Evaluating the Radiation Status of the Environment on the Underground Nuclear Explosion Site Code-Named Tavda

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Abstract. This paper analyzes the radiation status of environmental components on the underground nuclear explosion site codenamed Tavda, which is located in the Nizhnetavdinsky District of Tyumen Oblast. This underground nuclear explosion occurred in 1967 and was part of the Program #7 Nuclear Explosions for the National Economy; it is currently one of the sources of radiation pollution in its environment. The authors hereof present the analysis of technogenic radionuclide contamination of soils in the explosion epicenter as well as within 500 meters thereof, which analysis takes into account the horizontal and vertical migration of radionuclides, and the contamination of grassy vegetation with strontium-90 and caesium-137 (measurements were taken at 100 m intervals).

We have found out that the radiation burden is essentially a function of strontium-90 content in the soil. Maximum density of strontium-90 and caesium-137 contamination is observed in deeper soil layers. Technogenic radionuclide contamination is present in naturally growing grass on the Tavda site due to a high concentration of strontium-90 with a mean specific radionuclide activity of 288.33 Bq/kg, while the maximum permissible concentration of this element in natural hay is 180 Bq/kg. The concentration of caesium-137 in collected samples was not found to be in excess of the permissible concentrations.

1. Introduction

Scientific progress has greatly contributed to a redistribution of natural radionuclides in the natural environment, while artificial decay products have emerged due to nuclear explosions and accidents [1, 2, 3].

In the second half of the 20th century, the final stage of the Eastern-Ural and Karachai nuclear plume went through the Nizhnetavdinsky District in southern Tyumen Oblast. This plume originated in the Mayak accident. This accident contaminated vast areal expanses with hazardous technogenic radionuclides; the aftereffects have been widely studied and covered in modern research papers and books [4, 5, 6].

Seven kilometers away from the village of Chugunayevo, an underground nuclear explosion was engineered in 1967; its effects on the nature have not yet been thoroughly studied and shown in scientific literature. Code-named Tavda, this explosion was orchestrated for research purposes, being
the first underground nuclear explosion in Siberia; as such, it was part of the Program #7 Nuclear Explosions for the National Economy [7, 8, 9, 10].

Soils with high absorption capacity feature intensive absorption of various technogenic contaminants; they are therefore one of the natural components where decay products are localized. Soils form a powerful primary depot, from which man-made radionuclides are absorbed by grass and further make it to animal and human bodies [11, 12, 13].

In connection with the above, the research objective was to evaluate the radiation status of soils and vegetation on the Tavda site. To that end, we had to find the concentrations of man-made radionuclides in the gray forest soils in the epicenter and within 500 meters of it; we also had to find the specific activity of strontium-90 and caesium-137 in the grassy vegetation of the studied area.

2. Research Methods
The radiation status of soils in this area was evaluated by analyzing the samples collected in fall 2014 in the epicenter as well as every 100 meters within 500 meters north, west, east, and south of it. Samples were collected layer by layer at depths of 0 to 10 cm, 10 to 20 cm, 20 to 40 cm, 40 to 60 cm,...180 to 200 cm in accordance with GOST 28168-89 Soils. Soil sampling [14]. For radiological study, we sampled the ground layer of grassy vegetation from the sampling points. Samples of grassy vegetation mainly consisted of Brōmus inērmis and Poa pratēnsis; these cereal families are often used by private farms to produce hay and green fodder [15]. All the unprocessed soil and vegetation samples were analyzed using a Progress-2000 spectrometer.

We calculated some statistics of technogenic radionuclides collected from the sampling points; in particular, we found the representativeness errors and significance criteria, calculation of which led us to a conclusion that the field and laboratory samples were representative of the general population (significance criteria for the arithmetic mean, the standard deviation, and variance in excess of 3) [16, 17].

3. Results
Charts in figures 1 to 4 show the results of spectrometry.

![Figure 1](image-url)
Figure 2. Strontium-90 contamination density on the Tavda site, epicenter and south of it, 2014, Ci/km²

Legend: left to right – Center, South-100, South-200, South-300, South-400, South-500, upper right corner – depth of sample collection (cm)

As can be seen in these charts, strontium-90 contamination in the epicenter was at its peak at 80 to 100 cm (3.46 Ci/km²). East of the center, high concentrations were also observed in the lower layers of soil. At the same time, strontium-90 contamination was 0.003 to 0.295 Ci/km² in the 0- to 20-cm layer.

Correlation and regression analysis shows that high content of this radionuclide did correlate with the layer depth, which could be described by a linear equation. The correlation coefficient ranged from 0.82 to 0.98 depending on the distance to the process well [17].

Figure 3. Strontium-90 contamination density on the Tavda site, epicenter and west of it, 2014, Ci/km²

Legend: left to right – Center, West-100, West-200, West-300, West-400, West-500, upper right corner – depth of sample collection (cm)

In-field analysis carried out to the north, south, and west of the Tavda underground explosion site showed that strontium-90 contamination followed patterns similar to those of the eastern direction, with concentrations being higher at depth.
Two-factor ANOVA was used to statistically analyze the effect and interaction of the distance to the process well and the soil layer depth with the strontium-90 contamination values. Significant differences in strontium-90 concentrations were found to be dependent on the distance to the epicenter. For example, a $F_{05} = 2.44$ the $F_{\text{fact}}$ equaled 78.57 for Factor A (distance to the process well); for Factor B, significance was much lower $F_{05} = 1.95$, $F_{\text{fact}} = 16.60$; for the interrelationship of A and B, $F_{05} = 1.54$, $F_{\text{fact}} = 1.74$, an indication of weak synergy [16,17].

