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Research Article

Analysis of radioecological monitoring capabilities for assessing the impact of normalized NPP emissions on agroecosystems*

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Abstract

The regulations for radioecological monitoring (REM) of agroecosystems in areas surrounding operational nuclear power plants (NPPs) are characterized by a high degree of detail. Obtaining the required empirical data involves significant financial costs. This raises the question: to what extent do monitoring data reflect the impact of NPPs on the agricultural environment? Based on long-term emissions data from the Kursk and Rostov NPPs, the dynamics of radionuclide accumulation in soil originating from NPPs were calculated. It was shown that the concentrations of long-lived ^{137}Cs and ^{90}Sr in soil increase over time during NPP operation by 30–40 times. However, a comparison of the calculations with REM data over many years indicates that the contribution of NPP-derived ^{137}Cs and ^{90}Sr to the specific activity of these radionuclides in soil does not exceed 0.01–0.1%. Thus, REM primarily detects ^{137}Cs and ^{90}Sr of global and Chernobyl origin. Due to the negligible NPP contribution, the spatial distribution of ^{137}Cs within 30-km zones is uniform and follows a lognormal distribution. According to estimates, the activity levels of NPP-derived radionuclides in soil, recommended for REM, are below detection limits. The study concludes that REM guidelines for agroecosystems around NPPs should be optimized. Adjustments may include revising the list of radionuclides analyzed, reducing the types of agricultural products monitored, and increasing the intervals between sampling. The need to focus efforts on developing REM programs for assessing impacts in normal and emergency situations is emphasized.

Keywords

Nuclear power plants, radioecological monitoring, agroecosystems, NPP-derived radionuclides, Chernobyl fallout, specific soil activity, probability density distribution, population dose load

Introduction

Along with economic competitiveness, full use of resource potential and engineering support for non-proliferation resistance, a key prerequisite for the evolution of nuclear power is radiation safety for both the public and biota. The set of objectives in this field includes radioecological justification of the planned nuclear power facilities and their operational oversight, including monitoring studies and ensuring the possibility for predicting the consequences of radiation accidents (Spiridonov et al. 2019).

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The variety of radioecological objectives necessitates the developing and application of a range of methodological approaches, experimental techniques, and computational tools. This paper focuses on radioecological monitoring (REM) issues of for NPPs under normal operating conditions. It should be emphasized that monitoring activities during emergencies require planning based on special methods of predictive assessment.

The primary goal of REM in the NPPs' vicinity is to assess the nuclear power plant impact on the members of the public using long-term radioecological survey data (Kuznetsov et al. 2019; Fesenko et al. 2022). Particular attention is paid to agrarian ecosystems, since within the 50-km zone of currently operating nuclear power plants, 50 to 90% of the area is occupied by agricultural lands (MU 13.5.13-00 2000). Agricultural products from these areas constitute a major source of radionuclide intake for humans. To estimate the role of the agrosphere in the public radiation exposure from the NPPs' gas-aerosol emissions, calculations of partial doses formed by plant-originated radionuclides within various environmental components were performed (Spiridonov et al. 2021). These calculations revealed that radionuclides contained in agricultural products are the key contributors to the cumulative doses from NPP emissions.

To date, extensive data have been collected from REM studies of agroecosystems in Russian NPP deployment areas (Kuznetsov et al. 2019; Panov et al. 2019; Kuznetsov et al. 2020; Sanzharova et al. 2020; Fesenko et al. 2022). It appears to be necessary to analyze whether these empirical data adequately reflect the impact of NPPs on soil and agricultural products contamination. Such analysis results can be used to conclude on feasibility of detailed REM regulations for the agroecosystems within the NPPs' vicinities under the conditions of their normal operation.

As noted in (Spiridonov et al. 2019), one of the REM fundamentals is achieving reliable estimates for the public and environmental radiation exposure at minimal cost. In this connection, a key consideration of REM principles is the integration of experimental and computational methods for optimizing the surveying costs (sampling, sample preparation, measurements) (Spiridonov et al. 2019).

This study aims to analyze REM capabilities for assessing the NPP impact on agrosphere under normal operating conditions. A brief review of existing REM regulations for agroecosystems was conducted. The accumulation of regulated radionuclides in soil from NPP operations was calculated, and the impact of plant-originated radionuclides on soil contamination was estimated by comparing these results with long-term REM data.

Peculiarities of the agroecosystem REM regulations

The essential components of the agroecosystem REM regulations near NPPs are (MU 13.5.13-00 2000; Sanzharova et al. 2020; IAEA Safety Standards Series No. RS-G-1.8 (2005):

- list of monitored agroecosystem components and agricultural products;
- lists of monitored radionuclides;
- temporal parameters, i.e., sampling frequency of followed by sample preparation and measurement of radionuclide content in samples.

