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Radioactive inventories within the East-Ural radioactive state reserve on the Southern Urals

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Abstract. The large-scale nuclear accident took place at the production association "Mayak" in the Southern Urals in 1957. About 74 PBq of radioactive substances were released into the atmosphere, which resulted in the contamination of a vast area – East-Ural radioactive trace (EURT). The results of our study have shown that the density of contamination of ^{90}Sr and ^{137}Cs in the frontal part of the EURT are 6700–15000 and 200–400 kBq/m^2, respectively. The total deposition for ^{90}Sr within the East-Ural Radioactive State Reserve was 428.2 (286.4–643.4) TBq, for ^{137}Cs – 15.1 (10.2–22.4) TBq, for ^{239,240}Pu – 1.175 (0.623–2.242) TBq.

1. INTRODUCTION

Technogenic radionuclides are the main contaminants of all components of biosphere. Several nuclear enterprises are located in the Urals Region (the Russian Federation). The largest one is the Production Association "Mayak". It was established in 1940-s to produce plutonium for nuclear weapons and treat nuclear materials. Several nuclear accidents occurred on the first phases of the operation, resulting in radioactive contamination of the environment.

On September the 29th 1957, a tank containing 74×10^{16} Bq high-level radioactive wastes exploded at PA Mayak as a result of destruction and self-heating of the cooling system. The radioactive debris, moving in the NNE direction, contaminated a vast area (the Eastern-Ural Radioactive Trace – EURT). At the time of the accident, predominant isotopes in the composition of the radioactive fallout were ^{144}Ce (66%), ^{95}Zr (25%) and ^{90}Sr (7%). Over time, ^{90}Sr remained as the main contaminant, accounting for as much as 100% of the total content of radionuclides in the mixture of fission fragments, during 8–10 years already after the emission [1, 2].

Since the beginning of 1951, small natural Lake Karachay has been used for a deposition of media-level radioactive waste. In 1967, on the lake shore strip, resulting from draught and evaporation, silt and fine sand were raised by the wind. In this case the territory of EURT was again subjected to radionuclides contamination. The radioactive ^{137}Cs was predominant in the composition of this contamination. Nine years later, the East-Ural Radioactive State Reserve (EURSR) was established in the frontal part of this trace and in fact became a test ground for experiments in the natural environment. Due to secrecy of the entire process associated with the accident only fragmentary data were included in accessible publications, usually without indication of place and conditions of the contamination. General data were published only in the end of the 20th century [3]. In the earlier years, we work in cooperation with Risø? National Laboratory, Denmark and Institute of Biology of Southern Seas, Ukraine carrying out an estimation of radioactive inventories on the Kyshtym accident zone [4]. Samples from EURSR were inaccessible to us.

The purposes of this work were to evaluate recent levels and the pattern of distribution of radionuclides in the soils along the contamination gradient and estimate total inventories of ^{90}Sr and ^{137}Cs in the soils within the East-Ural Radioactive State Reserve.

2. MATERIAL AND METHODS

In the East-Ural Radioactive State Reserve area, several plots located at a distance of 6–30 km from the accident epicenter were studied (Fig. 1). The background plots were beyond the contaminated area. In order to obtain a representative sampling, two or three full profile cuts were made on the different locations. The samples were taken layer-by-layer to a depth of 30–60 cm with regard to the area and boundaries of genetic soil horizons. The samples of herbaceous plants were taken in the immediate vicinity of soil cuts. Concentration of ^{90}Sr in all samples was determined radiochemically from the content of daughter ^{90}Y. The isotopes of Pu were estimated radiochemically too with using ion-exchange columns and electrochemical deposition on stainless steel disks. The ^{137}Cs concentration was determined using a Canberra multichannel gamma-analyzer. The statistical error of measurements did not exceed 15%, ^{90}Sr and ^{137}Cs detection limit was 1 Bq/kg; ^{239,240}Pu – 0.1 Bq/kg. The content of ^{238}Pu was lower limit of determination as a rule.

