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STUDY OF THE CONSEQUENCES OF THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT: 35th ANNIVERSARY

The Chernobyl Nuclear Power Plant Accident: Countermeasures and Remedial Actions in Agriculture

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Abstract—A wide range of countermeasures and remedial actions has been developed and used to mitigate the consequences of the Chernobyl accident. This article summarizes the basic information on the application of countermeasures in agriculture over the 35 years after the accident and provides data on their effectiveness. The experience of using agricultural remedial measures and their influence on the radiological situation in different periods after the accident are analyzed. The most important aspects are highlighted, and the necessity of using the aftermath experience for improving emergency response systems in agriculture for potential emergencies is demonstrated.

Keywords: Chernobyl Nuclear Power Plant, agriculture, consequences, countermeasures, remediation, public exposure

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The accident at the Chernobyl Nuclear Power Plant (NPP) is the most serious radiation accident in the history of nuclear power development. It resulted in contamination of a significant area; in particular, the ^{137}Cs contamination density was over 37 kBq/m^2 on an area of over 150 000 km^2 [1]. The Chernobyl Nuclear Power Plant (ChNPP) is located in an intensive farming area; therefore, the accident had an extremely serious impact on the economy and population of rural areas in the three most heavily affected countries: Ukraine, Belarus, and Russia. The high contamination densities made it necessary to terminate or restrict the production of agricultural products over a large area. The accidental release included ecologically mobile radionuclides, such as isotopes of radioactive iodine, radioactive strontium, and radioactive cesium, two of which (^{90}Sr and ^{137}Cs) are characterized by sufficiently long half-lives (29.1 and 30.2 years, respectively) to have long-term effects on agriculture.

A typical feature of the affected areas is the dominance of low fertility sandy and peat soils, which are characterized by a high transfer of radioactive cesium to plants and then to livestock products. Since the accident occurred in the second half of the spring season, its impact on agriculture was extremely high; during this time, farm animals were grazed and there were almost no uncontaminated forage reserves that could be used as an alternative to green fodder. The consumption of contaminated food products was and still remains one of the main pathways of radiation doses to the population of the affected areas [2–8].

Radiocesium was the main dose-forming radionuclide in the Chernobyl accident zone, except for the short period immediately after the accident, when the main role was played by short- and medium-lived radionuclides. The ^{90}Sr concentrations in soil were and remain rather important for providing safe farming only in the 30-km zone around the Chernobyl NPP, where the economic activity was stopped, and in small areas outside this zone (Ivankovskii district, Ukraine, and Khoiniki district, Belarus) [7, 11, 12]. Therefore, the estimates of the radiological consequences of accidental releases from the Chernobyl NPP, as well as the planning and implementation of countermeasures, were based on information about the ^{137}Cs concentrations in the environment and trends in its change. At the same time, some countermeasures were developed and applied to decrease the ^{90}Sr transfer to products and made it possible to reduce its concentration by 2–4 times in grass and by approximately two times in grain after the radical improvement of fodder lands and use of mineral fertilizers, respectively [10].

The combination of these factors has determined the severity of the consequences of the accident, as well as the importance of agricultural countermeasures as one of the main elements of the strategy of response and remediation of the affected regions. Countermeasures were taken in all sectors of the agroindustrial complex: from crop and livestock management to processing of agricultural and food products.

Under conditions of the economic and social constraints characteristic of the early 1990s, the main task of countermeasures after the accident was to preserve the potential of agricultural production, taking into account the corresponding permissible levels of contamination in the food and the requirements for the radiation protection of the population. This task was also important for maintaining the social and psychological stability of the rural population, since the production of safe food products reduced the level of stress for the population living in the affected areas [11].

In recent years, many reviews of the use of countermeasures and remedial actions in agriculture have been made [10–17]. The purpose of this article was to analyze critically the effectiveness of countermeasures and remedial actions that were carried out in the affected regions after the Chernobyl accident, as well as their effect on the mitigation of the consequences of the accident for agriculture and the rural population.

ZONING OF CONTAMINATED AREAS

The organization and management of agricultural production in all periods after the accident were based on the determination of territories (areas) that were considered to be contaminated. Based on the preliminary knowledge about the behavior of radionuclides, the external demarcation of the "contaminated" area was established by a ^{137}Cs contamination density of 1 Ci/km^2 (37 kBq/m) [1, 9]. Areas with a contamination density of less than 37 kBq/m^2 were officially considered "uncontaminated." Based on this gradation, the proportion of contaminated areas was 3.2% of the territory of the European part of the Soviet Union.

Five regions of Belarus, 22 regions of Russia, and 12 regions of Ukraine were officially recognized as regions affected after the Chernobyl accident. To a certain extent, the large number of regions in Russia reflects the size of the country combined with the policy of inclusion of even those regions where insignificant areas with ^{137}Cs deposition densities above 37 kBq/m^2 were recorded. The highest levels of contamination of agricultural lands were reviled in three regions of Belarus (Gomel, Mogilev, and Brest regions), five regions of Ukraine (Kiev, Zhitomir, Rivne, Volyn, and Chernigov regions), and four regions of Russia (Bryansk, Kaluga, Tula, and Orel regions). Over 15000 settlements with a population of about six million people were located in areas with a ^{137}Cs contamination density above 37 kBq/m^2. The most affected areas on territories with contamination densities above 555 kBq/m^2 included 640 settlements with a population of about 230000 people.

CRITERIA OF POPULATION SAFETY AND PERMISSIBLE LEVELS OF RADIONUCLIDES IN AGRICULTURAL PRODUCTS

According to the Radiation Safety Standards [18], which entered into force in 1986, the USSR Ministry of Health introduced a temporary limit of the average equivalent dose to the entire body of a resident: 100 mSv during the first year after the Chernobyl release (from April 26, 1986, to April 26, 1987), 30 mSv during the second year, 25 mSv in 1988, and 25 mSv in 1989 [18]. On the whole, the maximum permissible dose to the population before January 1, 1990, was 173 mSv.

Temporary permissible levels (TPLs) for the concentration of radionuclides in food products were developed to limit the internal exposure of the population in the Soviet Union and later in Belarus, Russia, and Ukraine (Table 1).