These components determine the level of detail in surveying the NPP adjacent areas and the cumulative REM cost.

According to the agroecosystem REM regulations, samples of arable and pasture soils, water, crops (vegetables, potatoes, cereals, etc.), fodder and livestock products (meat, milk, etc.) must be collected in the NPP affected areas in the course of normal operation (MU 13.5.13-00 2000). It is recommended that milk samples should be taken five times a year. Radionuclide levels in soil, as stated in MU 13.5.13-00 2000, should be measured twice a year for arable land and three times a year for pastures and hayfields. Lists of monitored radionuclides include fission products (^{95}Zr+^{95}Nb, ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{131}I) and activation products (^{51}Cr, ^{54}Mn, ^{58}Co, ^{60}Co, ^{59}Fe). Besides, recommendations include measurement of the ^{3}H content in water during watering or fishing periods.

The IAEA document (IAEA Safety Standards Series No. RS-G-1.8 2005) on the source monitoring and environmental radiation monitoring programs and systems recommends measuring radionuclide levels in air, soil, drinking water, groundwater and a broad spectrum of farm products. In this case, the sampling frequency varies from one year (for soil) to one month (milk, pasture grass, leafy vegetables). Cumulative beta activity is mentioned as a typical measured parameter, and the possibility of using spectrometry methods is noted. There is no specified list of radionuclides in the NPP atmospheric emissions to be detected as part of REM.

The same IAEA document specifies detection limits for such plant-originated radionuclides as ^{54}Mn, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{90}Sr, ^{95}Zr+^{95}Nb and ^{137}Cs in soil and water. The minimum detected concentrations of these radionuclides in soil range from 2 to 4 Bq/kg for a 100 g sample (IAEA Safety Standards Series No. RS-G-1.8 2005). It should be noted that measuring ^{90}Sr content in soil and other environmental components is performed through a labor-intensive, time-consuming, and expensive radiochemical method, according to current standards. Beta spectrometry offers a cheaper alternative but has higher detection limits (Potapov et al. 2021): the minimum measured activity of ^{90}Sr in soil in this case is 60 to 100 Bq/kg while there are no other artificial radionuclides. This figure may amount to 200 Bq/kg with ^{137}Cs and ^{60}Co being present in soil.

A brief analysis of the peculiarities of REM regulations reveals that consistent detecting (throughout the year) an extensive list of radionuclides contained in numerous objects requires substantial financial and material resources. This raises questions about the feasibility of detecting plant-originated radionuclides in soil and farm products considering two factors:

- detection limit constraints;

- presence of additional sources for artificial radionuclides in the NPP vicinities, including global and Chernobyl fallouts.

When justifying the appropriate levels of detail for the agroecosystem REM regulations, it is crucial to consider that radioactive NPP emissions during normal operation are rigorously monitored and controlled. Available data on actual NPP emissions make it possible to estimate the levels of plant-originated radionuclides in agroecosystem components by utilizing radioecological models.

Content of plant-originated radionuclides in soils in near NPPs

Once released into the environment, radionuclides accumulate in soil, which serves as a pathway for their uptake by vegetation and their further migration through food chains. In this context, obtaining empirical data on the content of radionuclides in soil is essential for REM in the NPP vicinities (Fesenko et al. 2022; MU 13.5.13-00 2000; Sanzharova et al. 2020). The REM process is focused basically on radiologically significant long-lived ^{137}Cs and ^{90}Sr radionuclides as they are regulated in agricultural and food production (Kuznetsov et al. 2019; Panov et al. 2019; Kuznetsov et al. 2020; Sanzharova et al. 2020; Fesenko et al. 2022).

The CROM code (version 8.4.1) by Robles et al. 2007 was used to estimate the contributions of radioactive materials from NPPs to the soil contamination by artificial radionuclides. This tool was developed based on models presented in the IAEA document Safety Reports Series No. 19 2001 and is designed to forecast the distribution of radionuclides from the NPP emissions across various environmental components, as well as to calculate public exposure doses. The models were parameterized taking into account long-term average weather data and other areal characteristics. The concentration of soil-accumulated radionuclides was calculated using a conservative pointwise approach at the designated "point" at the boundary of the NPP buffer zones.