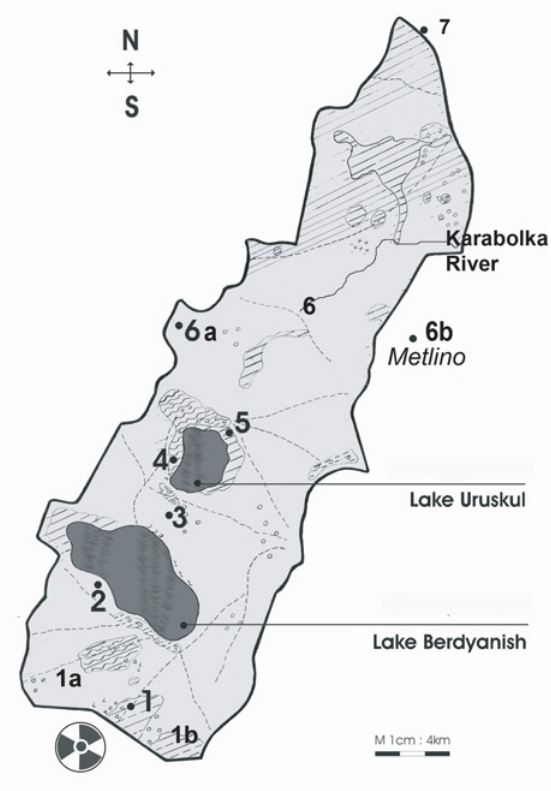

Figure 1. The scheme of EURSR: 1 – Lezhnevka (1a & 1b – plots along Lezhnevka's road), 2 – Berdenish, 3 – South Uruskul, 4 – West Uruskul, 5 – North Uruskul, 6 – Karabolka, 6a – West boundary of EURSR, 6b – Metlino, 7 – North-East boundary of EURSR.

3. RESULTS AND DISCUSSION

In each region the background level of radioactive contamination is determined both global and local fallout from atmosphere. From the UNSCEAR data (1982), the density of ^{90}Sr contamination is 1.5 kBq/m^{2}and that of ^{137}Cs contamination is 2.4 kBq/m^2 within a belt between 50° and 60° of the northern latitude. As the background plots we selected two ones. One of them was located 120 km away to the west of the accident epicentre in an old arable field and other plot was located in pine and birth forest 55 km away to the south of the accident epicentre. Within the background plots soil ^{90}Sr contamination was resulted mainly from global fallout. In fact, the amount of this radionuclide was 1.6 kBq/m^2. However the content of ^{137}Cs was higher than the level of global fallout – 4–5 kBq/m^2. The background level of ^{239,240}Pu was 0.06 kBq/m^2 [4].

The data on contamination levels at the reserve are represented in Tables 1–13. The data analysis indicates that over 50 years after the accident, ^{90}Sr remains the main contamination agent. In the reserve soils ^{90}Sr contents within the trace central axis decreases from 31.5 to 2.1 MBq/m^2, as the distance from PA Mayak increases. The average soil contamination density for ^{137}Cs is 20–30 times lower as compared to contamination density for ^{90}Sr. With the distance from PA Mayak the density changes from 922 to 93 kBq/m^2, which is 230–20 times higher than values of the background contents. In general, the same patterns of spatial distribution were identified for ^{239,240}Pu; its minimum contents in EURSR soils studied were 20 times over those found in the background soils.

Table 1. Radionuclides in soil (brown forest) and vegetation samples from location 1 (position: 55°45′ N 60°50′ E).

Sample	^{90}Sr		^{137}Cs		^{239,240}Pu	
	Bqkg^{-1}	kBqm^{-2}	Bqkg^{-1}	kBqm^{-2}	Bqkg^{-1}	kBqm^{-2}
Grass	72896 ± 10900	–	19.1±2.9	–		
Litter	500460 ± 350280	466 ± 298	3110 ± 2190	2.9 ± 1.9	352 ± 53	0.3 ± 0.05
Soil: 0–5 cm	263600 ± 35280	7242 ± 4935	16600 ± 16800	482 ± 191	1355 ± 203	74 ± 11
5–10 cm	175600 ± 33600	13559 ± 562	4390 ± 2030	300 ± 115	315 ± 50	22 ± 3.3
10–15 cm	87090 ± 13060	6096 ± 914	1167 ± 175	81 ± 12	65 ± 10	4.6 ± 0.7
15–20 cm	38460 ± 5769	2794 ± 419	476 ± 71	34 ± 5	51 ± 7.7	3.7 ± 0.6
20–25 cm	11549 ± 1730	962 ± 144	192 ± 29	16.0 ± 2.1	16.3 ± 2.4	1.4 ± 0.2
25–30 cm	3070 ± 4600	202 ± 30	64 ± 10	4.2 ± 0.6	10.7 ± 1.6	0.7 ± 0.2
30–35 cm	2264 ± 1050	171 ± 107	25 ± 13	1.6 ± 0.7	3.3 ± 0.5	0.2 ± 0.1
Total deposition		31492		922		107

Table 2. Radionuclides in soil (soddy low-podzolic) and vegetation samples from location 1a (position: 55°45′ N 60°48′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	1072 ± 23	–	11.7 ± 0.5	–
Litter	1455 ± 218	4.6 ± 0.8	742 ± 90	2.4 ± 0.6
Soil : 0–5 cm	507 ± 78	19.6 ± 3.4	349 ± 53	13.5 ± 2.0
5–10 cm	56 ± 8	13.6 ± 2.0	28 ± 11	2.0 ± 0.2
10–15 cm	29 ± 5.0	8.9 ± 1.3	8.3 ± 1.4	0.6 ± 0.1
15–20 cm	25 ± 5.4	1.4 ± 0.3	9.1 ± 1.5	0.7 ± 0.1
20–25 cm	5.6 ± 0.8	0.5 ± 0.1	9.8 ± 1.5	0.8 ± 0.2
25–30 cm	8.5 ± 1.3	0.6 ± 0.1	6.0 ± 1.0	0.4 ± 0.1
Total deposition		49.2		20.4

