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Research Article

Peculiarities of the exposure dose formation on the population in the most affected regions of Russia after the Chernobyl NPP accident*

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Abstract

The paper presents an analysis of the current radiation situation in the settlements of the Russian Federation located on the most radioactively contaminated territory after the Chernobyl accident. The assessment of ^{137}Cs content in local agricultural (milk, beef, pork, potatoes), natural (mushrooms) foodstuffs, doses of external, and internal irradiation of residents was carried out. 37 years after the Chernobyl NPP accident, 72 settlements with a total number of residents of 63869 remain in the zone of radioactive contamination whose average effective radiation doses exceed 1 mSv/year. All these settlements are located in five southwestern districts of the Bryansk region and are rural except for Novozybkov. In the private sector of settlements, potatoes and pork fully comply with radiological standards for the content of ^{137}Cs. In milk, the content of the radionuclide can exceed the standards up to 3, in beef up to 5, in mushrooms up to 8–17 times. Over the past 30 years, the number of settlements exceeding the legally established standard for the total exposure dose to the population (1 mSv/year) has decreased by 7.5 times. Due to the decrease in the levels of ^{137}Cs contamination of local foodstuffs and the volume of their consumption, the role of internal exposure dose has been decreasing in recent years. It was noted that in addition to a comprehensive assessment of the radiation situation in settlements, agricultural and natural ecosystems, when planning the rehabilitation of settlements with average annual radiation doses of residents above 1 mSv, it is important to take into account the current diets of residents and the real demographic situation in the territories affected by the Chernobyl accident.

Keywords

Chernobyl accident, radioactive contamination, ^{137}Cs, specific activity of radionuclides in foodstuffs, external exposure dose, internal exposure dose

Introduction

The accident at the Chernobyl NPP is the most severe radiological accident in the history of nuclear power, which led to the large-scale contamination with induced radionuclides of territories not only in the former USSR (predominantly in the Russian Federation, the Republic of Belarus and Ukraine) but also in many European countries. The most radiologically significant long-lived radioisotope in the fallout in the territory of Russia as the result of the emergency release is ^{137}Cs with a half-life of 30.17 years (IAEA 2006). The highest levels of contamination

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with this radionuclide were recorded in the Bryansk, Kaluga, Tula and Orel Regions, and the maximum levels were recorded in six southwest districts of the Bryansk Region (Izrael and Bogdevich (2009)). The fallout of radiocesium within settlement areas and in agricultural and natural ecosystems led to the local population having been exposed to internal and external radiation doses in addition to the natural background. Properly estimated exposure doses for the residents in the Chernobyl-affected regions during different periods of the accident response activities has formed the framework for analyzing the extent of the public radiation risk and the basis for the social support of the population (Vlasov et al. 2022; Order of the Russian Federation Government 2015).

The most current official data on the exposure doses for the population in the Chernobyl-affected areas are presented in Bruk et al. 2017. In 2017, as shown by the data in this catalog, there were 135 settlements within the radioactively contaminated territory with an annual average effective exposure dose (AAED) for the population in excess of 1 mSv. In accordance with the Federal Law on the Radiation Safety of the Population, integrated activities need to be undertaken for the above settlements to reduce the exposure doses for local residents to the legislatively defined level. Therefore, more than 37 years after the Chernobyl accident, no problems have been resolved in full within the areas affected by this radiological disaster despite a substantial improvement in the radiation situation.

It needs to be noted that the radiological, socio-economic and demographic situation has changed greatly in the course of time since the Chernobyl accident (Romanovich et al. 2016; Panov 2021). The levels of the soil cover contamination with ^{137}Cs and the radionuclide's specific activity in local food products are decreasing. The ratio of the public internal to external exposure doses is changing. A change is observed in the contribution of ^{137}Cs-containing agricultural and natural foods to the public internal exposure dose due to changes in the human diets (Travnikova et al. 2013; Travnikova 2014). At the current stage, the presented dynamic factors, taken together, define the peculiarities of the post-Chernobyl human dose formation and the efficiency of the measures taken to remediate residential areas. The purpose of the study is therefore to analyze the regularities of the exposure dose formation for local residents a long time after the Chernobyl accident and estimate the reduction rates of the population exposure doses.