The Kursk NPP with RBMK-1000 reactors and the Rostov NPP with VVER-1000 reactors were selected as sources of radionuclides emitted into the environment. The Kursk NPP's first reactor was launched in 1977, and the Rostov NPP's first reactor began operation in 2001. The calculations used long-term emission data from these NPPs (The radiation situation on the territory of Russia and neighboring states in 2002–2022. Yearbooks 2004–2023). It should be noted that annual emissions in the course of long-term NPP operation are presented only for ^{131}I, ^{137}Cs, ^{134}Cs, ^{60}Co and inert radioactive gases (IRG). At the Kursk NPP, monitoring of some radionuclides (^{54}Mn, ^{59}Fe, ^{140}Ba, etc.) began in 2020. Additionally, ^{90}Sr was detected within atmospheric emissions until 2004 (The radiation situation on the territory of Russia and neighboring states in 2002–2022. Yearbooks 2004–2023). The average values of their annual emissions were used to fill the gaps in initial data for individual radionuclides.

Fig. 1 illustrates the estimated maximum specific activity of plant-originated radionuclides in the topsoil layer (0 to 25 cm) near the Kursk NPP. The dynamics reflects superposing processes of different nature: radionuclide deposition onto the soil surface, radioactive decay, and ecological purification primarily due to the vertical migration through the soil. The half-life significantly influences the decrease rate of the radionuclide content in soil.

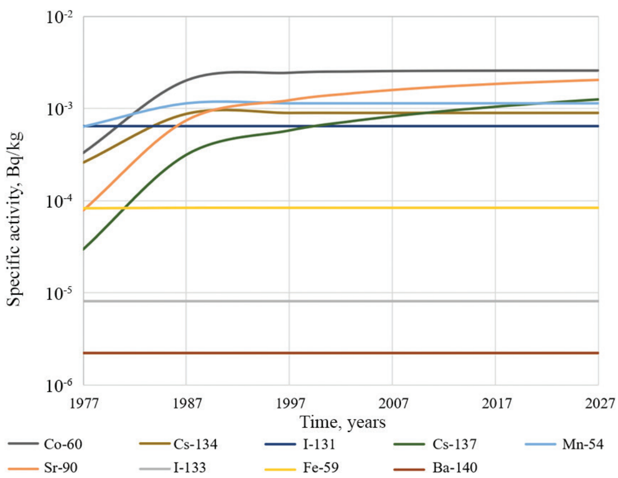

Figure 1. Calculated dynamics of the maximum specific activity in soil of radionuclides released by the Kursk NPP.

The specific activity of short-lived radionuclides (^{133}I, ^{131}I, ^{140}Ba and ^{59}Fe with half-lives of 0.83, 8, 12 and 44 days respectively) in soil remains constant starting from the first year of the NPP operation. The concentrations of ^{54}Mn, ^{134}Cs and ^{60}Co (half-lives of 312 days to 5.27 years) reach quasi-equilibrium in 10 to 15 years. Long-lived radionuclides, such as ^{137}Cs and ^{90}Sr, with half-lives of 30 and 29 years, persistently accumulate in soil throughout the plant operation time. Thus, in the period of 1977 to 2030, the concentration of ^{137}Cs in soil increases by a factor of 43, and the concentration of ^{90}Sr increases by a factor of 26. A certain difference exists due to the fact that ^{90}Sr migrates through the soil with a greater intensity compared to ^{137}Cs.

Fig. 2 illustrates the dynamics of the maximum specific activity of plant-originated radionuclides in the topsoil layer (0 to 25 cm) in the immediate vicinity of the Rostov NPP. Unlike ^{131}I, ^{134}Cs and ^{60}Co, long-lived ^{137}Cs continues to accumulate in soil at the present time as well.

Importantly, the concentrations of each of the considered plant-originated radionuclides in soil do not exceed $3 \cdot 10^{-3}$ Bq/kg (below the detection limit) throughout the NPP operation time. It will be valuable to compare the results obtained with REM data pertaining to the vicinities of the NPPs under consideration.

Comparison of calculation results and REM data

Artificial radionuclides measured in soil and agricultural products during REM in the NPPs' vicinities, primarily

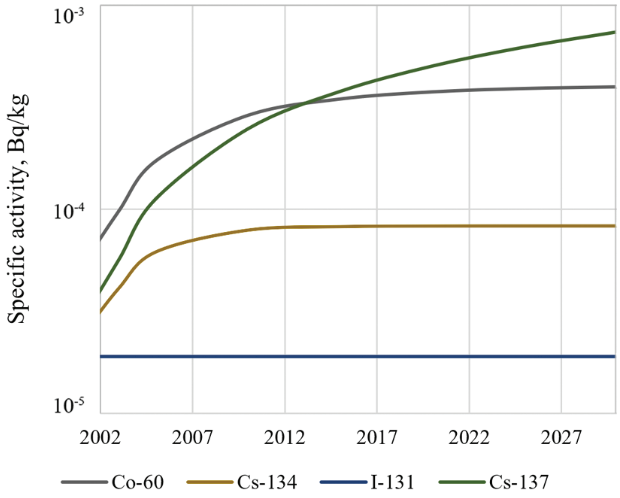

Figure 2. Calculated dynamics of the maximum specific activity in soil of radionuclides released by the Rostov NPP.