The first TPLs approved by the USSR Ministry of Health on May 6, 1986, concerned the limitation of the content of ^{131}I in products as the dominant factor of internal human exposure in the early period of the accident and were focused on limiting radiation doses to the thyroid glands of children. The TPLs accepted on May 30, 1986, limited the concentrations of all β-emitters in food products due to surface contamination. Later TPLs introduced in 1988 (TPL-88) and 1991 (TPL-91) concerned the sum of activity of ^{134}Cs and ^{137}Cs. TPL-91 was supplemented with restrictions on the concentrations of ^{90}Sr in food. This was followed by the introduction of sanitary regulations and standards (SanPiN), which were considered as nonemergency standards [25, 26] and valid throughout the Russian Federation.

The annual consumption of routine food by residents of rural settlements would cause an internal dose of less than 50 mSv if all food components contained cesium radionuclides at TPL-86, less than 8 mSv at TPL-88, and less than 5 mSv at TPL-91.

The general policy of the Soviet Union and then the policy of the regulatory bodies of the CIS were aimed at reducing both the radiological criteria and TPLs along with the improvement in radiological conditions because of the decay of radionuclides. The gradual decrease of TPLs was a factor determining certain conditions for farmers, which were obliged to use technologies ensuring the safe concentration of radionuclides in their products. The decrease of TPLs was focused primarily on reducing internal irradiation doses to the population; at the same time, it also took into account the possibility of managing agriculture and forestry in the contaminated areas. In some cases, restrictions resulted in unjustified losses in food production and influenced economic recovery processes in the affected areas.

Table 1. Temporary permissible levels (TPLs, Bq/kg, Bq/L) of radionuclide concentrations in basic food and drinking water, established in the Soviet Union (1986–1991) and the Russian Federation after the Chernobyl Accident [18–26]

TPL/PL	4104–88	129–252	TPL-88	TPL-91		PL 2001	
Date of approval	May 6, 1986	May 30, 1986	December 15, 1987	January 22, 1991		November 14, 2001	
Radionuclide	^{131}I	Σ β-emitters	$^{134+137}Cs$	$^{134+137}Cs$	^{90}Sr	^{137}Cs	^{90}Sr
Drinking water	3700	370	18.5	18.5	3.7	11	4.9
Milk	370–3700	370–3700	370	370	37	100	25
Dairy products	18 500–74 000	3700–18 500	370–1850	370–1850	37–185	50–200	25–100
Child nutrition	–	–	370	185	3.7	40	25
Meat and meat products	–	3700	1850–3000	740	–	200	–
Fish	37 000	3700	1850	740	–	130	100
Vegetables, fruits, potatoes, and root crops	–	3700	740	600	37	80	40
Bread, flour, and cereals	–	370	370	370	37	40–60	20–30

After the collapse of the Soviet Union in 1991, Belarus, Russia, and Ukraine pursued their own policies of radiation protection of the population and countermeasures in agriculture. At the same time, after the adoption of the annual limit of the effective dose rate to the population in practice (1 mSv) by the International Commission on Radiological Protection (ICRP) in 1990 [27], this level was also recognized as safe in post-emergency conditions [18]. Therefore, in the legislation of the Russian Federation, it is still used as a criterion for justifying the system of long-term remedial actions.

COUNTERMEASURES IN THE FIRST PERIOD AFTER THE ACCIDENT

The system of agricultural management at the time of the accident can be divided into two groups: large collective farms (kolkhozes and state farms) and the private sector. Collective farms used crop rotations and scientifically grounded systems of soil cultivation and agromelioration (mineral and organic fertilization, liming, application of dolomite powder, etc.) in agriculture. Special diets were developed for feeding animals and improved hayfields and pastures were created for forage preparation. In the private sector, the use of mineral fertilizers was not systematic and organic fertilizers (manure) were widely used. Private livestock was usually grazed in natural meadows, forest edges, etc. These differences led to a higher accumulation of radionuclides in products produced in personal subsidiary farms than their level in collective farms.

The accident occurred in the most vulnerable season in terms of impact of radioactive contamination on agriculture. Farm animals were already on grazing lands and it was hardly possible to prevent or reduce the contamination of livestock products due to lack of uncontaminated feed. In the first days and weeks after the accident, the concentrations of radiologically significant radionuclides were much higher than the national and international standards limiting the content of radionuclides in food products [4, 7, 28].

During the first weeks after the accident, ^{131}I was the main radionuclide that determined internal radiation doses. Other radionuclides (^{95}Zr, ^{95}Nb, $^{103/106}Ru$, ^{140}Ba and ^{140}La, and $^{141/144}Ce$) had little effect, since they have short half-lives. From June 1986, radioactive cesium prevailed in most of the environmental samples (except the 30-km zone of the ChNPP) and food samples [7].

The main goal of countermeasures in the first period was to limit (or prohibit) the consumption of contaminated milk for the population and reduce the concentration of ^{131}I in milk [10]. In the most contaminated areas, one of the priority measures was to provide the population (in particular, children) with milk imported from "clean" regions. The use of countermeasures was mainly aimed at reducing the levels of contamination of milk produced in the public sector. Recommendations on implementation of agricultural countermeasures included the following options [28, 29]:

• elimination of contaminated pasture herbage from the diet of animals by their transition from pasture management to housing;

• radiation monitoring and quality inspection of milk to discard products with the ^{131}I concentrations exceeding the permissible levels (3700 Bq/L); and

• milk processing to lower its contamination and production of products corresponding to TPLs (dry and condensed milk, butter, cheeses, etc.).

In some areas, the iodine transfer to milk led to the formation of high radiation doses due to the delay with application of restrictive and protective measures and became one of the main reasons of thyroid cancer [7, 11, 12].

According to the decision of the Soviet Government on the evacuation of the population from the 30-km zone around the Chernobyl NPP (from May 2, 1986), about 50000 cattle head, 13000 pigs, 3300 sheep, and 700 horses were evacuated together with the population [7]. Some of the animals were subsequently slaughtered due to lack of forage and management problems in the areas into which they were evacuated [7, 12, 30]. The animal carcasses were buried; however, some of them were stored in refrigerators, which made it necessary to solve sanitary and hygienic issues and caused economic losses [7]. The total number of slaughtered animals from May to July 1986 reached 95500 head of cattle and 23000 pigs.