Materials and methods

The study was conducted using the example of 135 settlements with an AAED of over 1 mSv (Bruk et al. 2017). All these settlements are situated in six southwest districts of the Bryansk Region (Table 1). As shown by data from the Bryansk Region Statistical Service, not all of these are populated (Official order of Bryansk Statistic Department 2023). Thus, the past 20 years have seen the number of populated settlements reduced by 22%, and the number of residents in these settlements reduced by 16%.

According to MU 2.6.1.2003-05, 2005, all settlements under investigation, except for the town of Novozybkov (population of 38680 in 2020), are rural districts, that is, have a population of less than 10 000. The residents in these settlements live predominantly in one-storied houses and have personal subsidiary plots. Some 35% of the settlements under investigation have a population of 100 to 500. Meanwhile, there is a trend observed with time for a decline in the number of populated settlements for all population size categories (Fig. 1). The reason for this is migration of the able-bodied population segments to more radiologically safe and economically developed districts of the Bryansk Region and to other regions over a long period of time and by the continuous aging of the remaining population in these settlements (Panov 2021).

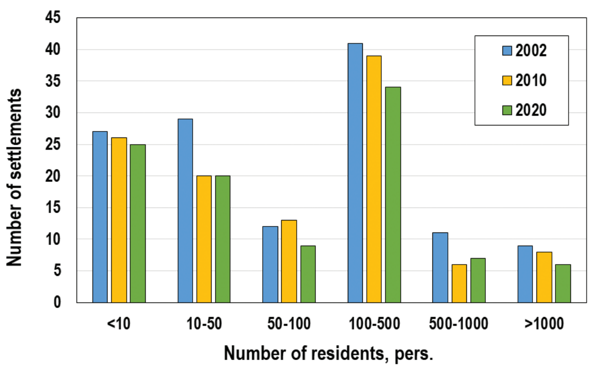

Figure 1. Dynamics in the number of populated settlements with an AAED of over 1 mSv/year.

Table 1. Dynamics in the number of settlements and the population size in southwest districts of the Bryansk Region with an AAED of over 1 mSv for 2002–2020

District	Number of settlements in 2017 (Bruk et al. 2017)	Number of populated settlements (Official order of Bryansk Statistic Department 2023)			Total number of residents, pers. (Official order of Bryansk Statistic Department 2023)		
		2002	2010	2020	2002	2010	2020
Gordeyevka	24	24	20	17	9670	8798	7649
Zlynka	25	24	17	15	11499	10813	9869
Klimovo	2	2	2	2	89	38	13
Klintsy	21	19	15	13	2167	1830	1477
Krasnaya Gora	18	15	14	14	3274	2192	1260
Novozybkov	45	45	44	40	54450	50660	47521
Total	135	129	112	101	81149	74331	67789

The public exposure doses within the settlements under investigation were calculated based on effective MU 2.6.1.2003-05, 2005. The results of a radiological survey by organizations of the Federal Service for Hydrometeorology and Environmental Monitoring, the Russian Federation Ministry for Agriculture, and the Russian Federation Ministry of Forestry were collected for each settlement (Table 2), based on which the databank has been formed for the ^{137}Cs contamination levels within the settlements (Vakulovsky SM (2022), their adjacent grassland areas (Panov et al. 2017, 2019), and forests (Marchenko et al. 2020). The GIS system for remediation of the Bryansk Region's southwest districts was used to take into account the radiological and soil characteristics of the natural and agricultural ecosystem portions within the settlement habitats (Titov et al. 2022).

