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ASSESSMENT OF THE INFLUENCE OF BN-800 OPERATION ON THE RADIOECOLOGICAL SITUATION IN THE VICINITY OF BELOYARSK NPP

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The aim of this work is to make an assessment of the dynamics of the radioecological conditions in the 30-km zone of influence of the Beloyarsk NPP after the commissioning of the BN-800 power-generating unit. Based on the established network of terrestrial ecosystems, it is shown that the operation of BN-800 did not increase the content of ^{90}Sr, ^{137}Cs, and $^{239+240}$Pu in the soil and vegetation. The ^{137}Cs contamination density of the soil, as a rule, fluctuates in the range 5–8 kBq/m^2. Exceptions are individual sections situated 3–10 km to the south-east of the NPP, where a gas-aerosol emission plume is dispersing. Here the ^{137}Cs contamination density is 2–3 times greater but these sections of the contamination were formed before BN-800 startup. The ^{90}Sr and $^{239+240}$Pu contamination density ranges are, respectively, 1.1–2.5 and 0.08–0.16 kBq/m^2, which fall within the limits of the fluctuations of the regional background level irrespective of BN-800 startup and distance from the reactor. It is shown that BN-800 emissions had no effect on the concentration of technogenic radionuclides in plants – the ^{137}Cs content is equal to 0.5–12 Bq/kg and ^{90}Sr to 1.4–19 Bq/kg.

The development of nuclear energy is largely determined by the solution of environmental problems, an important one being the radiation safety of humans and biota during the operation of nuclear power plants and the associated emissions and discharges of radionuclides into the environment. This problem cannot be solved without an integrated radiation-environmental monitoring system in the vicinity of NPP. In recent years, the strategy for increasing electricity production at NPP has been focused largely on substituent NPP with more efficient power-generating units at the sites of or near existing nuclear power plants, since this is less expensive than capital construction, the creation of engineering and social infrastructure, and the development of human resources.

One such example is the Beloyarsk NPP with different types of power units. The AMB-100 and AMB-200 thermal reactors have been shut down and are currently in the decommissioning stage; the BN-600 and BN-800 fast reactors are operating, generating more than eight billion kWh of electricity annually and supporting 16% of the energy consumption in the Sverdlovsk region. The Institute of Reactor Materials (IRM) with an operating 15 MW pool-type reactor IVV-2M situated next to the Beloyarsk NPP. The yearly emissions from the Beloyarsk NPP, which include radioactive noble gases, ^{60}Co, and ^{137}Cs, are equal to 0.01–1.86% of the permitted limits. The radionuclide composition of the emissions from IRM is similar, so that these objects are considered together on assessing the environmental impact caused by radioactive fallout.

Over more than 50 years of normal operation of the Beloyarsk NPP, local areas with high content of radionuclides were formed – the Olkhovskaya bog-river system where unbalanced waters entered [1]. This territory, which is a source of secondary radioactive contamination, is alienated and is included in the sanitary protection zone. The radioecological situation in the vicinity of the NPP and IRM is influenced not only by emissions and discharges from them, but also by the global

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radiation background, emissions from the Mayak Production Association, radioactive contamination of the East Ural track and, to some extent, fallout due to the accident at the Chernobyl NPP [2, 3]. Specific soil contamination by technogenic radionuclides as a result of global fallouts is, kBq/m^2: ^{90}Sr 1.3, ^{137}Cs 2.2, ^{239,240}Pu 0.01–0.3. The activities of the NFC enterprises in the Urals increase the density of soil contamination in the region, kBq/m^2: ^{90}Sr to 1.6–3 and ^{137}Cs to 4.6–6.8 [4, 5]. Gas and aerosol emissions make very small contributions to the technogenic pollution of the observation zone [5, 6]. But, at individual points of this zone the ^{137}Cs soil contamination density reaches 9 kBq/m^2 [4, 7]. Therefore, to assess the contribution to the total pollution of the area around the NPP, the standard emissions of technogenic radionuclides are usually compared with their regional background content in the components of the environment.