Feeding animals with clean feeds would be very effective for reducing the concentration of ^{137}Cs in products to the acceptable level within 1–2 months. However, this countermeasure was not widely used in the first period, mainly due to the lack of uncontaminated feed at the end of the period of animal housing [12].

The first maps of the radioactive deposition density in the contaminated areas were compiled in early June 1986. This made it possible to assess the levels of contamination of pastures and determine the lands where it was impossible to obtain milk corresponding to the TPLs [11]. These data served as a basis for introducing a ban on the maintenance of dairy cattle. Radiation control was introduced at all stages of production, storage, and processing of agricultural and food products [4].

Based on a radiological survey, about 130000, 17300, and 57000 ha of agricultural lands were excluded from economic use in Belarus, Russia, and Ukraine, respectively [7]. The criterion of land exclusion from economic use was the exceeding of the ^{137}Cs deposition density (1480 kBq/m^2). The following recommendations and countermeasures to reduce the input of ^{137}Cs into agricultural products were proposed for areas with a contamination density of over 185 and 555 kBq/m^2 [4]:

• exclusion of some technological operations during soil treatment and harvesting to reduce dust formation;

• application of increased doses of potassium–phosphorus fertilizers;

• radical improvement of hayfields and pastures;

• limiting the use of organic fertilizers, in particular, contaminated manure;

• feeding animals with clean feeds for 1.5 months before slaughter;

• limiting the consumption of milk produced in the private sector; and

• compulsory radiation control of agricultural products.

Decontamination, which includes the removal of the upper contaminated layer, was not included in agricultural measures due to its high cost, the disturbance of soil fertility, and problems related to the disposal of contaminated soil [4, 7].

PROTECTIVE MEASURES AT THE INTERMEDIATE AND RECOVERY STAGES AFTER THE ACCIDENT

Recommendations for the application of countermeasures have been revised and updated several times [32–36], depending on changes in the radiation situation, tightening of standards for the concentration of radionuclides in products, and the economic situation.

Agrochemical and Agrotechnical Measures

A set of agrochemical and agrotechnical (soil based) measures was used on arable lands; these measures included tillage (standard or real tillage), liming (with the addition of elevated lime doses, taking into account soil contamination levels), and addition of mineral fertilizers (with increased phosphorus and potassium doses) [4, 10]. The volumes of agrochemical and agrotechnical measures after the Chernobyl accident are given in Fig. 1.

During the remediation of contaminated areas, priority attention was given to the use of agrotechnical technologies for radical and surface improvement of hayfields and pastures to obtain fodder meeting the veterinary radiological requirements [31].

Ploughing is a technological method that was widely used in contaminated areas. Ploughing leads to the redistribution of radionuclides in the arable soil layer and a decrease in the concentration of radionuclides in the soil layer where plants receive mineral nutrition. It was possible to carry out real ploughing and deep ploughing (deeper than the standard arable layer) only in areas with fertile soils having a deep humus horizon. The multiplicity of the decrease in the coefficients of transfer of radionuclides to plants varied from two (normal ploughing) to 15–20 times (deep ploughing), and this effect persists for many years [4, 5, 10–14, 17].

Liming was applied on soils with low acidity, which are widespread in the most contaminated regions. Since the transfer of radionuclides to plants depends on soil acidity, liming maintains the soil solution reaction at a level close to the neutral one, thereby providing the minimum values of the coefficient of ^{137}Cs transfer to plants. Based on studies at the Russian

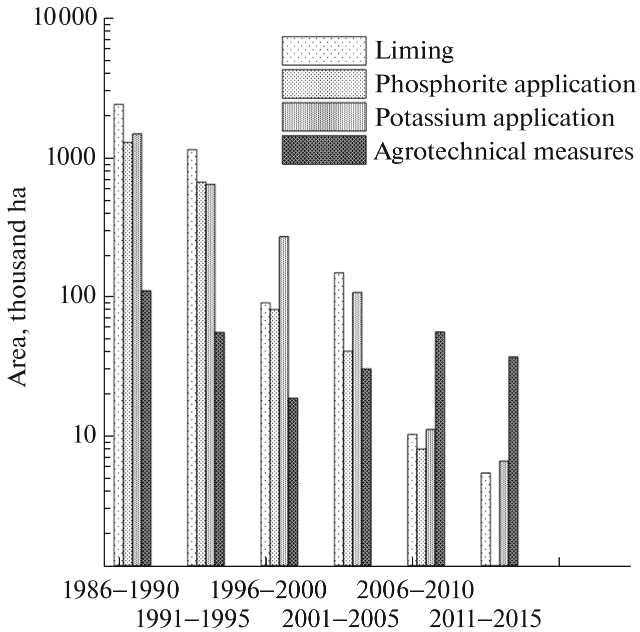

Fig. 1. Extent of agrochemical and agrotechnical measures implemented in Russia after the Chernobyl accident.

Institute of Radiology and Agroecology [31, 32], the doses of ameliorants were increased by an average of 1.5 times, depending on the soil properties and the crop species, and made it possible to reduce the input of radionuclides to plants by 1.5–4.0 times.

Mineral fertilizers were also widely used to reduce the accumulation of ^{137}Cs in agricultural crops; this option primarily concerns potassium fertilizers, since the decrease of the transfer of radionuclides is based on a decrease in the Cs : K ratio in the soil solution [7]. The optimal N : P : K ratio, determined by previous scientific studies and field tests, was 1 : 1.5 : 2 [23].

The radical improvement of fodder lands, which included sod disking, ploughing, liming, fertilization, and sowing of grass mixtures, proved to be a very effective measure and made it possible to decrease the input of radiocesium into the herbage by up to 2–3 times on mineral soils and by up to 3–5 times on organic soils. The effectiveness of the technology depends on the type of meadow and soil properties [37, 38]. One limiting factor is that radical improvement cannot be used on steep slopes and in river floodplains. In these cases, surface improvement is used; it includes disking, fertilization (at an N : P : K ratio of 1 : 1.5 : 2), liming, and overgrassing.