Table 2. Density of the ^{137}Cs contamination within settlement areas in southwest districts of the Bryansk Region with an AAED of over 1 mSv and their habitats in 2022, kBq/m^2

District	Settlement (Vakulovsky SM 2022)	Grasslands (Panov et al. 2017, 2019)	Forests (Marchenko et al. 2020)
Gordeyevka	375 (260–670)*	940 (650–1665)	710 (520–930)
Zlynka	380 (220–620)	960 (550–1545)	560 (320–910)
Klimovo	290 (275–310)	575 (550–600)	430 (400–450)
Klintsy	305 (240–450)	760 (600–1130)	730 (590–940)
Krasnaya Gora	685 (230–1830)	845 (305–1870)	460 (175–915)
Novozybkov	380 (225–705)	925 (550–1710)	850 (660–955)

* - arithmetic mean value (minimum and maximum values are given in brackets).

The annual average external exposure doses ($AAED_{ext}$) for the residents within the settlements under investigation were estimated using the following formula

$$AAED_{ext} = k_{\gamma} \times \sigma_{137}, \text{ mSv/year}, \quad (1)$$

where k_{γ} is the coefficient of $1.2 \cdot 10^{-3}$ mSv×m^2/kBq×year as per MU 2.6.1.2003-05, 2005; and σ_{137}, kBq/m^2, is the surface activity of ^{137}Cs in the soil within the settlements according to data in Vakulovsky SM (2022).

The annual average internal exposure doses ($AAED_{int}$) for the residents within the settlements under investigation were estimated using the following formula

$$AAED_{int} = d_k \cdot \sum_i A_i \cdot V_i^{eff} \cdot Ki, \text{ mSv/year} \quad (2)$$

where A_i is the average specific activity of ^{137}Cs in the i^{th} food product, Bq/kg(l); V_i^{eff} is the effective annual consumption of the i^{th} food product (milk, beef, pork, potatoes, mushrooms), kg(l)/year; K_i is the coefficient of the ^{137}Cs content reduction in the cooked i^{th} food product (milk – 1, beef – 0.4, pork – 0.4, potatoes – 0.8, mushrooms – 0.5), rel. units as per Gromov 2010; and d_k is the dose factor of the ^{137}Cs dietary intake (1.2×10^{-5} mSv/Bq) as per MU 2.6.1.2003-05, 2005.

The content of ^{137}Cs in the base dose forming foods was determined from the density of contamination with ^{137}Cs for settlements (potatoes and pork), grasslands (milk and beef), and forests (mushrooms) via coefficients of transition (CT) taking into account the soil characteristics for areas in the region of each settlement. The prevailing soil in this part of the Bryansk Region is sand and sandy loam sod-podzolic soil, and the CT values, according to Bratilova and Bruk 2018, are 0.17 for milk, 0.55 for beef, 0.34 for pork, 0.06 for potatoes, and 13 for mushrooms (10^{-3} m^2/kg).

Not only data on the specific activity of ^{137}Cs in locally produced foods but also the current human diets need to be used to estimate the internal exposure dose for the population. The annual per head consumption of milk (370 l) and mushrooms (6 kg) is taken into account for the calculations in MU 2.6.1.2003-05 MU 2.6.1.2003-05, 2005. However, these food consumption levels in southwest districts of the Bryansk Region have failed to comply with the actual situation for many years already. In recent years, regional food production by private farm households has been declining continuously, while the local food consumption levels have been decreasing as well due to the population aging (Travnikova 2014). Thus, according to data from the Bryansk Region Statistical Service, the annual per head consumption of base dose forming food products by private rural households in the Bryansk Region in 2021 was as follows: whole milk – 50.9 l, beef and veal – 0.4 kg, pork – 14.4 kg, potatoes – 73 kg, fresh mushrooms – 0.7 kg (Official order of Bryansk Statistic Department 2023). Current data on the population diets for the settlements within the area under investigation were used for the calculations.

The summary annual average (internal and external) exposure dose (AAED) for the critical group of the settlement residents was estimated using the following formula

$$AAED = AAED_{ext} \times 1.8 + AAED_{int} \times 3.0, \text{ mSv/year} \quad (3)$$

The calculations of the population exposure doses within the 135 settlements under investigation as of 2022, taking into account the present-day demographic data, have made it possible to estimate the actual scale of the outstanding issues involved in remediation of the radioactively contaminated areas in southwest districts of the Bryansk Region.

