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Research Article

Radioecological monitoring and its role in ensuring the safety of nuclear power plants*

Sergey V. Fesenko[1], Natalia I. Sanzharova[1], Yevgeny I. Karpenko[1], Nizametdin N. Isamov[1], Vladimir K. Kuznetsov[1], Aleksey V. Panov[1], Pavel N. Tsygvintsev[1]

1 *Russian Research Institute for Radiology and Agroecology, 109 km, Kievskoye Hwy, 249032 Obninsk, Kaluga Reg., Russia*

Corresponding author: Sergey V. Fesenko (corwin_17f@mail.ru)

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Abstract

The article presents methodological approaches to the organization of radioecological monitoring in the regions where nuclear power plants are located. The analysis of the monitoring results at the Beloyarsk, Kursk, Leningrad and Rostov NPPs showed that the contribution of the natural radiation background to the public exposure dose is within a narrow range from 3.13 to 4.16 mSv per year, and the dose from the existing technogenic contamination varies from 0.47 µSv (Rostov NPP) up to 150 µSv per year (Beloyarsk NPP). The variability of the exposure doses is determined by the influence of natural climatic conditions and by differences in characteristics of contamination sources, including differences in electricity generation technologies. The technogenic radiation background in the area of the Beloyarsk NPP is determined by environmental contamination as a result of previous activities, whereas in the areas of the Leningrad NPP and the Kursk NPP it is associated with Chernobyl fallout (91 and 14 µSv per year, respectively). The contribution of NPPs to the existing technogenic radiation background varies from 1% (Rostov NPP) to 10–11% (Kursk and Beloyarsk NPPs).

Keywords

Nuclear power plant, radiation safety, radioecological monitoring, exposure doses, technogenic contamination

Introduction

Environmental impact assessments of NPPs operation play a key role in the nuclear power safety justification (IAEA 2014). Ensuring the environmental safety of NPPs is started with substantiating the choice of a site for construction and with preparing a project documentation. As part of engineering and environmental surveys, the ecological state of the construction site should be assessed; the consequences of the operation of the NPP are predicted; and recommendations are developed in order to prevent negative consequences, organize environmental monitoring, etc. (SP 47.13330.2016 2016, SP 151.13330.2012 2013a, 2013b).

The objective of this paper was to analyze the outputs of radioecological monitoring in the regions where NPPs are located on the territory of the Russian Federation and presentation of the lessons learned based on that analyses.

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Organization of radioecological monitoring

Radioecological monitoring is carried out within the framework of the Unified State Ecological Monitoring System (USEMS) by the Federal Service for Hydrometeorology and Environmental Monitoring and the State Atomic Energy Corporation Rosatom (Decree of the Government). Radiation monitoring in the NPP potentially affected area is local and includes two basic components: (1) control of contamination sources and (2) monitoring of environmental conditions. The objectives of radioecological monitoring are: (1) ensuring the public radiation safety, (2) meeting the environmental quality requirements, and (3) identifying trends in changes in the radioecological situation during NPP operation. The main monitoring tasks include: (1) detecting contamination routes, (2) identifying priority contaminants, (3) studying the behavior of radionuclides, (4) predicting the environmental situation in relation to NPP functioning, and (5) providing information for making managerial decisions.

Radioecological monitoring programs are implemented in accordance with the developed regulating procedures (Table 1) (MR 2.6.1.27-2003 2007, MU-13.5.13-00 2000). Objects for monitoring are selected based on the analysis of data on emissions and discharges from NPPs, considering all pathways of the public exposure.

Monitoring data are evaluated according to sanitary-hygienic criteria and background radionuclide concentrations. A mandatory element is a background survey of the proposed NPP site and inclusion of control sites outside the NPP affected area in the monitoring network.

Sanitary-hygienic criteria are applicable primarily to assess the impact on the population. At the same time, a system of criteria for radiation impact on the environment: including assessments of the absorbed dose on reference biota species is being developed (ICRP Publication).

Results of radioecological monitoring in the NPP location areas

The article provides the results of the implementation of radioecological monitoring programs by the Russian Institute of Radiology and Agroecology at the Beloyarsk, Kursk, Leningrad, and Rostov NPPs. The monitoring procedure for each NPP considered the characteristics of both contamination sources and the NPP site. Consideration was given to various scenarios for forming radiation situations (actual or planned data on emissions and discharges, potential emergency situations), and periods of operation of radiation facilities. The following parameters were studied: ambient dose equivalent rates; radionuclide activity concentrations in surface water bodies, drinking waters, soils, subsoils, vegetation, human and animal feedstuffs; soil contamination density; radionuclides-to-plant transfer factors, etc.