The wide-ranging difference among soil contamination densities in the plots studied located in the close proximity from each other are shown (see Tables 4, 5, 8, and 9). Reinstatement works following the

Table 3. Radionuclides in soil (brown forest) and vegetation samples from location 1b (position: 55°44′ N 60°52′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	1440 ± 36	–	36.1 ± 11.1	–
Litter	2567 ± 388	2.6 ± 0.4	598 ± 76	0.6 ± 0.1
Soil: 0–5 cm	2711 ± 400	21 ± 4.0	11660 ± 1208	91 ± 14
5–10 cm	1342 ± 201	64 ± 9.6	1473 ± 170	71 ± 11
10–15 cm	488 ± 73	29 ± 4.3	42.8 ± 12.6	2.5 ± 0.4
15–20 cm	191 ± 30	12.5 ± 1.9	24 ± 3.6	1.6 ± 0.3
20–25 cm	150 ± 25	8.0 ± 1.2	7.5 ± 1.1	0.4 ± 0.1
25–30 cm	120 ± 18	7.0 ± 1.0	9.9 ± 1.5	0.6 ± 0.1
Total deposition		144		168

Table 4. Radionuclides in soil (grey forest) and vegetation samples from location 2 (position: 55°46′ N 60°53′ E).

Sample	^{90}Sr		^{137}Cs		^{239,240}Pu	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	18260 ± 2700	4.1 ± 0.6	143 ± 22	0.03 ± 0.01	0.06 ± 0.01	0.00001 ± 0.000001
Litter	146000 ± 21900	197 ± 30	5760 ± 610	7.8 ± 1.2	–	–
Soil : 0–5 cm	139100 ± 20900	3971 ± 600	5548 ± 596	158 ± 24	189 ± 29	5.4 ± 0.8
5–10 cm	137300 ± 20600	4062 ± 609	5382 ± 575	159 ± 25	540 ± 81	16.0 ± 2.8
10–15 cm	71740 ± 10760	2709 ± 406	1768 ± 200	66 ± 10	80 ± 12	3.0 ± 0.5
15–20 cm	24000 ± 3600	1353 ± 203	657 ± 81	26 ± 4.1	51 ± 8.0	2.1 ± 0.4
20–25 cm	5703 ± 900	303 ± 45	109 ± 21	5.8 ± 1.2	24 ± 3.6	1.3 ± 0.2
25–30 cm	1552 ± 233	115 ± 17	27 ± 10.8	2.0 ± 0.3	32 ± 4.8	2.4 ± 0.4
30–35 cm	1466 ± 2200	105 ± 15	31 ± 11.7	2.2 ± 0.4	22 ± 3.5	1.6 ± 0.3
35–40 cm	239 ± 36	18.5 ± 2.8	4.1 ± 1.7	0.3 ± 0.1	18.3 ± 2.9	1.4 ± 0.3
40–45 cm	156 ± 25	13.2 ± 2.0	3.5 ± 1.7	0.3 ± 0.1	–	–
Total deposition		12851		427		33.2

Table 5. Radionuclides in soil (antropogenic disturbed grey forest) and vegetation samples from location 2 (position: 55°46′ N 60°53′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	57030 ± 8550	12.9 ± 1.9	330 ± 50	0.08 ± 0.01
Litter	24350 ± 3650	13.5 ± 2.1	189 ± 28	0.1 ± 0.02
Soil: 0–5 cm	107600 ± 16140	1330 ± 200	5733 ± 890	70 ± 11
5–10 cm	137900 ± 20685	2636 ± 400	5298 ± 794	101 ± 16
10–15 cm	56550 ± 8480	926 ± 148	978 ± 149	16.0 ± 2.4
15–20 cm	44220 ± 6633	467 ± 70	370 ± 56	3.9 ± 0.6
20–25 cm	33700 ± 5005	743 ± 111	258 ± 39	5.7 ± 0.9
25–30 cm	24850 ± 3730	365 ± 55	142 ± 20	2.1 ± 0.3
30–40 cm	3357 ± 504	199 ± 30	27 ± 5.0	1.6 ± 0.3
40–50 cm	268 ± 40	21 ± 3.1	10.5 ± 1.5	0.8 ± 0.2
50–60 cm	160 ± 42	23 ± 3.4	4.5 ± 0.7	0.6 ± 0.1
Total deposition		6736		202

accident also contributed to this wide-ranging difference. Typically, they led to reducing radionuclides stocks in the soil. To evaluate intensity of radionuclides geochemical migration we previously studied geochemical couplings that were characterized with the highest diversity of plant communities types; this data are represented in the study [5].