The changes in the radioecological situation of both terrestrial and aquatic ecosystems in the zone of influence of the Beloyarsk NPP have been monitored since the mid-1970s [5, 6]. The emissions from BN-600 are significantly lower than from the AMB reactors preceding it. The commissioning of the more powerful BN-800 power unit for commercial operation raises the problem of assessing its environmental impact taking into account radionuclide intake pathways and the landscape-geographical features of the region.

The aim of the work is to analyze the changes in the radioecological situation in the vicinity of the Beloyarsk NPP after the commissioning of BN-800.

Materials and methods. Beloyarsk NPP is located 42 km from Ekaterinburg and 3 km from Zarechnyi on the bank of a cooling reservoir – the Beloyarsk reservoir formed on the Pyshma River. The radius of the sanitary protection zone is equal to 3–5 km within the boundaries of the NPP industrial site, including the Olkhovskoe bog (5 km from the plant) and a collector pipeline. The observation area lies within a radius of 13 km from BN-600.

The studies were conducted in 2013 before the physical start-up of the BN-800 power unit and in 2019 three years after commissioning and reaching full capacity. This made it possible to assess the impact of the operation of the new reactor on the change in the radioecological conditions. To assess the dynamics of the ingress of radionuclides into the environment, terrestrial ecosystems were selected; they contain mixed pine-birch forests, occupying about 85% of the territory in vicinity of NPP. The object of the study was the soil and vegetation cover. The soil carries the main technogenic load and makes possible an integral assessment of the contamination of the territory by radionuclides, and the accumulation capacity of plants (herbaceous layer) makes them indicators of radioactive contamination of natural ecosystems. The monitoring focused on the study of the accumulation and migration of long-lived radionuclides in soil and vegetation – ^{90}Sr, ^{137}Cs, and $^{239+240}$Pu [7, 8].

To solve the problems posed in this work, the territory around the NPP within a radius of 30 km was divided into three zones (Table 1). In each one, in 2013, control plots of terrestrial ecosystems were established, most (1–10) were situated within the station's sanitary protection zone. Three sections 11–13 were selected in the observation zone and two sections 14–15 at the border of the 30-km zone of influence to monitor the background contamination. All sections in the monitoring network were selected on the basis of the wind rose and the uniformity of the relief and soil-vegetation cover on the automorphic elements of the landscape as well as at different distances and directions from the BN-800 power unit. The soil and vegetation in the control plots were sampled at the same time (August) by the methods of [5, 11, 12]. To assess the vertical migration of radionuclides in areas 10–15, soil samples were taken layer-by-layer to a depth of 20 cm, with separation of the forest floor. Vegetation samples were taken together with the soil in order to determine the coefficients of transfer and accumulation of radionuclides. The ambient equivalent of the dose rate was measured on the control plots.

Samples were measured in the radiation monitoring laboratory at VNIIRAE (accreditation certificate RA.RU.21AD81). The content of radionuclides in soil and plants was analyzed using highly sensitive radiometric and spectrometric systems. Gamma emitting radionuclides were determined on a GAMMA-1P spectrometer with two measuring paths with semiconductor detectors made of ultrapure germanium (LSRM, Russia and EG&G ORTEC, USA) as well as on a CANBERRA multichannel gamma spectrometer (USA). ^{90}Sr and ^{239,240}Pu were isolated from the samples by a radiochemical method. ^{90}Sr was determined on a low-background alpha-, beta-radiometer with a silicon detector UMF-2000 (NPP Doza, Russia) and ^{239,240}Pu – on a liquid scintillation spectrometric system SKS-07P-B11 (Russia). The relative error in measuring the activity did not exceed 30%.

The parameters of migration of the radionuclides from soil to plants were determined by the accumulation coefficients and the transfer coefficients, where the accumulation coefficient is equal to the ratio of the specific activity of the radionuclide

TABLE 1. Control Sections of the Terrestrial Ecosystems in the 30-km Zone of the Beloyarsk NPP