Based on the analysis of the data of the initial survey and the results of radioecological monitoring, the public radiation doses from each radionuclide were assessed at the time of the observations and for 30–50 years of NPP normal operation.

Long-term observations in the area of the Leningrad NPP have shown that the radiation situation is associated

Table 1. Regulating Procedures for Radioecological Monitoring of Agroecosystems in the NPP Affected Zone during Normal Operation

Landuse or product	Sample type	Sampling frequency	Radionuclides of concern
Arable lands	Soil	1 – Before sowing crops 2 – During harvest	^{51}Cr, ^{54}Mn, ^{58,60}Co, ^{59}Fe, ^{95}Zr+^{95}Nb, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Vegetables	3 – During harvest	^{58,60}Co, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Fruits	4 – During harvest	^{60}Co, ^{90}Sr, ^{134,137}Cs
	Berries	5 – During harvest	^{54}Mn, ^{58,60}Co, ^{134,137}Cs, ^{131}I
	Cereals (grain)	6 – During harvest	^{51}Cr, ^{54}Mn, ^{58,60}Co, ^{95}Zr+^{95}Nb, ^{90}Sr, ^{134,137}Cs, ^{131}I
Natural and cultural haylands and pastures	Soil	1 – Before livestock cattle grazing 2 – During the first grass cutting and the first pasturing 3 – During the second grass cutting and the second pasturing	^{51}Cr, ^{54}Mn, ^{58,60}Co, ^{59}Fe, ^{95}Zr+^{95}Nb, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Feedstuffs	1 – Before livestock cattle grazing 2 – During the first grass cutting and the first pasturing 3 – During the second grass cutting and the second pasturing	^{51}Cr, ^{54}Mn, ^{58,60}Co, ^{90}Sr, ^{95}Zr+^{95}Nb, ^{134,137}Cs, ^{131}I
Animal products	Mutton	1 – During slaughtering	^{54}Mn, ^{58,60}Co, ^{59}Fe, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Beef	2 – During slaughtering	^{58,60}Co, ^{59}Fe, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Pork	3 – During slaughtering	
	Chicken	4 – During poultry slaughtering	
	Fish	5 – During fishing	^{54}Mn, ^{58,60}Co, ^{59}Fe, ^{90}Sr,^{134,137}Cs,^{131}I
	Milk	1 – Stall-feeding period 2 – Start of grazing 3 – During the first pasturing 4 – During the second pasturing 5 – After changing pasture	^{54}Mn, ^{58,60}Co, ^{59}Fe, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Eggs	1 – Before being sent for sale	^{58,60}Co, ^{59}Fe, ^{90}Sr, ^{134,137}Cs, ^{131}I
	Wool	During shearing	
	Water	2 – During irrigation or fishing for sale	^{54}Mn, ^{58,60}Co, ^{59}Fe, ^{90}Sr, ^{134,137}Cs,^{131}I, ^{3}H

mainly with the influence of radioactive fallout after the Chernobyl Accident (Tsygvintsev et al. 2020). Among technogenic radionuclides, the largest contribution to the existing exposure was made by ^{137}Cs (mainly of Chernobyl origin): 67% for the urban and 74% for the rural population. The contribution of the Leningrad NPP to the formation of the existing radiation background was 0.13% and cannot be determined by instrumental methods.

Assessments of the planned public exposures during the commissioning of four new VVER-1200 reactors after 50 years of the plant operation show that the contribution of radionuclides of plant origin will increase slightly up to about 0.2% of the natural radiation background. The main contribution to the formation of the dose from VVER-1200 along all the exposure pathways will be made by ^{14}C (63%), the contribution of inert radioactive gases (IRG) (18%) and ^{3}H (11%) will also be significant.