Table 6. Radionuclides in soil (soddy low-podzolic) and vegetation samples from location 3 (position: 55°49′ N 60°55′ E).

Sample	^{90}Sr		^{137}Cs	
	Bqkg^{-1}	kBqm^{-2}	Bqkg^{-1}	kBqm^{-2}
Grass	171075 ± 35000	–	88 ± 42	–
Litter	239000 ± 174000	163 ± 104	2522 ± 1562	1.8 ± 0.9
Soil: 0–5 cm	117800 ± 6776	1493 ± 1128	9774 ± 1630	118±66
5–10 cm	78620 ± 30800	4066 ± 560	1367 ± 811	86 ± 13
10–15 cm	26140 ± 3920	1471 ± 220	207 ± 31	11.7 ± 1.8
15–20 cm	3618 ± 544	211 ± 31	72 ± 11	4.2 ± 0.7
20–25 cm	1288 ± 193	121 ± 19	28 ± 4.2	2.6 ± 0.4
25–30 cm	849 ± 127	58 ± 10	8.2 ± 1.3	0.6 ± 0.1
30–40 cm	429 ± 64	42 ± 6.3	4.5 ± 0.8	0.4 ± 0.1
Total deposition		7625		225

Table 7. Radionuclides in soil (grey forest) and vegetation samples from location 4 (position: 55°49′ N 60°56′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	7214 ± 1082	0.7 ± 0.1	119 ± 19.0	0.01 ± 0.002
Litter	15400 ± 2310	20.2 ± 3.3	530 ± 66	0.7 ± 0.2
Soil: 0–5 cm	49798 ± 7400	77 ± 7.8	1265 ± 150	19.7 ± 3.0
5–10 cm	21276 ± 3191	1143 ± 170	651 ± 80	35.0 ± 5.3
10–15 cm	12633 ± 1895	843 ± 96	259 ± 38	17.4 ± 2.6
15–20 cm	9202 ± 1380	562 ± 84	170 ± 27	10.4 ± 1.5
20–25 cm	4103 ± 615	265 ± 40	42 ± 6.7	2.8 ± 0.9
25–30 cm	2022 ± 303	122 ± 19	19.1 ± 3.8	1.2 ± 0.2
30–35 cm	773 ± 116	78 ± 7.9	7.7 ± 2.1	0.8 ± 0.2
35–45 cm	166 ± 24	11.4 ± 1.8	4.3 ± 2.1	0.3 ± 0.1
Total deposition		3122		88

Table 8. Radionuclides in soil (meadow chernozemic) and vegetation samples from location 5 (position: 55°50′ N 60°56′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	15746 ± 5900	–	173 ± 22	–
Litter	35000 ± 3600	78 ± 12	360 ± 42	0.8 ± 0.2
Soil: 0–5 cm	24730 ± 2699	1202 ± 180	1331 ± 153	65 ± 9.8
5–10 cm	25750 ± 2778	952 ± 147	1148 ± 133	42 ± 6.4
10–15 cm	25960 ± 2829	1121 ± 165	904 ± 106	39 ± 6.0
15–20 cm	23430 ± 2537	980 ± 146	641 ± 79	27 ± 4.0
20–25 cm	12680 ± 1424	829 ± 120	172 ± 28	11.2 ± 1.7
25–30 cm	5888 ± 701	376 ± 56	28.3 ± 11.2	1.8 ± 0.3
30–35 cm	3414 ± 429	219 ± 32	5.5 ± 2.6	0.4 ± 0.1
35–40 cm	1997 ± 238	142 ± 22	–	–
Total deposition		5899		187

At early stages of the trace formation the radioactive fallouts were hampered by the plant cover and thin topsoil. Over 50-years period both spatial and vertical redistribution of radionuclides in soils occurred as a result of migration processes.

Herbaceous cover and forest leaf litter are characterized by the minimum ^{90}Sr stocks. The most of it is concentrated in the humus layer of soil profile (5–20 cm). Beyond this layer ^{90}Sr stocks decrease and at a depth of 40–45 cm only trace amounts of it could be found. In general the same vertical distribution

