227-XII. http://pravo.levonevsky.org/bazaby/zakon/text56/index.htm (in Russian).
56. Lihtarov, I.A., et al. 2012. *General dosimetry certification and monitoring results of human radiation counters in the settlements contaminated after the Chernobyl accident. Data on 2011*. 14 Collection. Kyiv, 99 p. (in Ukrainian).
57. Lihtarov, I.A., et al. 2013. *General dosimetry certification and monitoring results of human radiation counters in the settlements contaminated after the Chernobyl accident. Data on 2012.* 15 Collection. Kyiv, 33 pp. (in Ukrainian)
58. Maloshtan, I., Polischuk, S., Khomutinin, Yu., Kashparov, V. 2015. Dynamics of ^{137}Cs uptake to herbaceous plants at the peat-bog soils with abnormally high radiocesium bioavailability. *Nuclear Physics and Atomic Energy* **16**(3): 263 — 272
59. Mattsson, R., Hatakka, J. 1986. Hot particle in inhalate air after the Chernobyl accident. Finnish Association for Aerosol research. *Report Series in Aerosol Science* **2**: 28–30.
60. Mining Awareness. Fires around Chernobyl Revive Nuclear Nightmare, April 2015. https://miningawareness.wordpress.com/2015/04/30/fires-around-chernobyl-revive-nuclear-nightmare/
61. Ministry for Emergency Situations of the Republic of Belarus 1994. The concept of the keep of Exclusion and Evacuation Zones. Approved by the Head of the State Chernobyl Committee of Belarus, I.A. Kenik on 6/7/94, Minsk, 94 pp. (in Russian).
62. Ministry of Ukraine of Emergencies 2011. Twenty-five Years after Chornobyl Accident: Safety for the Future. *National Report of Ukraine*, KIM, Kiev, 328 pp. ISBN 978–966–1547–64–2.
63. Møller A. P. 1998. Developmental instability of plants and radiation from Cher- nobyl. *Oikos* **81**: 444–448.
64. Møller A. P., Mousseaue T.A. 2007. Species richness and abundance of forest birds in relation to radiation at Chernobyl. *Biol. Lett*. **3**, 483–486.
65. Møller A. P., Mousseaue T.A. 2009. Reduced abundance of insects and spiders linked to radiation at Chernobyl 20 years after the accident. *Biol. Lett.* **5**, 356–359.
66. Møller A. P., Mousseaue T.A. 2011. Efficiency of bio-indicators for low-level radiation under field conditions. *Ecological Indicators* **11**: 424–430.
67. Møller A. P., Mousseaue T.A., Milinevsky G., Peklo A., Pysanets E., Szép T. 2005. Condition, reproduction and survival of barn swallows from Chernobyl. *Journal of Animal Ecology* **74**: 1102–1111
68. Møller A. P., Nishiumic I., Suzukid H.,, Uedab K., Mousseaue T.A. 2013. Differences in effects of radiation on abundance of animals in Fukushima and Chernobyl. *Ecological Indicators* **24**: 75–81.
69. Mousseaue T.A., Møller A. P. 2014. Genetic and Ecological Studies of Animals in Chernobyl and Fukushima. *Journal of Heredity* **105**(5):704–709.
70. National Committee on Radiation Protection 1988. The Limit for the Individual Life Dose Established for the Population of Controlled Areas of the RSFSR, the Ukrainian SSR and Byelorussian SSR, Contaminated as the Result of the Chernobyl Accident, Concept.of National Committee on Radiation Protection 22/11/1988. Approved by the Ministry of Health of the USSR.

71. Otreshko, L.N., Levchuk, S.E., Yoschenko, L.V. 2014. Concentration of ^{90}Sr in grain on fuel traces of the Chernobyl radioactive fallout. *Nuclear Physics and Atomic Energy* **15**(20): 171–177 (in Ukrainian)
72. Otreshko, L.N., Zhurba, M.A., Bilous, A.M., Yoschenko, L.V. 2015. ^{90}Sr and ^{137}Cs content in wood along the southern fuel trace of Chernobyl radioactive fallout. *Nuclear Physics and Atomic Energy* **16**(2): 183–192.