include ^{137}Cs and ^{90}Sr (Kuznetsov et al. 2019; Panov et al. 2019; Kuznetsov et al. 2020; Sanzharova et al. 2020; Fesenko et al. 2022). Figs 3, 4 present data from long-term observations of the radionuclide specific activity in the topsoil layer (0 to 25 cm) within a 10 km radius of the Kursk NPP (Kuznetsov et al. 2019, 2020) (statistical parameters include median, and lower and upper quartiles, as well as the minimum and maximum values that delineate the boundaries of the empirical sample). These figures also show the calculated dynamics of specific activities of ^{137}Cs and ^{90}Sr that have accumulated in soil due to atmospheric emissions from the Kursk NPP.

A comparative analysis of the data obtained shows that the specific activity of the plant-originated ^{137}Cs in soil is four orders of magnitude lower than that measured during REM in the vicinity of Kursk NPP. A similar comparison for ^{90}Sr demonstrates that the total concentration of this radionuclide

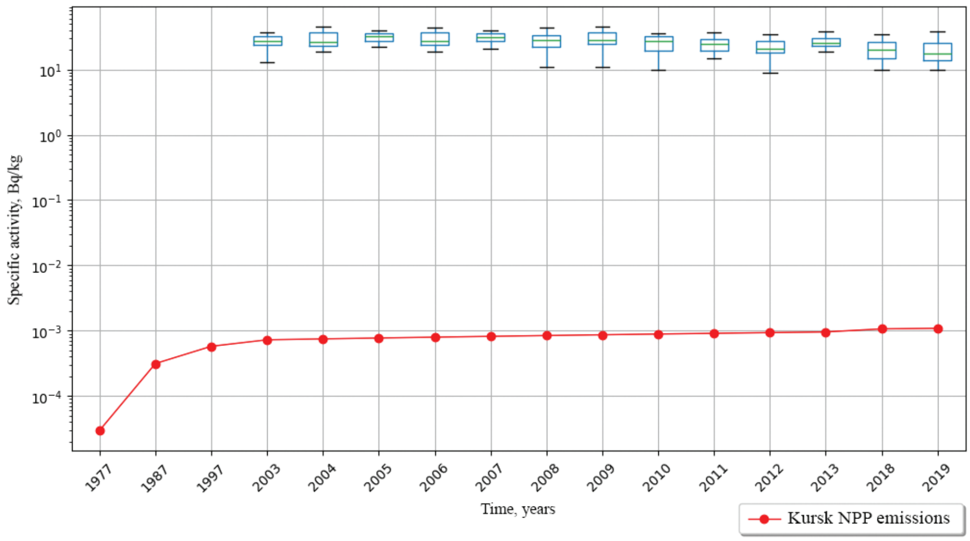

Figure 3. Comparison of specific activities of ^{137}Cs in soil in the immediate vicinity of the Kursk NPP obtained through REM and calculated based on data from the plant's atmospheric emissions.

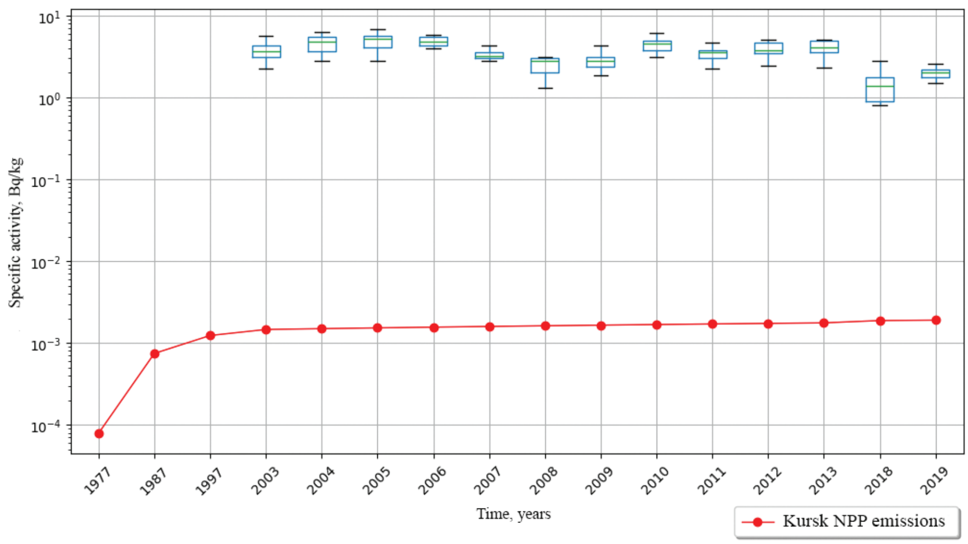

Figure 4. Comparison of specific activities of ^{90}Sr in soil in the immediate vicinity of the Kursk NPP obtained through REM and calculated based on data from the plant's atmospheric emissions.

in measured soil exceeds the content of ^{90}Sr originating from the Kursk NPP by three orders of magnitude.