Section No.	Direction and distance from NPP, km	Coordinates	Ambient equivalent of dose rate, μSv/h	
			2013	2019
Sanitary-protection zone (1–3 km)				
1	S–E, 2.5	N 56°50′16″ E 61°19′58″	0.12 ± 0.01	0.14 ± 0.01
2	S–W, 3	N 56°49′58″ E 61°18′41″	0.15 ± 0.02	0.12 ± 0.01
3	S, 2.7	N 56°50′08″ E 61°18′56″	0.16 ± 0.02	0.11 ± 0.02
4	S–W, 2.3	N 56°50′21″ E 61°18′49″	0.16 ± 0.02	0.11 ± 0.01
5	S, 2.4	N 56°50′17″ E 61°19′26″	0.14 ± 0.01	0.12 ± 0.01
6	W, 0.7	N 56°51′33″ E 61°18′36″	0.12 ± 0.01	0.10 ± 0.01
7	N, 0.9	N 56°52′03″ E 61°19′18″	0.14 ± 0.01	0.13 ± 0.01
8	N–E, 1	N 56°52′01″ E 61°19′50″	0.13 ± 0.01	0.13 ± 0.01
9	N–W, 1.2	N 56°52′08″ E 61°18′44″	0.14 ± 0.01	0.13 ± 0.02
10	S–E, 2.9	N 56°50′22″ E 61°21′09″	0.13 ± 0.01	0.13 ± 0.02
			0.08 ± 0.04*	0.09 ± 0.05*
Observation zone (3–13 km)				
11	N–W, 3.6	N 56°52′52″ E 61°16′41″	0.10 ± 0.01	0.13 ± 0.01
12	S–E, 7.5	N 56°48′47″ E 61°24′44″	0.14 ± 0.01	0.11 ± 0.01
13	S–E, 11.5	N 56°46′24″ E 61°25′47″	0.12 ± 0.01	0.11 ± 0.01
			0.08 ± 0.02*	0.08 ± 0.02*
Zone of influence (13–30 km)				
14	E, 25.5	N 56°50′22″ E 61°44′16″	0.13 ± 0.01	0.11 ± 0.01
15	S–W, 28.5	N 56°36′40″ E 61°11′43″	0.09 ± 0.01	0.10 ± 0.01
			0.12 ± 0.01*	0.11 ± 0.01*

*Annual average ambient equivalent of the dose rate according to ASKRO date [9, 10].

in the aboveground mass of plants (Bq/kg dry weight) to the specific activity of the radionuclide in the soil (Bq/kg); the transfer coefficient is equal to the ratio of the specific activity of the radionuclide in the aboveground mass of plants (Bq/kg dry weight) to the soil contamination density (Bq/m^2).

Results and discussion. The studies showed that before the start-up of the BN-800 power unit as well as after the commissioning of industrial operation the ambient equivalent dose rate in the NPP-influenced zone remained at the background level (less than 0.3 μSv/h). In the control plots within the sanitary-protection zone, it was equal to 0.12–0.16 μSv/h in August 2013 and lower in 2019 – 0.1–0.14 μSv/h (see Table 1). In the observation zone, this indicator in 2013 varied in the range of 0.1–0.14 μSv/h and in 2019 it did not change, amounting to 0.11–0.13 μSv/h. On the border of the 30-km zone of influence, the ambient equivalent dose rate fluctuated in the range 0.09–0.13 μSv/h throughout the observation period. According to ASKRO data, the annual average ambient equivalent dose rate was lower than the observed value and amounted to 0.08–0.12 μSv/h.

The specific activity of natural radionuclides in the soil of the control plots of all three studied zones around the NPP was in the range typical for the Ural region and did not change significantly during the entire observation period. Thus, the content of ^{40}K in the soil in 2013 varied in the range 238–597 Bq/kg and in 2019 – 260–660 Bq/kg (Table 2). The range of variation of the average ^{226}Ra content in soil in 2013 was 16–52 Bq/kg and lower in 2019 – 13–35 Bq/kg. In 2013, the specific activity of ^{232}Th in the soil of the control plots was recorded in the range of 15–38 Bq/kg and in 2019 at the level 15–39 Bq/kg.