73. PL-2006, 2006. State hygiene standards GN.6.1.1–130–2006. Permissible levels of ^{137}Cs and ^{90}Sr in food and drinking water (PL-2006). 2006. *Ofitsiinyi visnyk Ukrayiny* **29**: 142. (in Ukrainian)
74. Radiation Safety Standards of Ukraine (RSSU-97). 1998. State Hygiene Norms, Kyiv. (in Ukrainian).
75. Radiological state of the territories referred to the radioactively contaminated zones. 2008. (ed. V.I. Kholosha). Veta, Kyiv, 54 pp. (in Ukrainian).
76. RSS-2000, 2000. Radiation Safety Standards of Belarus RSS-2000. State Hygiene Norms 2.6.1.8–127–2000, Minsk, Belarus (in Russian).
77. RSS-99/2009. Radiation Safety Standards RSS-99/2009. SanPin 2.6.1.2523–09. 2009. Rospotrebnadzor, Moscow. (in Russian).
78. Salbu, B., Krekling, T., Oughton, D.H., Ostby, G., Kashparov, V.A., Brand, T.L., Day, J.P. 1994. Hot Particles in Accidental Releases From Chernobyl and Windscale Nuclear Installations. *Analyst* **119**: 125–130.
79. Sanzharova N. 2015. Deputy Director for Research of the All-Russian Scientific-Research Institute Radiology and Agroecology. Pers. comm.
80. SAUEZ, 2015a. Official site of the State Agency of Ukraine for Exclusion Zone. http://dazv.gov.ua/anonsi/756-informatsijne-povidomlennya-pro-provedennya-kruglogo-stolu-na-temu-zona-vidchuzhennya-sogodennya-ta-majbutne
81. SAUEZ, 2015b. Official site of the State Agency of Ukraine for Exclusion Zone. /http://dazv.gov.ua/news/770-urochista-peredacha-insineratora/
82. Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2000. *Sources and Effects of Ionizing Radiation (Report to the General Assembly)*. United Nations, New York.
83. Smith J. T. 2008. Comment. Is Chernobyl radiation really causing negative individual and populationlevel effects on barn swallows? *Biol. Lett.* **4**, 63–64.
84. SSSAR-2005, 2005. Sanitary standard of specific activity of radionuclides ^{137}Cs and ^{90}Sr in wood and products of wood. Approved by the Ministry of Health of Ukraine, Decree No 73 on 31/10/2005, 3 pp. (in Ukrainian)
85. Steinhauser G., Brandl A., Johnson T. E. 2014. Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts. *Science of the Total Environment* **470–471:** 800–817.
86. Stohl A., Seibert P., Wotawa G. 2012. The total release of xenon-133 from the Fukushima Dai-ichi nuclear power plant accident. *Journal of Environment Radioactivity* **112**:155–159.
87. Talerko, N.N. 1990. Calculation of radioactive admixture release from the accidental unit of Chernobyl power plant. *Meteorology and hydrology* **10**: 39–46. (in Russian)
88. The Academy of Sciences of the USSR 1992. The Concept of Population Habitation in Areas Affected by the Chernobyl Accident. 1992. Decree number 164 of April 8, 1991 Approved by the Cabinet of Ministers, *Nuclear power. Questions and answers*. 48 pp.
89. The Atlas of recent and predictable aspects of consequences of Chernobyl accident on polluted territories of Russia and Belarus (ARPA Russia-Belarus). 2009. (eds. Yu.A. Izrael & I.M. Bogdevich). Foundation "Infosphere" - NIA-Nature, Moscow-Minsk, 140 pp.
90. The Catalog of average annual effective doses at inhabitants living on contaminated territories of the Republic of Belarus. 2015. Approved by the Ministry of Health of the Republic of Belarus on 08/18/2015. Repablican Scientific Center for Radiation Medicine and Human Ecology, Gomel, 86 pp.
91. Tsybulko N.N. 2015. Deputy Head of Department in the aftermath of the Chernobyl disaster Ministry of Emergency Situations of the Republic of Belarus. Pers. comm.