Thus, REM of the NPP impact zone includes determination of the content of “background” artificial radionuclides (^{137}Cs and ^{90}Sr) in soil, which originate from global and Chernobyl fallouts. The contributions of ^{137}Cs and ^{90}Sr, which entered soil due to emissions from the Kursk NPP do not exceed 0.013% and 0.22 , respectively, of the total specific activity of these radionuclides in the soil (conservative estimates of the NPP’s contributions were based on minimal monitoring data and maximum calculated values for the period 2003–2019). A smaller contribution of the plant-originated ^{137}Cs compared to ^{90}Sr can be explained by the fact that Chernobyl contamination of the studied area is primarily associated with ^{137}Cs.

Fig. 5 compares the dynamics of the maximum specific activity of plant-originated ^{137}Cs in soil near the Rostov NPP with long-term radioecological monitoring data (Panov et al. 2019). As shown in the figure, according to the most recent year of REM data, the ^{137}Cs content in soil, primarily formed by global fallout, exceeds the content of this radionuclide accumulated as a result of emissions from the Rostov NPP by four orders of magnitude.

The obtained results indicate that NPPs’ emissions have no significant impact on the increase in specific activities of ^{137}Cs and ^{90}Sr in soil, relative to the background levels resulting from global and Chernobyl fallout.

This conclusion is further supported by data characterizing the spatial distribution of ^{137}Cs in soil within the 30-km zones of the Kursk and Rostov NPPs, based on sample sizes of 300 and 590 measurements, respectively. Statistical analysis of the data for the Kursk NPP revealed that the distribution of ^{137}Cs contamination density (A, kBq/m^2) follows a lognormal law (Fig. 6A). The

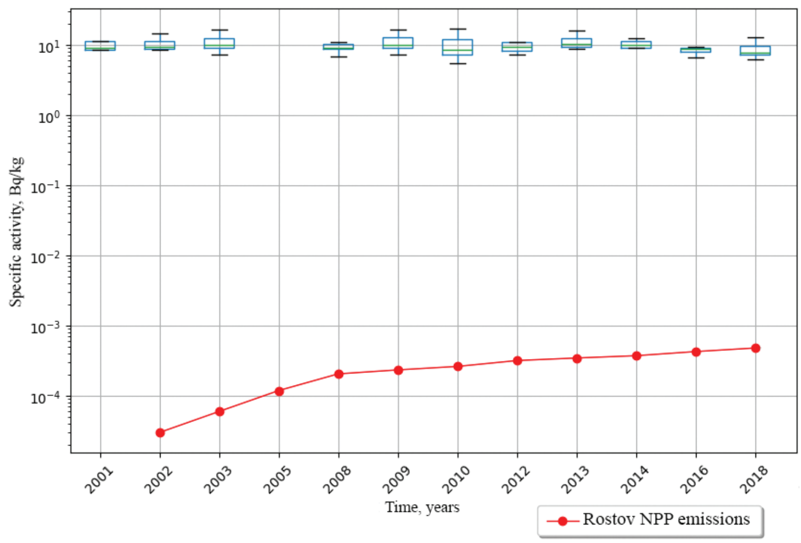

Figure 5. Comparison of specific activities of ^{137}Cs in soil in the immediate vicinity of the Rostov NPP obtained through REM and calculated based on data from the plant’s atmospheric emissions.