TABLE 2. Radionuclide Content in the Soil of the Control Plots in the 30-km Zone of the Beloyarsk NPP

No.	^{40}K		^{226}Ra		^{232}Th		^{90}Sr		^{137}Cs		$^{239+240}$Pu	
Sanitary-protection zone												
1	479 ± 135*	660 ± 132**	19.8 ± 8.4	26.2 ± 7.9	15.2 ± 9.1	26.9 ± 8.1	5.16 ± 0.72	5.9 ± 0.8	29.9 ± 7.8	21.1 ± 6.3	–	–
2	437 ± 131	590 ± 118	34.4 ± 10.9	23.1 ± 6.9	18.5 ± 9.9	23.2 ± 6.9	–	–	26.2 ± 7.7	14.5 ± 4.2	–	–
3	553 ± 144	488 ± 97	19.8 ± 8.6	24.7 ± 7.4	18.8 ± 9.2	28.1 ± 8.4	3.5 ± 0.49	2.3 ± 0.3	28.5 ± 7.5	33.3 ± 10.2	–	–
4	402 ± 120	490 ± 88	38.5 ± 12.5	26.3 ± 7.9	31.0 ± 11.8	27.3 ± 8.1	–	–	25.8 ± 8.6	15.4 ± 4.6	–	–
5	597 ± 154	657 ± 131	32.6 ± 9.7	27.7 ± 8.3	21.9 ± 9.7	34.0 ± 10.2	–	–	30.5 ± 7.8	33.6 ± 10.1	–	–
6	354 ± 116	491 ± 93	27.9 ± 8.9	31.4 ± 9.3	24.4 ± 9.3	27.9 ± 8.4	–	–	21.2 ± 6.9	22.3 ± 6.7	–	–
7	393 ± 150	490 ± 98	51.5 ± 15.9	34.7 ± 10.2	36.1 ± 12.4	25.1 ± 7.5	–	–	70.3 ± 15.3	67.5 ± 20.3	–	–
8	361 ± 123	436 ± 87	26.7 ± 10.2	34.6 ± 10.1	38.2 ± 12.7	39.4 ± 11.5	6.62 ± 0.93	7.9 ± 1.1	39.1 ± 9.6	26.4 ± 7.9	–	–
9	343 ± 121	458 ± 92	24.8 ± 10.1	34.5 ± 9.8	35.1 ± 10.4	27.1 ± 8.1	–	–	50.7 ± 10.9	37.4 ± 11.1	0.82 ± 0.4	0.43 ± 0.1
10	483 ± 90	470 ± 73	22.8 ± 11.3	20.8 ± 2.7	21.3 ± 3.1	22.7 ± 4.2	–	–	101 ± 19.9	96.5 ± 28.9	0.31 ± 0.1	0.65 ± 0.3
Observation zone												
11	514 ± 154	530 ± 79	25.5 ± 7.6	24.3 ± 5.1	18.2 ± 5.5	24.4 ± 1.1	–	–	34.4 ± 10.3	34.8 ± 13.1	–	–
12	290 ± 87	272 ± 35	25.1 ± 7.5	19.4 ± 3.5	23.9 ± 7.2	18.4 ± 1.7	8.2 ± 1.1	9.8 ± 1.4	28.6 ± 8.6	20.2 ± 6.1	0.64 ± 0.2	0.54 ± 0.3
13	289 ± 84	421 ± 20	27.4 ± 8.2	13.3 ± 1.3	15.1 ± 4.5	15.3 ± 2.0	–	–	115 ± 10.6	83.3 ± 24.9	0.92 ± 0.2	0.24 ± 0.2
Zone of influence												
14	332 ± 99	260 ± 23	20.8 ± 6.2	21.8 ± 1.9	16.8 ± 5.1	16.8 ± 3.8	–	–	43.4 ± 13.9	38.5 ± 11.3	–	–
15	238 ± 71	328 ± 27	16.2 ± 4.9	17.8 ± 5.3	24.9 ± 7.5	20.0 ± 1.3	10.6 ± 1.48	9.6 ± 1.3	29.2 ± 8.8	24.2 ± 7.2	–	–

*, ** 2013 and 2019, respectively.

The range of variation of the specific activity of natural radionuclides is determined by the properties of the soil cover and falls within the limits of measurement errors.