Change in the Land Use

Farming in contaminated areas is based on a scientifically grounded land use, which determines the location and ratio of different land areas (natural and cultural pastures and hayfields, arable lands, fallow lands, orchards, etc.). The transfer coefficients of radionuclides can differ by up to 100 times or more for different species of cultivated crops [7, 10, 39]. Therefore, the contamination of agricultural products depends both on the type of soil and on the type of land use. Estimates of the ^{137}Cs deposition density at which the radionuclide content in agricultural products produced on different types of lands in 1994 would not exceed TPL-93 can are given in Fig. 2 as an example.

Significant differences in the possibility of obtaining products corresponding to the TPLs on agricultural lands of different types open up the potential for optimizing the structure of land use by planting crops

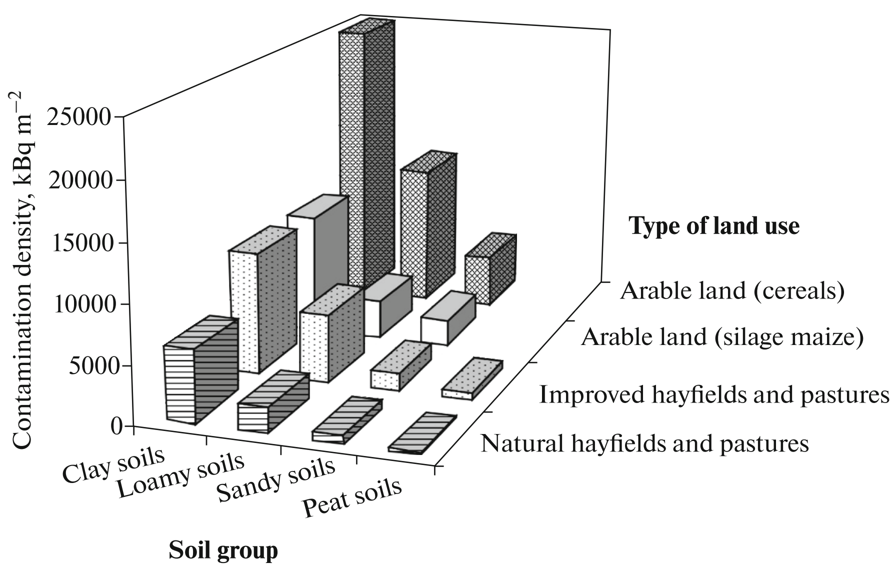

Fig. 2. Deposition densities at which it is possible to obtain products meeting the TPL 93 requirements.

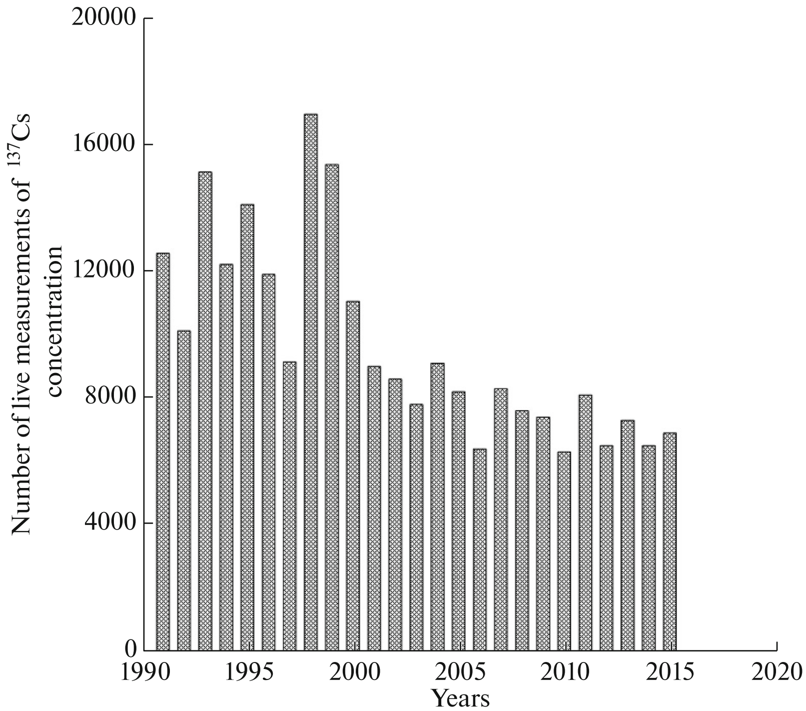

Fig. 3. Number of live measurements of ^{137}Cs concentrations in animals after the ChNPP accident in Russia.

with a low accumulation of radionuclides in areas with higher levels of contamination and crops with a high accumulation of ^{137}Cs in areas with a lower deposition density.

A promising option is the use of contaminated lands for cultivating industrial crops. Thus, rape was sown in Belarus on the most contaminated agricultural lands; its seeds were processed into edible oil, fuel, and protein oil cake for feeding animals [40]. The production of rapeseed oil proved to be an effective, economically viable way of using contaminated lands.

Feeding Animals with Clean Feeds

The purpose of feeding animals with clean feeds, i.e., feeds that are not contaminated with radionuclides (or with a low level of their content), is to prevent the f radionuclides transfer to farm animals and the resulting products (milk and meat). This measure is particularly effective during the fattening of beef cattle prior to their slaughter. In areas contaminated as a result of the Chernobyl accident, the effectiveness of this technology and duration of its application were monitored by in vivo measurements of the ^{137}Cs concentration in the body of farm animals. Over 447000 live monitoring measurements were carried out to justify the maintenance of animals on clean feeds and prevent the slaughter of livestock with higher ^{137}Cs concentrations in muscles than the TPL over the period from 1986 to 2000. This made it possible to avoid significant losses during meat production in the contaminated areas (Fig. 3).

The extent of application of the technology of feeding animals with clean feeds consistently increased in 1986–1992, reaching 55000 to 75000 head of cattle in the Russian Federation. In 2000–2008, the number of cattle treatments decreased to 5000–20000 head.

Use of Cesium Binders

When the technology for using cesium-binding sorbents in the gastrointestinal tract (GIT) of animals was developed in 1994, this type of countermeasures became one of the most common methods for producing livestock products (milk and meat) meeting the standards for areas with high contamination levels.

The development of this technology was accompanied by studying the effectiveness of using different sorbents, which were used in the form of chemical compounds or clays added to the diet components or introduced in the form of boluses allowing for the slow release of the sorbent in the GIT. Studies showed a high efficiency of ferrocin (hexanoferrate) compounds as radioactive cesium binders [7, 41, 42]. The use of ferrocin reduced the ^{137}Cs content in livestock products by up to 3–5 times or more [42]. All the forms of hexaferrocyanide compounds have a low toxicity and were therefore safe for the animals. The number of cattle treatments based on annual use of ferrocin in different forms is shown in Fig. 4.