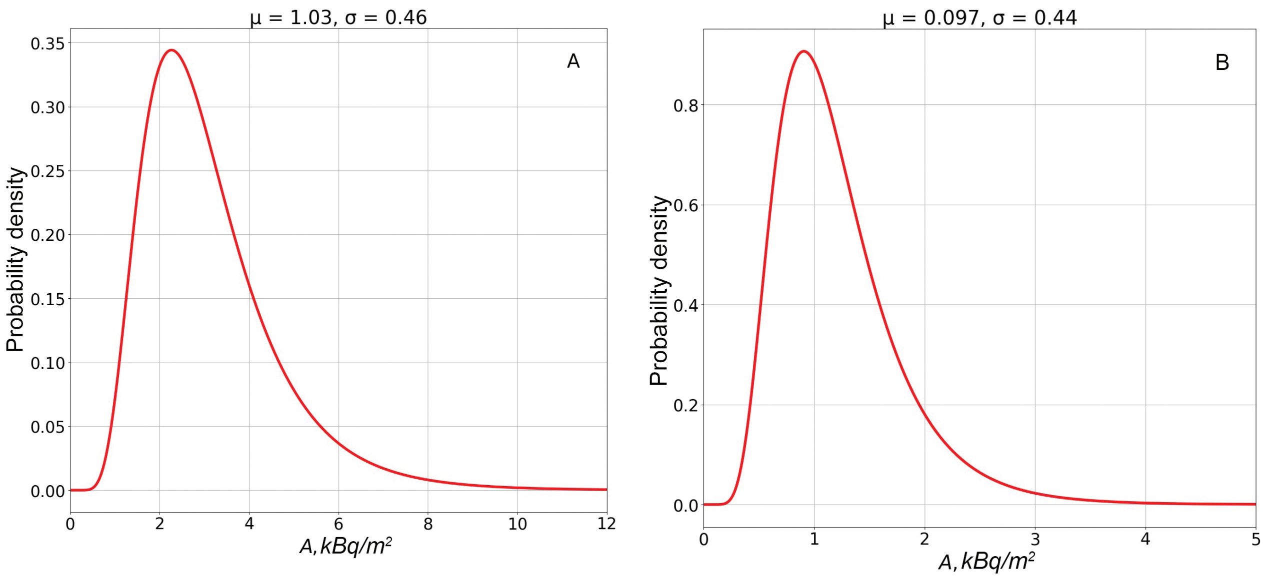

Figure 6. Probability distribution densities of ^{137}Cs soil contamination density values in the 30-km zones of the Kursk (**A**) and Rostov (**B**) NPPs.

Kolmogorov-Smirnov goodness-of-fit test statistic for assessing the normality of the ln(A) distribution was 0.0773, which complies with the critical value at a 0.01 significance level (1%). A lognormal distribution was also observed for ^{137}Cs contamination density in the 30-km zone of the Rostov NPP (Fig. 6B).

The parameters of the normal distribution $N(\mu,\sigma)$ were estimated for the logarithm of ^{137}Cs soil contamination density in the 30-km zones of the studied NPPs (Spiridonov et al. 2019). The values of μ and σ for the Kursk NPP were 1.03 and 0.46, respectively, while for the Rostov NPP, they were 0.097 and 0.44. The lower mean value μ for the Rostov NPP is likely attributed to the absence of Chernobyl fallout in its region. The σ values remain similar despite differences in the primary sources of ^{137}Cs contamination (e.g., the presence of a "Chernobyl contribution" for the Kursk NPP).

Based on the analysis of empirical data characterizing the distribution of ^{137}Cs within the 30-km NPP zones, it can be concluded that the soil contamination density of this radionuclide behaves as a random variable that follows a theoretical lognormal distribution. Furthermore, both study areas can be regarded as contamination-homogeneous (gradient-free) with respect to ^{137}Cs, given the negligibly small contribution of NPP emissions to the formation of a spatial gradient in radioactive fallout.

Analysis of the results obtained

Comparison of long-term dynamics of ^{137}Cs and ^{90}Sr content in soil, from multi-year emission data of the Rostov and Kursk NPPs, with REM results over an extended period, demonstrates that NPPs do not contribute significantly to soil contamination by these radionuclides. The contribution of the plant-originated ^{137}Cs and ^{90}Sr to the specific activity of these radionuclides in soil does not exceed the interval of 0.01 to 0.1%. Radioecological monitoring of the NPP vicinities determines ^{137}Cs and ^{90}Sr originating from global and Chernobyl fallout. Statistical validation confirms that the spatial distribution of these radionuclides near NPPs adheres to a lognormal distribution.

Calculated estimates indicate that the activity of plant-originated radionuclides (^{54}Mn, ^{134}Cs, ^{60}Co, ^{131}I, ^{59}Fe, ^{140}Ba) in soil – most of which are recommended for monitoring under the REM protocol for agroecosystems in NPP impact zones during normal operation (MU 13.5.13-00 2000; Sanzharova et al. 2020) – remains below the minimum detectable activity. Consequently, the content of these radionuclides and plant-originated ^{137}Cs and ^{90}Sr in agricultural products will not exceed detection limits throughout the NPP operational lifespan. Soil-to-plant transfer factors for radionuclides are generally <1, with rare exceptions. The integral impact indicator of NPPs on the public (exposure dose calculated based on the actual Kursk and Rostov NPP emissions) does not exceed 4.6 µSv/year. This value is lower than the dose quota threshold for NPPs (10 µSv/year) (SP AS-03 2003).