The results of monitoring for 17 years around the Kursk NPP show that the formation of the radioactive contamination of the environment was mainly determined by long-lived ^{137}Cs and ^{90}Sr (Kuznetsov et al. 2020). The external exposure from radionuclides in the soil dominates among the pathways of existing exposure (83%). The contribution to the dose from food consumption was also significant (17%). The main dose-forming radionuclide is ^{137}Cs, which is explained by the influence of Chernobyl fallout. The expected effective internal doses due to ^{137}Cs and ^{90}Sr are 2.5 and 5.0 μSv×yr.$^{-1}$, respectively. Public exposures from atmospheric emissions of the Kursk NPP currently determined by external exposure from IRGs which amount to about 40%. The contribution of ^{131}I (oral pathway) is 5% and ^{60}Co is about 4%. The contribution of gas-aerosol emissions to the formation of the radiation dose is approximately 10 times lower than that from the existing contamination with technogenic radionuclides.

The results of monitoring for 18 years around the Rostov NPP show that ^{131}I and ^{137}Cs provide the main fraction of the total activity of NPP' radionuclides coming to humans through a variety of the pathways (Isamov et al. 2020). After 30 years of the NPP normal operation, contamination levels of ^{137}Cs due to NPP discharges will increase by no more than 10% for milk and meat, and from 9 to 20% for potatoes, winter wheat and vegetables. Currently, the concentrations of ^{137}Cs from the NPP discharges in food products are 20–650 times lower than that of global fallout. Their contribution to the total radiation dose is 0.23–2.4%, and in 30 years it will increase up to 0.61–5.9%. The contribution to the existing exposure made by gas-aerosol emissions from NPPs is 0.41 μSv×yr^{-1}, which is more than 10 times lower than that from technogenic radionuclides (4.74 μSv×yr^{-1}).

The results of radioecological monitoring in the region of the Beloyarsk NPP show that the concentrations of natural and technogenic radionuclides in the components of various natural environments are at the level of the regional background (Panov et al. 2020). The total public exposure due to technogenic radionuclides ise 0.13 mSv×yr^{-1} for the rural population and 0.09 mSv×yr^{-1} for the urban population. Considering the exposure dose from natural background radiation, the total average annual effective dose was 2.23 mSv×yr^{-1} for the rural population and 1.99 mSv×yr^{-1} for the urban population. The effective annual public exposure dose due to emissions from the Beloyarsk NPP, excluding tritium, is formed mainly due to the consumption of food products (85%) and is 0.59 μSv×yr^{-1}. The external public exposure was at the level of 0.1 μSv×yr^{-1}. The contribution of ^{41}Ar to the radiation dose from the cloud was 85%, the dose from fallout on the soil due to ^{137}Cs was 91%. A significant contribution to the internal exposure dose was made by food consumption, i.e., 50% due to ^{137}Cs and 40% due to ^{90}Sr (excluding ^{3}H). The data obtained show that the Beloyarsk NPP does not have a significant impact on the public exposure population in the 30-kilometer area. An increased concentration of radionuclides in the environmental compartments was noted only on the territory of the Olkhovskoye swamp.

Radiation safety analysis of NPP functioning

The presented results of monitoring at the four NPPs of various types are quite general for conducting radioecological monitoring on the territory of the Russian Federation and make it possible to assess the effectiveness of monitoring systems. Radioecological monitoring was carried out simultaneously with observations of both discharges sources and the environmental conditions (Safety Guide 2005, IAEA 2014). These two types of monitoring are interrelated and equally important for assessing the radiation situation.

To monitor contamination sources, i.e., radioactive emissions and discharges from NPPs, two types of information are used: design data on permissible, maximum permissible or planned emissions and data on actual emissions (The Radiation Situation 2019). The design data on permissible emissions are calculated based on dose quotas, i.e., human exposure doses from the critical population group due to gas-aerosol emissions from NPPs during normal operation will not exceed 10 μSv×yr^{-1} (SanPin 2.6.1.24-03 2003). The maximum permissible emissions (MAE) are also regulated at the level of 20 permissible emissions (or 200 μSv×yr^{-1} in terms of dose), and for NPPs designed and under construction at the level of five permissible emissions (50 μSv×yr.$^{-1}$). The maximum permissible discharges (MAD) for all the NPPs exceed the admissible discharge by five times. These values are set based on public exposure quotas equal to 250 μSv×yr^{-1} for operating NPPs and 100 μSv×yr^{-1} for NPPs being designed and under construction.

These values are used to calculate the MAE of radionuclides from NPPs into the atmosphere and the MAD of radionuclides into surface waters. The established MAEs and MADs are the upper limits for emissions and discharges during the NPP normal operation. The minimum significant dose equal to 10 μSv×yr^{-1} is taken as the lower limit for optimizing the public radiation protection during the NPP normal operation. The same dose limit is used to calculate permissible emissions (AE) and admissible discharges (AD) (SanPin 2.6.1.24-03 2003).