The use of ferrocin was particularly effective in rural settlements where it was impossible to provide improved pastures for private livestock. Ferrocin was widely used in Russia and Belarus. In Ukraine, its use was very limited due to the very high cost of its preparations purchased from Western Europe. Instead, locally available clay minerals were used in small amounts here. They are less effective than ferrocin; however, their use was cheaper [7].

Processing of Agricultural Products

After the Chernobyl accident, technologies for processing agricultural products were developed and successfully introduced in the food processing industry, which made it possible to reduce the concentration of radionuclides in the final products. A set of methods for milk processing made it possible to decrease the concentrations of ^{90}Sr and ^{137}Cs in dairy products (butter, cheeses, and powdered and condensed milk) by 7—10 times compared to the initial level.

It was shown that the use of standard methods of product processing in the food industry makes it possible to produce a number of food products (starch, vegetable oil, alcohol, etc.) meeting the sanitary and hygiene requirements. One should particularly emphasize the high efficiency of processing agricultural products in the acute phase after the accident.

EFFICIENCY OF COUNTERMEASURES AND REMEDIAL ACTIONS IN AGRICULTURE

The application of countermeasures and remedial actions in agriculture pursued three main goals: (1) to ensure the production of food products meeting TPLs, (2) to reduce radiation doses to the population to the level of less than 1 mSv as soon as possible, and (3) to minimize the collective doses to the population based on the ALARA principle.

Reducing the Contamination of Agricultural Products

According to radiation monitoring data, large volumes of products in which the concentration of radionuclides exceeded the TPL for ^{137}Cs were revealed in four regions of Russia (Bryansk, Tula, Kaluga, and Orlov regions) from May 1986. In the most contaminated areas of Bryansk region, the fraction of grain, milk, and meat with concentrations of radiocesium higher than of the TPL reached 80% or more during the first year after the accident (Fig. 5) [38, 41].

Since 1987, high concentrations of radioactive cesium in agricultural products, mainly livestock products, and application of countermeasures to reduce ^{137}Cs concentrations in milk and meat became the key areas of the agricultural remediation strategy. The large-scale use of a number of countermeasures made it possible to achieve a sharp reduction in the amount of animal products with radioactive cesium concentrations above TPLs. The radiocesium concentrations in grain, potatoes, and root crops were rather low in most of the contaminated areas. By 1991, the fraction of grain with ^{137}Cs exceeding 370 Bq/kg was less than 0.1% (Fig. 5).

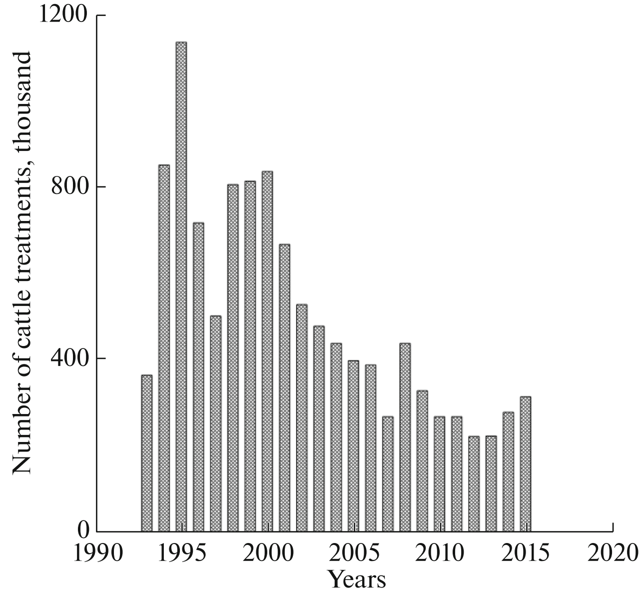

Fig. 4. Number of cattle treatments with ^{137}Cs binding sorbents.

After 2001, the fraction of grain with the ^{137}Cs concentration exceeding the TPLs increased due to the toughening of TPLs for the ^{137}Cs concentration in grain (not more than 160 Bq/kg), as well as due to the decrease in the volume of remedial actions, and reached about 20% in the most contaminated areas.

The maximum effect from the application of countermeasures in agriculture was achieved in the years 1986—1992. The application of countermeasures in the affected areas (mainly the radical improvement and transition to "clean" feeding) led to a consistent decrease in the levels of contamination of livestock products. Since 1991, the proportionfraction of products with cesium concentrations exceeding the TPLs has been less than 10% of the gross volume of products obtained in the contaminated areas.

In the mid-1990s, the use of countermeasures in crop production (application of mineral fertilizers, liming, and agrotechnical measures) was reduced due to the economic problems. At the same time, the optimization of the available resources provided sufficient effectiveness of countermeasures against ^{137}Cs contamination to maintain an acceptable concentration of ^{137}Cs in most livestock products (Fig. 5).

Assessment of the effectiveness of remedial actions in the post-accident period should take into account the decrease in product contamination not only as a