Table 9. Radionuclides in soil (chernozem antropogenic disturbed) and vegetation samples from location 5 (position: 55°50′ N 60°56′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	5306 ± 795	0.8 ± 0.2	79.5 ± 11.8	0.01 ± 0.001
Litter	4058 ± 600	2.3 ± 0.3	240 ± 32	0.14 ± 0.02
Soil: 0–5 cm	3523 ± 439	149 ± 23	928 ± 108	39 ± 6.0
5–10 cm	2726 ± 352	161 ± 24	666 ± 81	39 ± 5.9
10–15 cm	3270 ± 416	197 ± 30	113 ± 21	6.8 ± 1.0
15–20 cm	2597 ± 341	151 ± 20	205 ± 31	12.0 ± 2.0
20–25 cm	3669 ± 459	207 ± 30	37.0 ± 11.6	2.1 ± 0.3
25–30 cm	4727 ± 569	278 ± 45	40.6 ± 12.3	2.4 ± 0.4
30–35 cm	8832 ± 1008	456 ± 70	141 ± 23	7.3 ± 1.1
35–40 cm	11650 ± 1307	569 ± 85	164 ± 26	8.0 ± 1.2
Total deposition		2171		117

Table 10. Radionuclides in soil (ordinary chernozem) and vegetation samples from location 6 (position: 55°54′ N 61°02′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	394 ± 176	0.2 ± 0.03	3.6 ± 0.9	0.02 ± 0.003
Litter	500 ± 46	1.0 ± 0.2	34 ± 5.1	0.07 ± 0.02
Soil: 0–5 cm	640 ± 121	32 ± 4.6	81 ± 13	4.1 ± 0.6
5–10 cm	691 ± 125	31 ± 4.5	92 ± 15	4.1 ± 0.6
10–15 cm	705 ± 148	42 ± 6.2	77 ± 12	4.6 ± 0.7
15–20 cm	772 ± 157	36 ± 4.9	94 ± 16	4.4 ± 0.7
20–25 cm	610 ± 132	31 ± 4.2	72 ± 11	3.7 ± 0.6
25–30 cm	645 ± 131	33 ± 4.2	30 ± 4.5	1.6 ± 0.2
30–40 cm	208 ± 61	27 ± 3.9	–	–
Total deposition		233		23

Table 11. Radionuclides in soil (ordinary chernozem) and vegetation samples from location 6a (position: 55°50′ N 60°52′ E).

Sample	^{90}Sr		^{137}Cs	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	47 ± 17	0.04 ± 0.01	2.3 ± 0.6	0.002 ± 0.0005
Litter	315 ± 37	0.12 ± 0.02	23.7 ± 14.0	0.009 ± 0.001
Soil: 0–5 cm	162 ± 24	2.5 ± 0.3	242 ± 36	3.7 ± 0.6
5–10 cm	169 ± 25	6.9 ± 0.9	242 ± 35	9.8 ± 1.0
10–15 cm	91 ± 14	4.1 ± 0.6	42 ± 12.4	1.9 ± 0.3
15–20 cm	70 ± 11	3.1 ± 0.5	20.0 ± 4.4	0.8 ± 0.2
20–25 cm	31 ± 4.5	1.8 ± 0.3	4.8 ± 0.8	0.3 ± 0.1
25–30 cm	22 ± 3.3	1.0 ± 0.2	–	–
30–35 cm	20.4 ± 3.1	1.4 ± 0.3	–	–
35–40 cm	14.0 ± 1.9	0.9 ± 0.2	–	–
Total deposition		21.8		16.5

is typical for ^{137}Cs and ^{239,240}Pu. The feature of these radionuclides is that their maximum contents are associated with 10–20 cm layer.

A sharp decline in the radionuclide contamination gradient from the center to periphery, both in the vicinity of the accident epicenter – plots 1, 1a, 1b (see Tables 1–3) and within reach of it – plots 6, 6a, 6b (see Tables 10–12) is shown. These data confirm a sharp decline in the radionuclide contents within the trace cross-section that was identified earlier [2].

Table 12. Radionuclides in soil (antropogenic disturbed chernozem) and vegetation samples from location 6b (position: 55°46′ N 60°53′ E).

Sample	^{90}Sr		^{137}Cs		^{239,240}Pu	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Grass	1034 ± 134	0.4 ± 0.1	18.4 ± 5.2	0.006 ± 0.001	–	–
Litter	1038 ± 135	2.3 ± 1.5	606 ± 15	1.2 ± 0.6	–	–
Soil: 0–5 cm	1495 ± 58	54 ± 29	1372 ± 234	47 ± 17	8.4 ± 0.2	0.3 ± 0.1
5–10 cm	1294 ± 10	56 ± 7.9	1088 ± 265	48 ± 18	6.8 ± 1.9	0.3 ± 0.03
10–15 cm	769 ± 25	36 ± 2.1	404 ± 146	19.2 ± 6.9	3.7 ± 0.8	0.2 ± 0.03
15–20 cm	307 ± 83	15.1 ± 2.2	99 ± 19	4.9 ± 1.6	1.2 ± 0.2	0.2 ± 0.01
20–25 cm	209 ± 49	9.8 ± 1.5	49 ± 16.7	2.3 ± 0.4	1.1 ± 0.2	0.15 ± 0.03
25–30 cm	125 ± 46	8.1 ± 1.2	89 ± 13.4	5.8 ± 0.6	1.7 ± 0.5	0.11 ± 0.03
30–40 cm	21.9 ± 3.3	3.6 ± 0.4	–	–	0.3 ± 0.1	0.05 ± 0.01
40–50 cm	22.7 ± 3.4	3.1 ± 0.5	–	–	–	–
50–60 cm	19.5 ± 2.9	1.5 ± 0.2	–	–	–	–
Total deposition		190		128		1.31