Given these findings, it appears reasonable to optimize the regulatory framework for REM in agroecosystems surrounding NPPs. Such optimization could include revising the list of radionuclides subject to monitoring—particularly reducing efforts on radionuclides not measurable by gamma spectrometry – narrowing the range of agricultural products under control, and extending sampling intervals.

Special attention should be paid to radionuclides that contribute most significantly to the total public dose, notably ^{14}C and ^{3}H (Vasyanovich et al. 2019; Spiridonov et al. 2021). Monitoring of these isotopes in emissions from Russian NPPs commenced in 2018–2020. As noted in Sazykina et al. 2024, artificial ^{14}C production is comparable to its natural generation, leading to its accumulation in the biosphere and potential incorporation into genetic structures. An important research direction is the improvement of experimental methods for determining ^{14}C and ^{3}H in natural environments and the development of models describing their behavior in the environment.

When planning REM for agroecosystems in territories adjacent to NPPs, regional characteristics must be considered, particularly the presence of additional sources of anthropogenic contamination (beyond global and Chernobyl fallout). For instance, the Leningrad NPP is not the primary "dose-forming facility" for the public in its region (Spiridonov et al. 2018). The greatest contribution to the radiation exposure of public comes from the radioactive waste processing and disposal facility – "RosRAO".

In some regions, additional contamination of agricultural products may be caused by specific processes, including sprinkler irrigation. As noted in Kuznetsov et al. 2004, when consuming products obtained from agricultural lands irrigated with water from NPP cooling reservoirs, the total internal radiation dose to the population may reach 100 mSv/year. This value exceeds the lower boundary of the dose quota for NPPs – 10 µSv/year (Spiridonov et al. 2023). Therefore, REM regulations for agroecosystems should be developed considering the specifics of agricultural production in regions where particular NPPs are located.

Conclusion

Radioecological monitoring for NPP impact zones is undoubtedly necessary from the perspective of periodic public information regarding the radiological situation. Assessment by independent specialists and experts represents an important complement to research conducted by NPP staff ecologists. According to IAEA recommendations (The radiation situation on the territory of Russia and neighboring states in 2002–2022. Yearbooks 2004–2023), radiation control of locally produced agricultural products is an integral condition for NPP operation.

As a key premise in revising REM protocols for agroecosystems must be the optimization of resource allocation for sampling, sample preparation, and analytical measurements. One approach to achieving this goal is the use of predictive assessments based on radioecological models alongside experimental methods, provided that comprehensive information characterizing NPP atmospheric releases is available.

The optimization mentioned above pertains to REM regulations for agroecosystems in NPP impact zones during normal operational conditions (Safety Reports Series No. 19 2001; Sanzharova et al. 2020). However, given the current geopolitical context, efforts should prioritize the development of REM systems capable of evaluating agrosphere consequences arising from non-routine incidents at NPPs and other nuclear fuel cycle facilities. A core component of such systems is the methodological framework for establishing operational intervention levels (OILs) based on monitoring data (Spiridonov et al. 2023). For solving two interrelated tasks – radioecological forecasting and correct establishment of OILs – it is advisable to employ unified computational tools (Spiridonov and Mikailova 2024).