In terms of the radiation safety of humans and biota, it is more important to analyze the effect of the BN-800 power unit on the dynamics of the ingress of the technogenic radionuclides ^{90}Sr, ^{137}Cs, and $^{239+240}$Pu into the environment. According to the monitoring data, the specific activity of ^{137}Cs in the soil of the control plots in 2013 varied within 21–102 Bq/kg in the sanitary protection zone and 29–115 Bq/kg in the observation zone (see Table 2). In these two zones, local territories were noted (plot 10 in the sanitary protection zone and plot 13 in the observation zone) with 2.5–3.5-fold higher content of ^{137}Cs in the soil compared to other control plots. Without these two observation points, the specific activity of ^{137}Cs in the soil of both zones was at the level in the zone of influence of the NPP, where it was 29–43 Bq/kg (regional background). The plots with higher specific activity of ^{137}Cs in the soil are located to the southeast of the NPP, where the plume of gas aerosol emissions dissipates (less than 3–10 km from BN-600). At the same time, the plot 12 located between them was characterized by background contamination. It should be noted that plots 10 and 13 cannot be classified as radioactively contaminated, since the ^{137}Cs contamination density was 19 and 23 kBq/m^2, which is lower than the limit for distinguishing this category (37 kBq/m^2). The 2013 survey showed that the territories with a heightened ^{137}Cs content in the soil of the sanitary-protection and observation zones were formed before the start-up of BN-800 at the early phases of the NPP and IRM operation and are local in nature.

Three years after the BN-800 was put into operation the specific activity of ^{137}Cs in the soil of the control plots decreased to, Bq/kg, 15–97, 20–83, and 24–39 (background) in the sanitary protection, observation, and influence zones, respectively. Thus, the three-year operation of BN-800 did not increase the ^{137}Cs content in the soil in the vicinity of the NPP. According to data obtained from control plots in 2013–2019, the ^{137}Cs content in the soil decreased in the sanitary protection, observation, and influence zones by 13, 22 and 14%, respectively; this can be explained by the decay of radionuclides, migration processes, and their low additional ingress with gas and aerosol emissions from NPP and IRM.

TABLE 3. Radionuclide Contamination Density of Terrestrial Ecosystems in the 30-km Zone of the Beloyarsk NPP, kBq/m^2

Year	^{90}Sr	^{137}Cs	$^{239+240}$Pu	Data source
Sanitary-protection zone				
1978–1985	1.4 ± 0.2	5.9 ± 1.3	–	[5, 6]
2000–2015	2.2 ± 0.6	7.3 ± 3.9	–	[13]
2005–2015	1.3 ± 0.4	4.4 ± 2.4	0.099 ± 0.047	[7]
2013	1.1 ± 0.3	7.5 ± 4.1	0.075 ± 0.023	Present work
2019	1.1 ± 0.6	6.5 ± 4.3	0.085 ± 0.052	
Observation zone				
2000–2015	2.1 ± 0.7	4.7 ± 2.6	–	[13]
2005–2015	2.4 ± 0.9	4.4 ± 1.9	0.101 ± 0.064	[7]
2013	1.64 ± 0.2	12.9 ± 8.9	0.155 ± 0.039	Present work
2019	1.95 ± 0.2	10.21 ± 6.29	0.078 ± 0.042	
Zone of influence				
1978–1985	1.8 ± 0.6	6.8 ± 3.5	–	[5, 6]
2000–2015	2.0 ± 0.9	2.5 ± 1.2	–	[13]
2005–2015	1.4 ± 0.6	3.2 ± 1.2	0.096 ± 0.052	[7]
2013	2.52 ± 0.3	6.83 ± 0.18	–	Present work
2019	2.29 ± 0.2	5.85 ± 0.13	–	

The content of ^{90}Sr and $^{239+240}$Pu was not determined in all soil samples. It is clear from the measurements that the radioecological situation did not deteriorate after the BN-800 was started up. In 2013, the ^{90}Sr content in the soil of the vicinity of the NPP was in the range of 3.5–10.6 Bq/kg with an average of 6.8 Bq/kg. In 2019, this metric changed little and amounted to 7.1 Bq/kg with the spread of data from 2.3 to 9.8 Bq/kg. The specific activity of $^{239+240}$Pu in the soil of the considered territory also did not increase over six years. In 2013, it averaged 0.67 Bq/kg; in 2019 at the same control plots, it was 0.47 Bq/kg. The difference in the content of ^{90}Sr and $^{239+240}$Pu in the soil of the control plots during the observation period is within the range of measurement errors.