Table 13. Radionuclides in soil (grey forest) and vegetation samples from location 7 (position: 55°55′ N 61°03′ E).

Sample	^{90}Sr		^{137}Cs		^{239,240}Pu	
	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}	Bq kg^{-1}	kBq m^{-2}
Soil: 0–5 sm	23056 ± 2090	830 ± 11	2027 ± 230	73 ± 1	100 ± 8	3.6 ± 0.3
5–10 cm	21304 ± 3010	980 ± 13	371 ± 36	17.1 ± 0.2	7.4 ± 0.24	1.34 ± 0.008
10–15 cm	3787 ± 350	250 ± 3	21.2 ± 8.5	1.4 ± 0.03	2.0 ± 0.02	0.13 ± 0.013
15–20 cm	15.8 ± 1.2	1.5 ± 0.03	1.1 ± 0.1	0.1 ± 0.03	0.1 ± 0.05	0.01 ± 0.003
20–25 cm	39.2 ± 4.3	2.8 ± 0.04	4.2 ± 0.8	0.3 ± 0.02	0.7 ± 0.07	0.05 ± 0.008
25–30 cm	35.1 ± 4.1	3.5 ± 0.05	9.1 ± 2.3	0.9 ± 0.04	0.5 ± 0.05	0.05 ± 0.009
Total deposition		2068		93		5.2

Because the soil samples were taken from 2003 to 2007, for correct calculations below, we used the radioactive decay correction k, thus adjusting the data to the unified time phase (contamination levels of 2007):

$$k = \frac{A}{A_0} = 2^{-n}, \quad where \quad n = \frac{t}{T_{1/2}}$$

G. Romanov and A. Aarkrog evaluated radioactive contamination of soils in EURT by ^{90}Sr considering its area as a sector with 15° angle and 300 km radius from the conventional center – PA Mayak [2], from boundary of EURSR [4]. This simplified model we used and for calculation of radionuclide stocks within EURSR (6–30 km to the north-east from PA Mayak). Here, an area of the territory modeled totals 113.1 KM^2, which is ≈70% of the total reserve area (166.2 km^2). 15° sector selected does not include plots from the EURSR periphery (see Figure 1 plots 1a, 1b, and also plots 6a and 6b and not consider them in calculations. Densities of soil cover contamination by radionuclides in the reserve along the central transect decrease as the distance from PA Mayak increases (Fig. 2).

This dependence could be best described by exponential law as follows:

$$y(x) = e^{(b_0 + b_1 \cdot x)},$$

where $y(x)$ – radionuclides contents in the soil, kBq/m^2,
x – distance (km) from PA Mayak, and
b_0 & b_1 – linear regression coefficients.