92. UIAR, 2015. Official site of the Ukrainian Institute of Agricultural Radiology. http://www.uiar.org.ua/
93. Ukrainian radiation protection society. Problems of revival in conditions of post-Chernobyl syndrome. 3/17/2014. http://urps-notices.blogspot.com/2014/03/problemy-vidrodzhennja-v-umovakh-postchornobyljskogho-syndromu.html (in Ukrainian)
94. United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR, 2008. 2011. *Sources and effects of ionizing radiation.* Report to the General Assembly with Scientific Annexes, vilume II, Annex D. Health effects due to radiation from the Chernobyl accident. United Nations, New York, 178 pp.
95. Verkhovna Rada of Ukraine. On Amendments and Ceasing to be Invalid Some Legislative Acts of Ukraine. 2015. *Bulletin of Verkhovna Rada* **6:** Paragraph 40. http://zakon5.rada.gov.ua/laws/show/76–19 (in Ukrainian).
96. Verkhovna Rada of Ukraine. On the Concept of the Population Habitation in the Territory of the Ukrainian SSR with Elevated Levels of Radioactive Contamination from the Chernobyl Accident. Resolution of the Supreme Soviet on 27 February, 1991 No 791-XII. 1991. *Bulletin of Verkhovna Rada* **16**: paragraph 197. http://zakon3.rada.gov.ua/laws/show/79http://zakon3.rada.gov.ua/laws/show/791-121–12 (in Ukrainian).
97. Verkhovna Rada of Ukraine. On the Legal Regime of the Territories Exposed to Radioactive Contamination in Consequence of the Catastrophe at the Chernobyl NPP. The Law of Ukraine is being entered into force by the Supreme Council Decree No 795–12 of the Supreme Soviet on 28/02/91. 1991. *Bulletin of Verkhovna Rada* **16**: paragraph 199. http://zakon2.rada.gov.ua/laws/show/791%D0%B0–12 (in Ukrainian).
98. Verkhovna Rada of Ukraine. On the Status and Social Protection of Citizens Suffered from the Chernobyl Disaster, the Law of Ukraine is being entered into force by the Supreme Council Decree No 797–12 of the Supreme Soviet on 28/02/91. 1991. *Bulletin of Verkhovna Rada* **16**: paragraph 201. http://zakon5.rada.gov.ua/laws/show/796–12 (in Ukrainian).
99. Verkhovna Rada of Ukraine. Resolution of Cabinet of Ministers of Ukraine number 106 on 23 July, 1991 Appendix 1. *The list of the settlements referred to the radioactively contaminated zones after the Chernobyl accident*. http://zakon5.rada.gov.ua/laws/show/600–94-%D0%BF/page (in Ukrainian).
100. Verkhovna Rada of Ukraine. Resolution of Cabinet of Ministers of Ukraine number 662 on 12 May 2004, 2004. Official site http://zakon5.rada.gov.ua/laws/show/622–2004-%D0%BF
101. Watanabe, Y., Ichikawa, S., Kubota, M., Hoshino, J., Kubota, Yo., Maruyama, K., Fuma, Sh., Kawaguchi, I., Yoshenko, V.I & Yoshida, S. 2015. Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant. Scientific Reports 5, doi: 10.1038/srep13232. http://www.nature.com/srep/.
102. Yoschenko, V., Kashparov, V, Melnychuk, M., Levchuk, S., Bondar, Yu., Lazarev, M., Yoschenko, M., Farfán, E., Jannik, G. 2011. Chronic irradiation of Pinus sylvestris in the Chernobyl exclusion zone: dosimetry and radiobiological effects. Health Physics 101: 393–408.
103. Yoschenko, V.I., et al. 2006a. Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part I. Fire experiments. Journal of Environmental Radioactivity 86(2): 143–163.
104. Yoschenko, V.I., Kashparov, V.A., Levchuk, S.E., Glukhovskiy, A.S., Khomutinin, Yu.V., Protsak, V.P., Lundin, S.M., Tschiersch, J. 2006b. Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part II. Modeling the transport process. Journal of Environmental Radioactivity 87(3): 260–278.