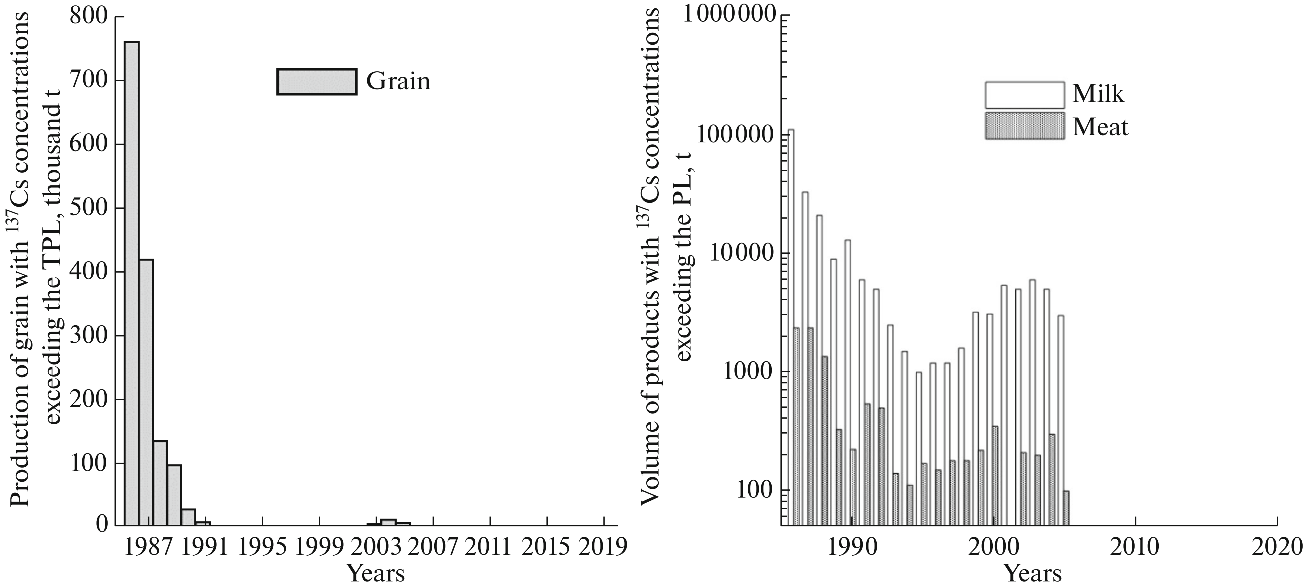

Fig. 5. Production of grain, milk, and dairy products with radiocesium concentrations exceeding the TPL.

result of remedial actions, but also as a result of physical decay and the gradual fixation of radionuclides in the soil, i.e., the decrease in their bioavailability for inclusion in food chains. The rates of decrease in the concentration of ^{137}Cs in food products (in particular, milk) also significantly differed between the affected areas in the course of time after the accident. This was largely determined by the allowable volumes of radical improvement of hayfields and pastures, which was carried out stage by stage, taking into account the number of animals and area of forage lands required for their maintenance. The effectiveness of agricultural countermeasures to reduce the concentration of ^{137}Cs in the main food products increased from 1987 to 1992, the period when measures were taken in the affected areas in the required amounts. The ecological period of decrease in ^{137}Cs concentrations in milk (T_{ec}) calculated for 1987–1992 was significantly shorter in Bryansk region (1.0–2.8 years), where countermeasures were started earlier and on a large scale, than in Kaluga region (2.3–4.8 years), where the main contribution to the decrease in ^{137}Cs content in products was made by natural biogeochemical processes determining the binding of radionuclides in soils and a decrease in their mobility [41].

Assuming that the decrease in the ^{137}Cs concentration in food products was determined by the influence of three groups of factors (natural biogeochemical processes, countermeasures, and radioactive decay), the contribution of each of these factors was estimated for areas with different rates of application of countermeasures (Table 2).

From 1987 to 1994, the contribution of countermeasures to the reduction of contamination of agricultural products in regions with intensive application of countermeasures was 60%. In regions with limited use of countermeasures, natural biogeochemical processes contributed most significantly to reducing the contamination of products with ^{137}Cs (up to 70%).

Table 2. Contribution of factors determining the reduction of the ^{137}Cs concentration in agricultural products in Russian regions contaminated as a result of the ChNPP accident [41]

Factors	Areas with intensive use of countermeasures (Bryansk region)		Areas with limited use of countermeasures (Kaluga region)	
	milk and meat	potatoes and grain	milk and meat	potatoes and grain
Natural biochemical processes	0.33	0.36	0.60	0.73
Countermeasures	0.61	0.57	0.28	0.12
Radioactive decay	0.06	0.07	0.12	0.15

Effectiveness of Remedial Actions to Reduce Radiation Doses to the Population

The use of countermeasures and remedial actions in agriculture after the Chernobyl accident led to a significant decrease in both individual and collective radiation doses to the local population. In 1991–1999, the use of countermeasures made it possible to reduce the annual effective doses by an average of 22% for the rural population living in the zone with a radioactive contamination density of 185–370 kBq/m^2, by an average of 32% for the population living in the zone with a contamination density of 370–55 kBq/m^2, and by over 40% in human settlements with contamination of over 555 kBq/m^2 [43].

Assessment of the averted collective dose after the application of countermeasures in agriculture is a rather difficult problem and requires data on both the use of countermeasures and use of food products/feeds produced in contaminated areas. In addition, the countermeasures were carried out in both the private and public sectors, which influenced the reduction of radiation doses to both the rural and urban populations. Estimates of the averted dose based on the approach proposed in [43] showed that the averted dose after the application of countermeasures in the private sector of rural settlements in Belarus and Russia was 7300 man-Sv during the 20 years after the accident. The main contribution to the averted collective dose (5500 man-Sv) in the rural population was made by the most contaminated Gomel and Bryansk regions.

Food products produced in the collective sector are consumed mainly by the urban populations living in both contaminated and uncontaminated areas. Taking into account the export of products from the contaminated regions, it was shown that about a half of the averted internal collective dose (7500 man-Sv in the Russian Federation) was determined by the use of countermeasures in collective farms. These results are consistent with the conclusions of the IAEA Chernobyl Forum [7], where the internal radiation doses to the population in contaminated areas (taking into account the effect of countermeasures) for the same time period were estimated at 6000 man-Sv for the Russian Federation. Therefore, the averted dose using agricultural countermeasures was about 55% of the internal radiation dose that could be obtained without using countermeasures and remedial actions in agriculture.

The main factors contributing to the reduction in the collective dose were countermeasures in animal husbandry, since milk contributed most significantly to the internal exposure of the population after the Chernobyl accident. In Bryansk region, these countermeasures contributed 65–75% of the total averted dose [8, 44].

Despite the significant improvement in the radiation situation in the contaminated areas 35 years after the accident, there are still rather large areas of agricultural lands where the production of agricultural products does not meet the sanitary, hygienic, and veterinary requirements. The fraction of such products does not exceed 10% and is recorded in the most contaminated areas of Bryansk region. However, these areas cannot be considered fully remediated and it is necessary to justify the long-term strategy for carrying out the necessary agricultural activities.