Results and discussion

The levels of the ^{137}Cs specific activity in the key dose forming agricultural and natural food products for each of the settlements under investigation (Table 3) are close to the investigation results from other authors (Belous et al. 2019). The data obtained in this study demonstrate that the private farm households based within settlements with an AAED of over 1 mSv produce currently potatoes and pork with the content of ^{137}Cs being fully in compliance with the sanitary and hygienic requirements (SanPiN). The radionuclide content in food privately produced within these settlement areas may exceed the SanPiN boundary level by up to 3 times (1.5 times on the average) for milk and by up to 5 times (2.5 times on the average) for beef. The estimated specific activity of ^{137}Cs in mushrooms that may be picked in the most radioactively contaminated forests in the vicinity of settlements with an AAED of over 1 mSv shows that the ^{137}Cs sanitary and hygienic standard for all settlements will be exceeded for the given food product by 8 to 17 times.

Table 3. Specific activity of 137Cs in local food products for settlements in southwest districts of the Bryansk Region with an AAED of over 1 mSv in 2022, Bq/kg(l)

District	Milk	Beef	Pork	Potatoes	Mushrooms
Gordeyevka	160 (110–285)*	520 (355–915)	60 (40–90)	25 (15–40)	7290 (5315–9560)
Zlynka	165 (95–265)	525 (300–850)	55 (35–85)	20 (15–35)	5780 (3290–9320)
Klimovo	95 (90–100)	315 (305–330)	45 (40–50)	17 (15–20)	4380 (4130–4630)
Klintsy	130 (100–190)	420 (330–620)	50 (40–70)	20 (15–30)	7490 (6070–9620)
Krasnaya Gora	145 (50–325)	460 (165–990)	40 (15–85)	40 (15–85)	4720 (1780–9390)
Novozybkov	155 (95–290)	510 (300–940)	25 (15–40)	25 (15–40)	8740 (6785–9795)
SanPiN - 2001/2010	100	200	200	80	500

* - arithmetic mean value (minimum and maximum values are given in brackets).

The calculation results for the public exposure doses demonstrate that, as compared with 2017 (135 settlements), the AAED in 2022 exceeds 1 mSv in the event of 98 settlements, which is explained by the decay of ^{137}Cs and the reduction in both external and internal exposure doses (Table 4). Apart from a decrease in the total number of settlements with excessive exposure doses for the population, redistribution of the constituent doses (both external and internal exposure) can be noted as well. Table 4 presents the approach developed in Panov et al. 2007 that makes it possible to classify settlements with the exposure doses exceeded for the population in terms of the surface ^{137}Cs contamination density levels within the settlement areas and in terms of the internal exposure doses. In 2017, as it can be seen from official data, 58% of settlements with the exposure dose limit exceeded for residents had internal exposure doses in a range of 0.5 to 1 mSv/year. In 2022, as estimated, the share of settlements in this range decreased to 48%, and most of these (52%) have been reclassified as settlements with an internal exposure dose of less than 0.5 mSv/year, that is, the internal exposure contribution to the exposure within settlements in the presented range prevails. All this suggests that the dose forming role of internal exposure has declined with the actual population diets taken into account. The distribution of settlements with an AAED of over 1 mSv is uniform enough in terms of the ^{137}Cs contamination density within the settlements (areas with 185–370 and 370–555 kBq/m^2), except for the highly radiation-contaminated area. The role of internal exposure in the AAED formation grows with the increase in the ^{137}Cs contamination density. In 2017, as shown by the catalog data in Bruk et al. 2017, the largest contributor to the summary dose was internal exposure (64%, with a variability of 43 to 72%). The situation is different in the event of the calculations for 2022. The contribution of internal exposure to the AAED has turned out to be smaller and amounts to 36% on the average with the data scatter in a range of 19 to 39%. Such differences are explained more by the population food rations which are larger in MU 2.6.1.2003-05, as compared with actual data, by a factor of 7.5 for milk and by a factor of 8.5 for mushrooms.