Comparison of the density of soil contamination with technogenic radionuclides in the designated zones in the vicinity of the NPP in 2013 and 2019 with the data of other studies showed good agreement for ^{90}Sr and $^{239+240}$Pu (Table 3). The density of soil contamination with these radionuclides did not differ significantly in time and distance from the NPP and was 1.1–2.5, 0.08–0.16 kBq/m^2 for ^{90}Sr and $^{239+240}$Pu, respectively. The ^{137}Cs contamination density is characterized by a wider variability – 5.8–12.9 kBq/m^2 – and depends on the sampling site. The ^{137}Cs contamination density of the control plots decreased over the considered period and was close to the results of other studies [7, 13]. It should be noted that the Beloyarsk NPP data values [9, 10] are smaller and amount to 0.9–1.6 kBq/m^2, but the dynamics of the lowering of the ^{137}Cs contamination level is discernible there too. The lower contamination density is probably due to the methodology used to calculate this metric.

The ^{137}Cs/^{90}Sr contamination density ratio is highly variable. So, if in the control areas of the affected zone it was equal to 2.6–2.7 before and after the BN-800 was put into operation and was close to the global fallout value 1.6, then in the sanitary protection zone and the observation zone this ratio was higher. In 2013, the ^{137}Cs/^{90}Sr ratio for all control plots was equal to 7.2–7.9 and in 2019 it decreased to 5.2–5.9. Excluding the two sites with an increased level of contamination, the ^{137}Cs/^{90}Sr ratio was closer to the background value and amounted to 4.8–5.9 in 2013 and 2.4–4.3 in 2019, i.e., it tended to the regional background metrics.

Analysis of the vertical distribution of ^{137}Cs in the soil profile of six control plots shows that from 70 to 90% of radionuclides are in the upper 5-cm layer of soil, which indicates that there is no effect of anthropogenic activity on the soil