The caesium-137 contamination degree was found to be at max east of the epicenter, see Figures 5 to 8. Higher concentrations of this radionuclide were observed in lower layers. As can be seen in Figure 8, the distribution of caesium-137 was rather stable, varying from 0.9 to 1.3 Ci/km$^2$ at East-100 and from 0.2 to 1.3 Ci/km$^2$ at East-500.

These results do not contradict the data of other researchers studying the radioecological situation on the sites of underground nuclear explosions. In Ivanovo Oblast, caesium-137 contamination was found to be at maximum in the turf layer (59.3%) with the 0- to 20-cm layer containing 1.903 Ci/km$^2$ of this radionuclide [18].
When analyzing the caesium-137 deposition density in other sampling locations shown in Figures 5 to 7, we were able to trace a smooth transition of this element into lower layers; only at West-400, 60 to 80-cm deep did we identify a peak concentration of 0.720 Ci/km$^2$.

Having calculated the caesium-137 concentration and layer depth correlation coefficient, we found out that an expressed linear dependency was observed in the epicenter and within 200 meters of it; the coefficient ranged from 0.87 to 0.93. Going further from the process well, this dependency was becoming less pronounced; 500 meters away from the epicenter, the coefficient equaled 0.55.
Figure 8. Caesium-137 contamination density on the Tavda site, epicenter and east of it, 2014, Ci/km²
Legend: left to right – Center, East-100, East-200, East-300, East-400, East-500, upper right corner – depth of sample collection (cm)

Analysis of data on the technogenic radionuclide contamination of soils in the Nizhnetavdinsky District, southern Tyumen Oblast, led us to a conclusion that the bulk of long-lived radionuclides was concentrated in the lower layers. This was probably due to the fact that the Tavda explosion was a camouflet explosion, i.e. its decay products never surfaced. When such explosions occur, a gas- and water-proof container emerges in the bowels of the Earth; however, this container will probably not stay intact forever [19, 20].

Speaking of the activity of caesium-137 and strontium-80 in the grassy vegetation on the underground nuclear explosion site in the Nizhnetavdinsky district, we observed that these elements had different concentrations, see Figures 10 and 11. Caesium-137 concentration in grass samples was at max in the North-400, North-500, West-400, South-300, and South-400 samples, ranging from 404.0 to 122.3 Bq/kg. The concentration was minimum in the East-400 sample (10.49 Bq/kg). In most of this area, the activity of caesium-137 ranged from 40.0 to 14.8 Bq/kg.

Figure 9. Caesium-137 concentration in the grassy vegetation on the Tavda site, 2014, Bq/kg.
Legend (left to right): Center, North-100, North-200, North-300, North-400, North-500, West-100, West-200, West-300, West-400, West-500, South-100, South-200, South-300, South-400, South-500, East-100, East-200, East-300, East-400, East-500, average 71.42 Bq/kg

Analysis of the strontium-90 concentration in the grassy vegetation notably showed a very wide range of the spectrometry data. The activity of this element was at peak in the North-100 sample (1,251.0 Bq/kg). The lowest concentration of radiostrontium was observed in the South-400 (34.30 Bq/kg) and South-500 (30.00 Bq/kg) samples. In most of this area, strontium-90 concentration ranged from 576.00 to 181.00 Bq/kg.
Figure 10. Strontium-90 concentration in the grassy vegetation on the Tavda site, 2014, Bq/kg.

Legend (left to right): Center, North-100, North-200, North-300, North-400, North-500, West-100, West-200, West-300, West-400, West-500, South-100, South-200, South-300, South-400, South-500, East-100, East-200, East-300, East-400, East-500, average 288.33 Bq/kg

Since natural grass is the most frequently used raw material for hay production, it would be reasonable to compare the obtained data against the maximum permissible concentrations of technogenic radionuclides in natural-grass hay.

Therefore, the mean concentration of caesium-137 in the natural grass on the Tavda underground nuclear explosion site was 71.42 Bq/kg, while the maximum permissible concentration is 400 Bq/kg. Only in the North-500 sample did the concentration exceed the MPC (404.0 Bq/kg). The mean concentration of strontium-90 was 288.33 Bq/kg, while the hay MPC of this element is 180 Bq/kg; besides, some samples had 1.5 to 2 times higher-than-permissible concentration of this element [21, 22]. Contamination of grassy vegetation on the explosion site in the Nizhnetavdinsky District was mainly attributable to strontium-90. This was quite logical, as radioactive strontium accounted for the bulk of the soil contamination density in this area. Besides, the transfer factor (TF) of strontium-90 in a soil-plant system is considerably higher than that of caesium-137. Calculations showed that the radiostrontium TF (9.561 Bq/kg:kBq/m²) for soil-to-overground plant transfer was almost 1.5 times that of caesium-137. Cattle pasturage and use of grassy vegetation for hay production involves an increased content of technogenic strontium-90.

4. References
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