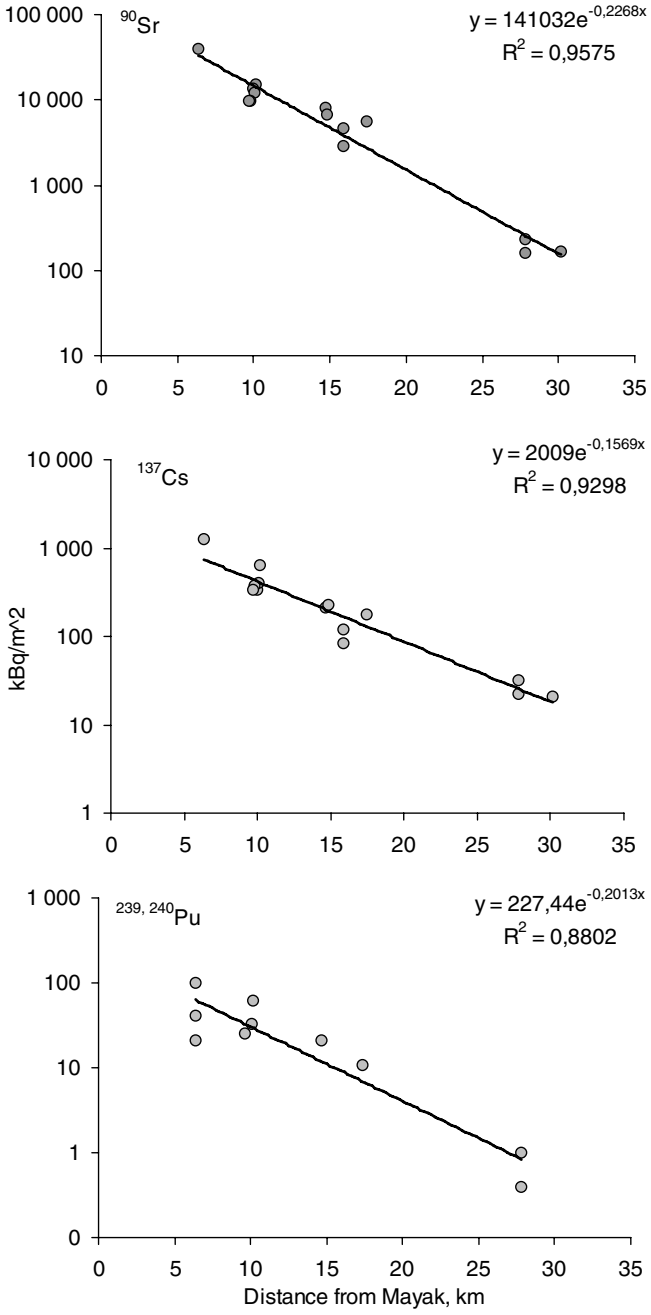

Figure 2. Deposition of radionuclides in the soils of EURSR.

Based on radionuclides contamination densities (for the period 2007) the following model coefficients were obtained:
for ^{90}Sr: $b_0 = 11.857 \pm 0.240$; $b_1 = -0.227 \pm 0.014$, determination coefficient R^2=0.96; for ^{137}Cs: $b_0 = 7.605 \pm 0.216$; $b_1 = -0.157 \pm 0.012$, determination coefficient $R^2 = 0.93$; for ^{239,240}Pu: $b_0 = 5.918 \pm 0.378$; $b_1 = -0.224 \pm 0.022$, determination coefficient $R^2 = 0.95$. (coefficients are given with the standard error values).