In addition, several tens of thousands of people still live in settlements with an annual effective dose of over 1 mSv, where measures to protect the population must be taken. The time change in the number of settlements and residents of contaminated areas who may potentially receive annual effective doses above 1 mSv is shown in Fig. 6.

It is obvious that the use of remedial actions on a limited scale will remain necessary for at least several decades (until 2045–2050), and it is necessary to continue the application of measures to remediate the contaminated areas to optimize their use in the long term after the accident. After 2050, radiation doses exceeding 1 mSv can occur only in abandoned areas excluded from economic use.

PLANNING OF REMEDIAL ACTIONS IN THE LONG TERM AFTER THE ACCIDENT

The planning of remedial actions in the long term after the Chernobyl accident should take into account factors that are specific to individual settlements, regions, and countries. These include parameters of ^{137}Cs transfer to agricultural products, the features of soil and agricultural production technologies, the effectiveness of remedial actions, and preferences in their choice. The justification of remedial actions for individual human settlements is determined by the optimization of options aimed at reducing the radiation exposure of the population to the level of less than 1 mSv per year. At the regional level, primary attention is focused on justifying the remediation costs and assessing their effectiveness in terms of mitigation of consequences for public health, improvement of the economic situation in the affected regions, and their return to normal life conditions.

With the support of the IAEA, the ReSCA decision support system was created to solve these problems [45, 46]. A feature of this system is the use of the regulatory criteria for radiation safety, proposed in ICRP publication 103 and recommended by the new IAEA safety standard [47]; i.e., this system considers the situation of the existing exposure and carries out the optimization process for the "representative person." The system was adapted for the conditions and radiological parameters of Belarus, Russia, and Ukraine [48].

The remediation strategy is built as a sequence of measures conducted at the local, regional, or country levels. Optimization is achieved by organizing all pos-

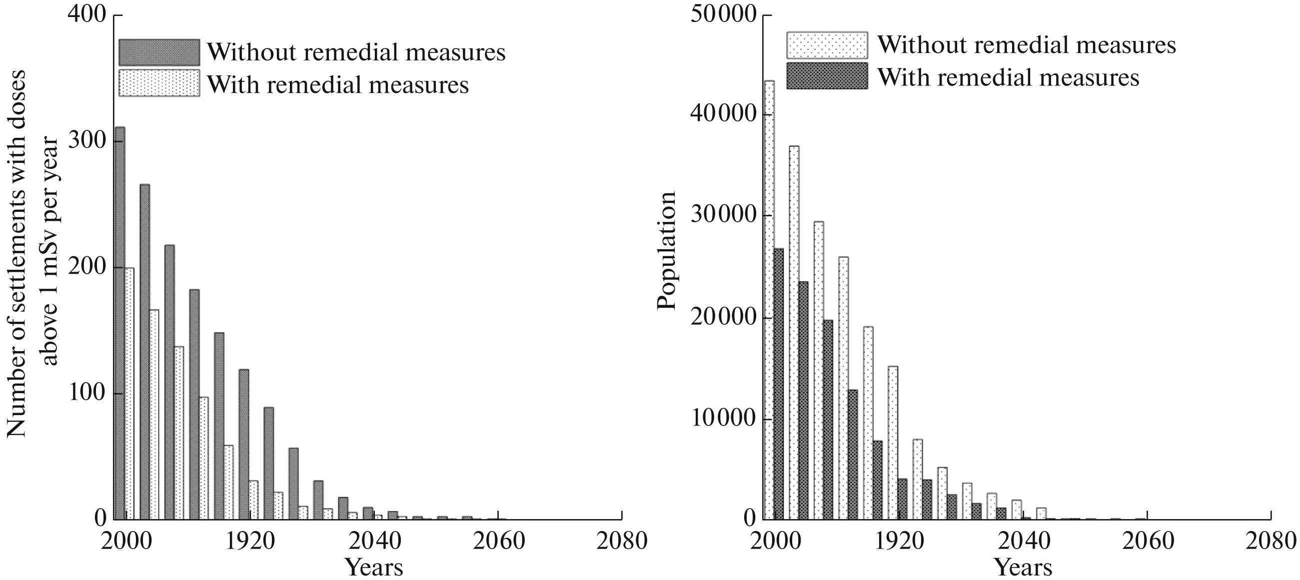

Fig. 6. Time change in the number of rural settlements with annual doses exceeding 1 mSv/year. Estimates are based on data from [43].

sible measures according to a certain optimization criterion and implementing measures with the highest value of the optimization criterion. In the ReSCA system, the optimization process is regulated by two criteria. The first criterion is the cost and radiological effectiveness of the remedial action, and the second is the preference of people responsible for the remediation of contaminated areas for the choice of these actions. The user can change the balance between these criteria, thereby giving greater preference to either cost effectiveness or the choice of remedial measures. Therefore, the system considers different strategies for remediation of contaminated sites: from estimates based on radiological and cost–radiological indicators to estimates in which the choice of measures is completely based on the expert preferences of the population or managers responsible for the results of remediation of contaminated areas.

The main features of the remediation planning based on this approach are illustrated using data on 290 rural settlements in Belarus, Russia, and Ukraine, where the annual effective doses exceeded 1 mSv in 2004 (Fig. 6). The population in these settlements was 78 172 people, including 57 960 people on the territory of the Russian Federation [48]. The collective dose estimated for 2004 was about 65 man-Sv, with three-quarters of this dose being recorded for the population in the affected Russian regions [47]. The distribution of external and internal radiation doses in human settlements differs in the three countries: external exposure prevails in Belarus; both pathways are equally important in Russia; and internal irradiation prevails in Ukraine. In about a half of the human settlements in Belarus and Russia, the annual dose from the consumption of mushrooms and forest products is comparable to the annual dose from milk. In Ukraine, milk was the main source of internal radiation exposure in most of the settlements affected.

At the present time, the averted dose falls outside the restriction criteria and is used mainly for optimization purposes. At the same time, this criterion can be used to assess the medical consequences and makes it possible to estimate investments in remediation by the criterion of decrease of detrimental health effects of the population exposed to radiation.

The effect of remediation depends both on local–specific factors, which are directly included in the analysis, and on the availability of funds for remediation purposes. Therefore, the relationships reflecting the dependence of the averted doses on remediation costs differ in the affected countries (Fig. 6). In Belarus and Ukraine, trends reflecting the increase in the averted dose owing to investments become similar for the radiological and social strategies if the remediation funds exceed 1.0 and 0.1 million Euro, respectively (Fig. 7).