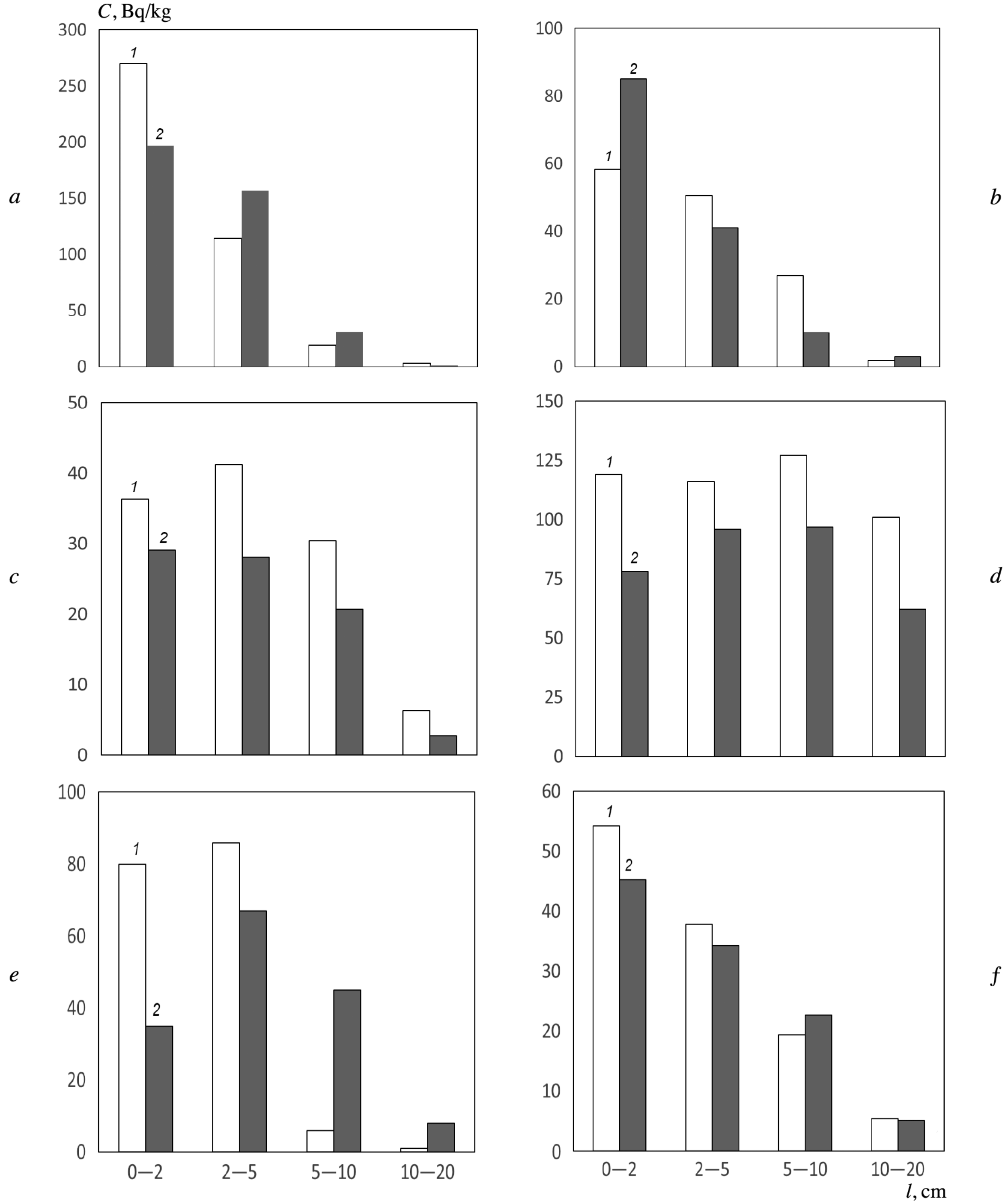

Fig. 1. Distribution of ^{137}Cs in the soil profile of the control sections 10 (*a*), 11 (*b*), 12 (*c*), 13 (*d*), 14 (*e*), and 15 (*f*) in the 30-km zone of the Beloyarsk NPP in 2013 (*1*) and 2019 (*2*).

(see Fig. 1). The exception is plot 13, where radionuclides are evenly distributed over the soil layers and, therefore, this section was previously subjected to mechanized work. The deposition patterns of most of the radionuclides in the upper soil horizons of natural terrestrial ecosystems were also noted for earlier periods of research (1978–1985 and 2005–2015) [7]. Over the six-year period under consideration at all sites, except for the 11th, there was a redistribution of radionuclides in the upper root-inhabited layer of natural soil, which is due to both the absence of an additional significant input of ^{137}Cs and migration processes in the soil profile.

TABLE 4. Accumulation and Transfer Coefficients for ^{90}Sr and ^{137}Cs in Grass Stands in Plots in the 30-km Zone of the Beloyarsk NPP in 2013 and 2019