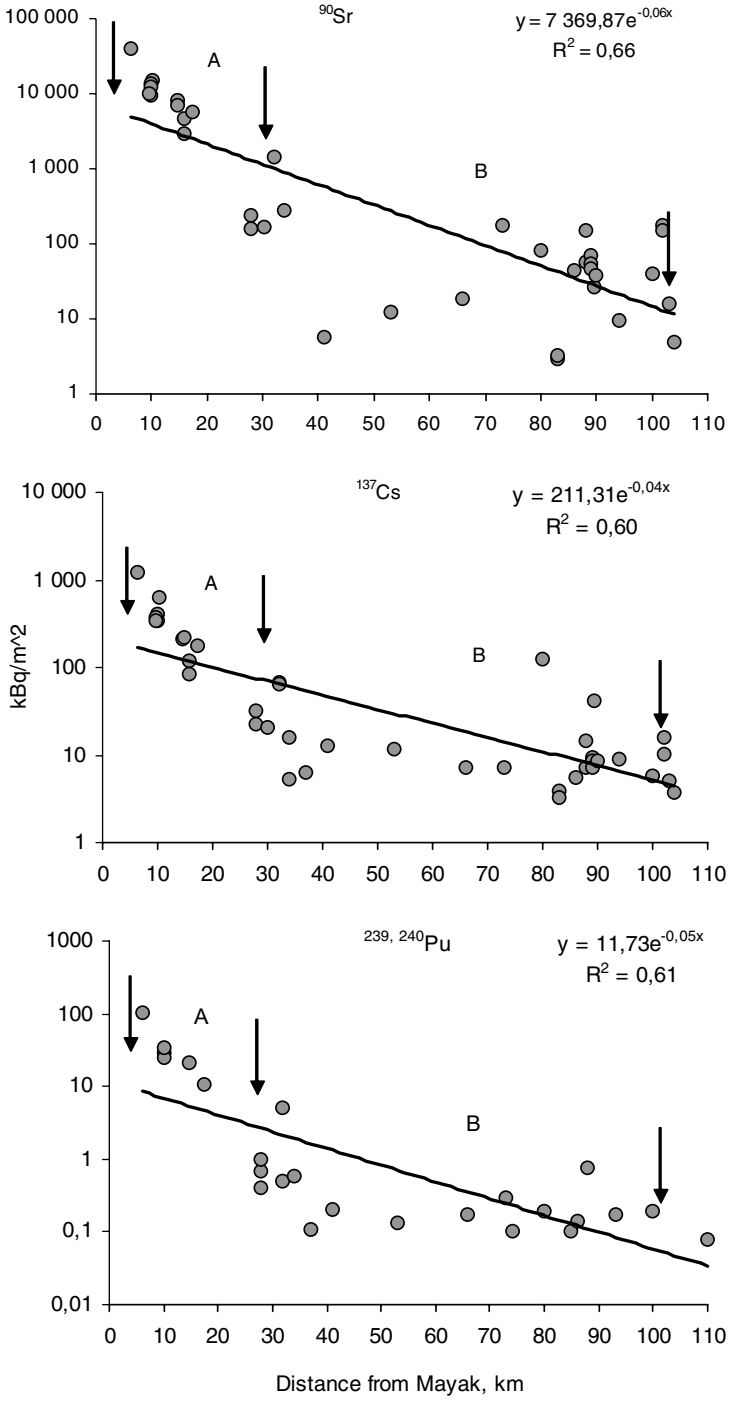

Figure 3. Radionuclide stocks in soils of EURT. Area: A – reserve, B – outside reserve (30–100 km from the accident epicenter).

Using these functions of soil contamination densities distribution $y(x)$, we evaluated radionuclides stocks in the study area within a distance of 6–30 km with the aid of certain integral (integral over the surface in the polar coordinate system):

$$I = 2\pi \times \frac{15}{360} \times 10^{-3} \times \int_{6}^{30} x \cdot e^{(b_0 + b_1 \cdot x)} dx, \text{ TBq}$$

In addition, integral uncertainty resulting from uncertainty of the integrand coefficients should be evaluated. For this purpose, upper and lower boundaries for I must be found using values of coefficients b_0 and b_1 and considering their standard errors. Here, confidence interval for I corresponds approximately to the 1st standard deviation.

Summarizing the data gathered for EURT outside the reserve in previous years [4] and the above results for the impact zone, we can formulate the general relation of changing radionuclide soil contamination densities with distance from PA Mayak (Fig. 3).

Calculations of integral radionuclide stocks for EURT are represented in Table 14.

Table 14. Total amount of radioactive inventories in soils of EURT, TBq (in brackets confidence intervals are given).

Area, distance from epicenter of accident	^{90}Sr	^{137}Cs	^{239,240}Pu
EURSR, 6–30 km	428.2 (286.4-643.4)	15.1 (10.2-22.4)	1.175 (0.623-2.242)
EURT, 30–100 km	143.0 (70.0-357.0)	51.0 (26.0-56.0)	0.5 (0.4-0.6)
Total	571.2	66.1	1.675

As can be seen from the table above, 75% of ^{90}Sr, and some 70% of Pu isotopes are concentrated in soils of the reserve, while most of ^{137}Cs (77%) was recorded in the area outside the reserve. This disproportion in radionuclide distribution is due to Karachay's accident in 1967 that contributed to contamination of area over 30–100 km.

4. CONCLUSION

Emergency situation at production association Mayak in 1957 resulted in formation of East-Ural radioactive trace. This study presents the data on long-lived radionuclide contamination levels in the soil and plant cover of the head part of the trace, at a distance of 6–30 km from the accident epicenter. Within central axis of the trace, changes in ^{90}Sr, ^{137}Cs and ^{239,240}Pu contents in soils with the distance increase from the contamination source are approximated by the exponential relationship. In the direction from the central axis to the periphery of the trace for all radionuclides a profound decline in the contamination gradient was recorded. Anthropogenic disturbance of the area associated with post accident remediation works also accounts for spread in their content values, and also do so the factors that determine intensity of migration processes. Calculations performed indicates that in present in soil cover of the head part of the trace 75% of ^{90}Sr, 70% of ^{239,240}Pu and only 23% of ^{137}Cs are concentrated, of their total amount within entire EURT. Most of ^{137}Cs is located outside the study area, to where it was introduced as a result of Karachaey's accident in 1967.

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References

[1] B.V. Nikipelov, in *IAEA SM 316/55*, Vienna, 1989.
[2] G.N. Romanov, B.V. Nikipelov and E.K. Drozhko, in *Proceedings of Seminar on Comparative assessment of the environmental impact of radionuclides released during three major nuclear accidents: Kyshtym, Windscale, Chernobyl* (Commission of the European Communities. EUR 13574. Luxemburg, 1991), p. 25–40.
[3] Yu. A. Izrael, Yu.S. Tsaturov and V.N. Petrov, in *Proceedings International Symposium on Remediation and Restoration of Radioactive-contaminated Sites in Europe, Antwerpen, 1993,* p. 325–350.
[4] A. Aarkrog, H. Dahlgaard, S.P. Nielsen, A.V. Trapeznikov, I.V. Molchanova, V.N. Pozolotina, E.N. Karavaeva, P.I. Yushkov and G.G. Polikarpov, The Science of the Total Environmental **201** (1997).
[5] V.N. Pozolotina, I.V. Molchanova, L.N. Mihkaylovskaya and E.V. Ul'yanova, Russian Journal of Ecology **36** (2005).