References

- Fesenko SV, Sanzharova NI, Karpenko EI, Isamov NN, Kuznetsov VK, Panov AV, Tsigvintsev PN (2022) Radioecological monitoring and its role in ensuring safety of Nuclear Power Plants. Nuclear Energy and Technology 8(1): 43–48. https://doi.org/10.3897/nucet.8.82619
- IAEA Safety Standards Series No. RS-G-1.8 (2005) Environmental and source monitoring for purposes of radiation protection. International Atomic Energy Agency, Vienna, 119 pp.
- Kuznetsov VK, Sanzharova NI, Alexakhin RM (2004) Radiation-hygienic aspects of the use of waters of cooling pond NPP for irrigating the agricultural land. Medical Radiology and Radiation Safety 49(6): 27–36. [in Russian]
- Kuznetsov VK, Sanzharova NI, Panov AV, Isamov NN (2019) Radioecological monitoring of agroecosystems in the NPP vicinity: Methodology and results of investigations. Medical Radiology and Radiation Safety 64(4): 25–31. https://doi.org/10.12737/article_5d1102809c5ac3.32613968 [in Russian]
- Kuznetsov VK, Panov AV, Sanzharova NI, Isamov NN, Andreeva NV, Geshel IV, Sidorova EV (2020) The analysis of radioecological monitoring results in the vicinity of the Kursk Nuclear Power Plant. Radiation Hygiene 13(2): 19–30. https://doi.org/10.21514/1998-426X-2020-13-2-19-30 [in Russian]
- MU 13.5.13-00 (2000) Organization of state radioecological monitoring of agroecosystems in the zone of influence to radiation hazardous objects. Publisher of the RAAS, Moscow, 28 pp.
- Panov AV, Isamov NN, Kuznetsov VK (2019) Radioecological monitoring in the vicinity of Rostov NPP. The analysis of results of long-term investigations. Radiation Hygiene 12(2): 54–65. https://doi.org/10.21514/1998-426X-2019-12-2s-54-65 [in Russian]
- Potapov VN, Ivanov OP, Luk'yanov VV, Stepanov VE, Korobova EM, Mikhailovskaya LN (2021) Portable β-spectrometer for 90Sr activity field-measurements in radioecology and rehabilitation of Nuclear Energy Facilities. Atomic Energy 129(3): 155–162. https://doi.org/10.1007/s10512-021-00728-5
- Robles B, Suárñez A, Mora JC, Cancio D (2007) Models implemented in the CROM code (CROM code for impact assessment). Madrid, 2007, 60 pp. [in Spanish]
- Safety Reports Series No. 19 (2001) Generic models for use in assessing the impact of discharges of radioactive substances to the environment. International Atomic Energy Agency, Vienna, 229 pp.
- Sanzharova NI, Panov AV, Isamov NN, Kuznetsov VK, Karpenko EI, Andreeva NV, Gordienko EV (2020) Concept and program of radiation-ecological monitoring in the areas of nuclear power plant placement. Monitoring of natural and agricultural ecosystems in areas of nuclear power plants: Proceedings of the RIRAE. Issue 3 (Ed. Prof. S.V. Fesenko). Obninsk, RIRAE Publ., 9–21. [in Russian]
- Sazykina TG, Kryshev AI, Kryshev II (2024) Analytical methods for dosimetry of ionizing radiation in the environment. LLC "IPC "Maska" Publ., Moscow, 236 pp. [in Russian]
- SP AS-03 (2003) Sanitary rules for the design and operation of nuclear power plants. Sanitary rules and hygiene standards SanPin 2.6.1.24-03. Ministry of Health of Russia, Moscow, 41 pp. [in Russian]
- Spiridonov SI, Kurtmulaeva VE, Karpenko EI (2018) Comparative assessment of the dose load on the population from atmospheric emissions of enterprises of the nuclear-industrial complex in the region of the Leningrad Nuclear Power Plant. Current issues of radioecology: Proceedings of the RIRAE. Issue 1. Ed. Corresponding Member of the RAS N.I. Sanzharova. RIRAE Publ., Obninsk, 58–66. [in Russian]
- Spiridonov SI, Kuznetsov VK, Panov AV, Titov IE (2019) To the question of optimisation of radioecological monitoring in the vicinity of nuclear fuel cycle enterprises. Radiation and Risk 28(4): 44–53. https://doi.org/10.21870/0131-3878-2019-28-4-44-53 [in Russian]
- Spiridonov SI, Mikailova RA, Nushtaeva VE (2021) About the assessment of radiation doses for the population from NPP atmospheric releases within the compliance with the dose constraint for a single facility. Radiation Biology. Radioecology 61(6): 664–670. [in Russian]
- Spiridonov SI, Mikailova RA, Fesenko SV (2023) Evaluation of the operational intervention levels for radiation protection of the public based on the emergency scenarios at Russian nuclear power plants. Radiation and Risk 32(1): 36–47. https://doi.org/10.21870/0131-3878-2023-32-1-36-47 [in Russian]
- Spiridonov SI, Mikailova RA (2024) Approach to assessing monitoring operational intervention levels after an accident at a nuclear power plant using the RODOS system. Radiation and Risk 33(3): 66–79. https://doi.org/10.21870/0131-3878-2024-33-3-66-79 [in Russian]
- Vasyanovich ME, Ekidin AA, Vasilyev AV, Kryshev AI, Sazykina TG, Kosykh IV, Kapustin IA (2019) Determination of radionuclide composition of the Russian NPPs atmospheric releases and dose assessment to population. Journal of Environmental Radioactivity 208–209: 106006. https://doi.org/10.1016/j.jenvrad.2019.106006
- Yearbooks (2004–2023) The radiation situation on the territory of Russia and neighboring states in 2002–2022. Roshydromet, FSBI "NPO Typhoon" Publ., Obninsk. [in Russian]