Table 4. Post-Chernobyl distribution of settlements in Russia with an AAED of over 1 mSv

Average internal exposure dose, mSv/year	Density of contamination with ^{137}Cs for settlement area, kBq/m^2			
	37–185	185–370	370–555	> 555
1991 (Panov et al. 2007)				
< 0.5	0	30	18	33
0.5–1	19	69	25	30
> 1	73	74	72	97
1996 (Panov et al. 2007)				
< 0.5	0	6	22	2
0.5–1	0	28	70	84
> 1	7	12	11	65
2001 (Panov et al. 2007)				
< 0.5	0	0	18	2
0.5–1	3	7	47	97
> 1	6	7	6	23
2017 (Bruk et al. 2017)				
< 0.5	0	0	0	0
0.5–1	0	55	21	2
> 1	0	4	34	19
2022				
< 0.5	0	43	6	2
0.5–1	0	0	36	11
> 1	0	0	0	0

In 2022, as one can see from comparing data on the public exposure doses in southwest districts of the Bryansk Region with the present-day demographic situation, 72 out of 98 settlements with an AAED in excess of 1 mSv are really populated (Fig. 2). At the present time, these settlements have a population of 63 869. Out of this

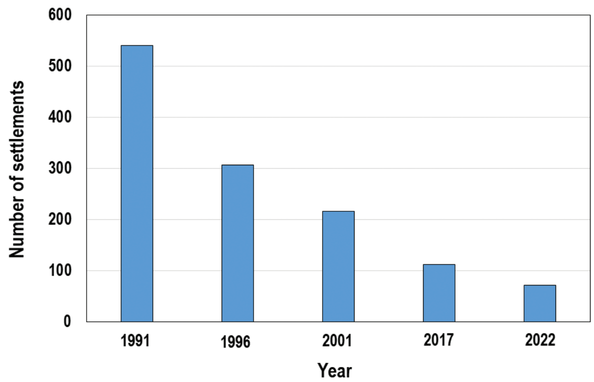

Figure 2. Settlement distribution dynamics for southwest districts of the Bryansk Region with an AAED of over 1 mSv in terms of the number of residents for 2002–2020.

number, rural settlements account for 39%, and the town of Novozybkov accounts for the remaining 61%.

As compared with 1991 (that is, for a time span of 30 years), the number of settlements with an AAED in excess of 1 mSv has declined by 7.5 times and, while this reduction in the initial 10 to 20 after the Chernobyl accident was largely due to protective and remediation measures (Panov et al. 2007), the effect from the countermeasures taken has decreased in recent years, being defined predominantly by the decay of ^{137}Cs. Taking into account the fact that the preferred technologies in the strategy of protective measures taken in the 1990s for residential areas were those aiming to reduce the internal exposure doses for the population (Panov et al. 2007), while the current dose forming role of this component has declined, approaches need to be updated for remediating further the settlements and identify the most efficient technologies in present-day conditions.

Conclusions

The data obtained as part of the study reflect the scale of the outstanding tasks for remediation of settlements within the area radioactively contaminated in the wake of the Chernobyl NPP accident. For 72 settlements with excessive exposure doses for the population, target remediation programs need to be developed to have them backed to radioactively normal life conditions. The results of the investigation also show that it is essential to take into account the actual population diets and the actual demographic situation in the Chernobyl-affected areas, in addition to the radiation situation, when evaluating the need for remediation of settlements. On the whole, the need should be noted for continuing radioecological monitoring within the settlements with an AAED of over 1 mSv, while focusing on estimating the specific activity of ^{137}Cs in local food products, critical in terms of dose formation, which, as a rule, are not mandatorily monitored for radioactive contamination. To estimate the annual average effective exposure doses for the population, as shown in MU 2.6.1.2003-05, taking into account a major difference between the data on diets used in them and the currently actual levels of local food consumption by rural residents in the Bryansk Region, there is a need for updating the respective dietary guidelines.

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