Unlike Belarus and Ukraine, the cost efficiency of the radiological and social strategies in Russia is similar when the total amount of funds used for remediation is less than 0.5 million Euro, while the social strategy begins to be less effective by the averted dose criterion than the radiological strategy with increase in costs.

CONCLUSIONS

A wide range of effective countermeasures and remedial measures in agriculture have been developed and applied over the 35 years since the Chernobyl NPP accident to provide safe agricultural management in the contaminated areas. Their large-scale

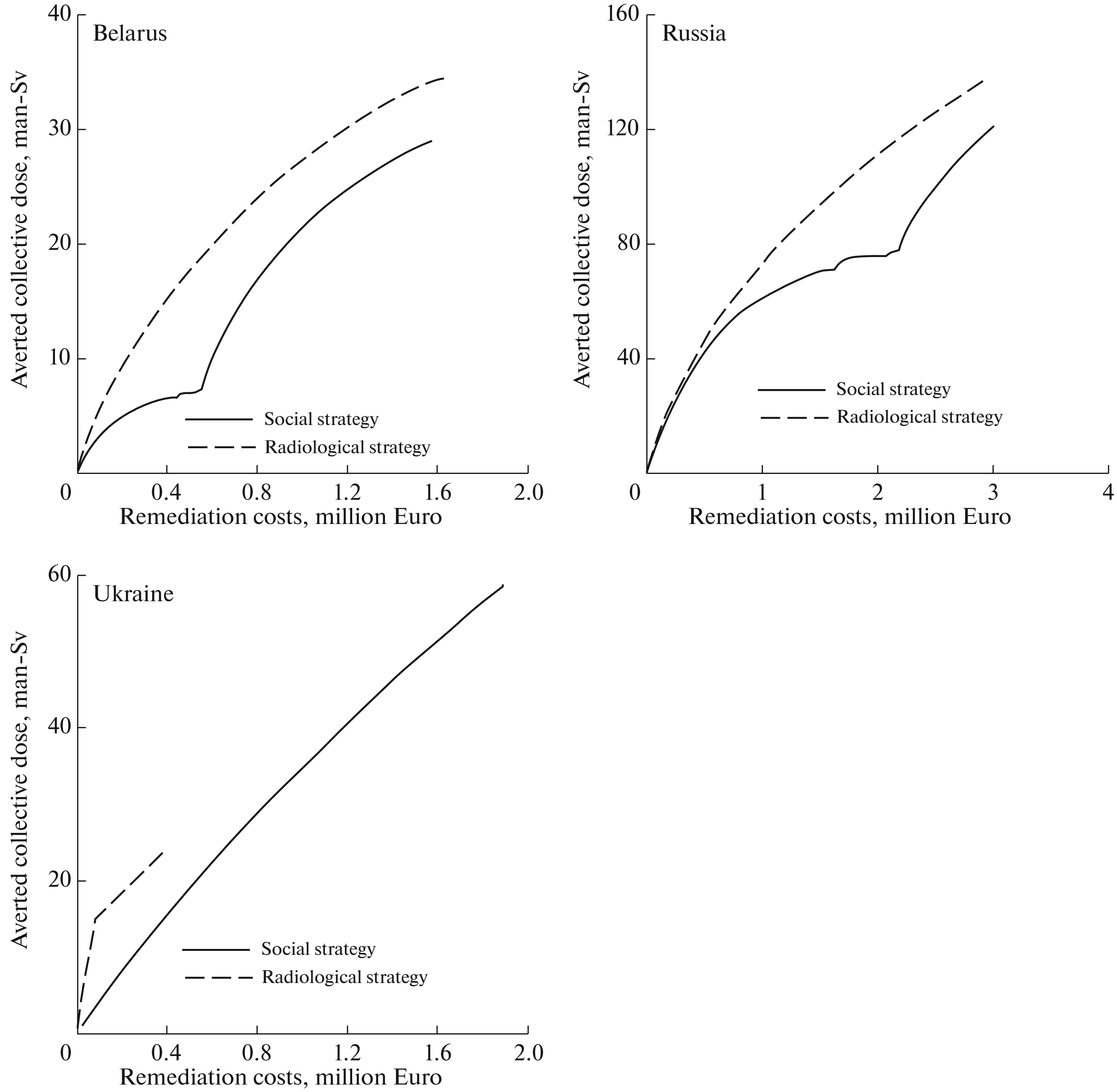

Fig. 7. Total averted collective dose (man-Sv) depending on investments in remediation (the solid line corresponds to the social strategy and the dotted line corresponds to the radiological strategy).

application on an area of over 4.5 million ha has made it possible to continue agricultural production in the contaminated areas and significantly reduce the volume of products that do not meet sanitary–hygiene and veterinary requirements for the concentration of radionuclides. The effectiveness of the use of countermeasures and remedial measures depended on many factors; among them, it is reasonable to highlight the following factors: time after radioactive depositions, natural and climatic conditions, features of agricultural production, and social and economic conditions.

The effectiveness of protective measures depended also on time after the accident and was highest in the first (acute) period after the fallout. At this stage, an important aspect is the timeliness of information delivered to the stakeholders and the population. Thus, measures in agriculture were only partially effective in terms of reducing the input of radioactive iodine as a result of milk consumption due to the absence of timely information and the prompt development of the necessary countermeasures.

The effectiveness of countermeasures and scales of their application depend on the available resources. For instance, the radical improvement of fodder lands is carried out stage by stage, taking into account the number of farm animals and the area of fodder lands required for their maintenance and cannot simultaneously cover the whole contaminated area. Some effective technologies were developed during the liquidation of the accident; for instance, ferrocin began to be used for animals only six years after the accidental release.

The effectiveness of measures in the private sector largely depended on the attitude of the rural population to these measures. Here, the acceptability of decisions can be increased by involving the human population in the analysis of these issues and providing full information about the consequences of the accident and effectiveness of the recommended measures.

The analysis of the experience of countermeasures and remedial measures implementation in agriculture clearly shows their potential to increase significantly the effectiveness of the emergency response in the case of other accidents related to the release of radionuclides into the environment.

COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflicts of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

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