No.	^{90}Sr						^{137}Cs					
	Specific activity, Bq/kg		Accumulation coefficient, (Bq/kg)/(Bq/kg)		Transfer coefficient, (Bq/kg)/(kBq/m^2)		Specific activity, Bq/kg		Accumulation coefficient, (Bq/kg)/(Bq/kg)		Transfer coefficient, (Bq/kg)/(kBq/m^2)	
Sanitary-protection zone												
1	1.65 ± 0.98*	1.36 ± 0.27**	0.32	0.23	1.55	1.12	2.94 ± 2.89	0.88 ± 0.2	0.10	0.04	0.48	0.20
2	–	–	–	–	–	–	1.61 ± 0.93	0.55 ± 0.1	0.06	0.04	0.27	0.17
3	2.88 ± 1.25	1.61 ± 0.34	0.82	0.70	3.94	3.35	2.75 ± 1.5	1.8 ± 0.8	0.10	0.05	0.46	0.26
4	–	–	–	–	–	–	2.59 ± 2.34	2.4 ± 1.5	0.10	0.16	0.42	0.66
5	–	–	–	–	–	–	1.12 ± 0.83	1.9 ± 0.7	0.04	0.06	0.15	0.23
6	–	–	–	–	–	–	0.81 ± 0.65	0.95 ± 0.5	0.04	0.04	0.18	0.20
7	–	–	–	–	–	–	2.91 ± 2.74	0.97 ± 0.3	0.04	0.01	0.45	0.16
8	2.91 ± 1.1	0.86 ± 0.18	0.44	0.11	2.17	0.54	0.55 ± 0.35	0.94 ± 0.4	0.01	0.04	0.07	0.18
9	–	–	–	–	–	–	1.50 ± 0.94	0.63 ± 0.2	0.03	0.02	0.27	0.15
10	–	–	–	–	–	–	4.21 ± 2.07	4.62 ± 0.2	0.04	0.05	0.22	0.26
Observation zone												
11	–	–	–	–	–	–	2.73 ± 1.65	1.4 ± 0.2	0.08	0.04	0.28	0.14
12	12.17 ± 1.7	5.48 ± 1.07	1.48	0.56	7.44	2.80	3.55 ± 1.2	1.32 ± 0.21	0.12	0.07	0.61	0.33
13	–	–	–	–	–	–	12.1 ± 1.54	7.9 ± 3.1	0.11	0.09	0.53	0.48
Zone of influence												
14	–	–	–	–	–	–	1.73 ± 0.91	1.54 ± 0.3	0.04	0.04	0.26	0.26
15	18.9 ± 2.65	4.63 ± 0.99	1.78	0.48	7.49	2.02	0.47 ± 0.32	0.7 ± 0.2	0.02	0.03	0.07	0.12
Data in [9, 10]			–		–		0.89 ± 0.18	0.13 ± 0.11	–		–	
Data in [13, 14]			0.26–2.8		–		2.17 ± 0.21		0.01–0.99		–	

*, ** 2013 and 2019, respectively.

The accumulation parameters of technogenic radionuclides in the herbaceous layer of the control plots were determined by the density of radioactive contamination, soil characteristics, and plant species, which included cereals, ferns, horsetails, and others. In the area of the studies, the most widespread soils are the turf-podzol and gray and dark-gray soils of medium and light granulometric composition [6]. In 2013, the specific activity of ^{137}Cs in plants in the control plots varied in the range 0.5–12.1 Bq/kg, ^{90}Sr – 1.7–18.9 Bq/kg (Table 4). In 2019, a reduction in the level of plant contamination, averaging 1.7 times for ^{137}Cs and 2.5 times for ^{90}Sr, was noted in most control plots. This is due to a complex of factors, including low emissions of radionuclides during the operation of the Beloyarsk NPP and IRM, vertical migration of radionuclides in the soil, and their fixation in the soil-absorbing complex. A tendency towards reduction in the accumulation of technogenic radionuclides in plants was also noted in other studies [7, 9, 10]. The parameters of migration of radionuclides (accumulation factors and transfer factors) from soil to plants in the control plots over the period under consideration slightly decreased in most cases. Thus, the accumulation coefficients in plants were 0.11–1.78 for ^{90}Sr and 0.01–0.16 for ^{137}Cs (Bq/kg)/(Bq/kg), which fits into the range of metrics for grass stands on this type of soil according to IAEA recommendations [14].

Conclusion. It was shown that the operation of BN-800 did not result in higher ambient equivalent dose rates both in the sanitary protection zone and in the areas of observation and influence of the Beloyarsk NPP. The content of technogenic radionuclides in the soil of the control sites in the 30-km zone decreases in the following order: $^{137}Cs > {}^{90}Sr > {}^{239+240}Pu$. ^{137}Cs is unevenly distributed in the soil in the sanitary protection and observation zones. Separate areas were identified with 2–3 times higher ^{137}Cs contamination in comparison with the regional background. However, in general, no additional input of technogenic radionuclides into environmental objects was revealed in the surveyed area after the BN-800 was put into operation. The ^{137}Cs contamination density decreased before and after the start-up of the new reactor. The regularities of the vertical distribution of ^{137}Cs in the soil of the control plots allow us to conclude that most of them are deposited in the upper layer 0–5 cm; the local foci with heightened radioactivity formed during the operation of the first AMB power units.

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