Actual release data are important sources for more realistic assessments of radiation effects on the population and environment. To estimate the results of radioecological monitoring, both sources of information were used: planned emissions for conservative estimations, and actual emissions data (together with the results of radioecological monitoring) for realistic estimations.

There are various approaches to assessing the contribution of emissions from nuclear power facilities to the environment. As a rule, direct methods for measuring radionuclides in the environment do not allow to measure the contribution of NPPs to existing contamination. More informative is the analysis of time series, which combines data on the concentration of radionuclides in the soil over a sufficiently long period of time. The analysis of data for individual control plots in the Rostov NPP affected area showed that the change in the concentration of ^{90}Sr in the soil occurs with a half-life of 28.76 years, which corresponds to the half-life. For ^{137}Cs, the share of which in gas-aerosol emissions is quite large, the half-life of the radionuclide concentration in the soil (58.1 years) significantly exceeds its half-life (Fig. 1) (Isamov et al. 2020). The increase of ^{137}Cs activity in the soil of the control sites due to the NPP operation can be described by the equation:

$$q(t) = 0.13 \cdot t$$

where t is the time since the beginning of the fallout; $q(t)$ is the concentration of ^{137}Cs. This means that there is a permanent source of ^{137}Cs of plant origin in the NPP observation area, which determines additional soil contamination.

The presented data are one of the first experimental evidence of the effect of ^{137}Cs emissions on the increase in its concentration in the soil sampled in sites around the NPPs. At the same time, these data emphasize a need in the long-term systematic observations.

An analysis of the results of radioecological monitoring of the four NPPs shows that the public exposure doses formed due to the natural radiation background vary within a rather narrow range from 3.13 to 4.16 mSv×yr^{-1} (Doses of Radiation Exposure 2019), while the

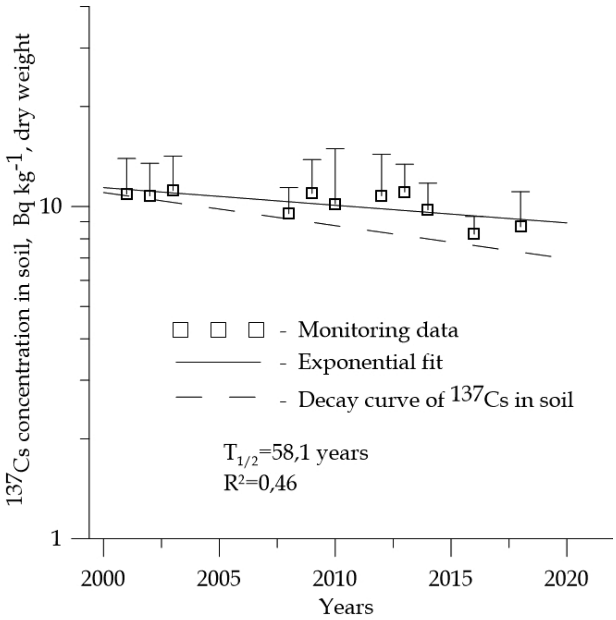

Figure 1. Dynamics of ^{137}Cs concentrations in the soils of the control plots in the Rostov NPP observation area

contribution of food products to the dose from natural background is relatively small and ranges from 3 to 5% (Isamov et al. 2020, Kuznetsov et al. 2020, Panov et al. 2020, Tsygvintsev et al. 2020). It is necessary to note the influence of environmental conditions on the accumulation of radionuclides in food products and the formation of public exposure doses. The minimum levels of radionuclides in agricultural products are noted in the areas of the Kursk and Rostov NPPs, which is associated with the predominance of highly fertile soils characterized by a high sorption capacity for radionuclides (Table 2).

Table 2. ^{137}Cs concentration in agricultural products, Bq×kg^{-1}

Product types	Beloyarsk NPP	Kursk NPP	Leningrad NPP	Rostov NPP
Milk	0.11 (0.06–0.20)	0.14 (0.02–0.30)	0.1 (0.03–0.21)	0.06 (0.01–0.16)
Potatoes	0.06 (0.03–0.09)	0.08 (0.01–0.48)	0.5 (0.1–0.7)	0.34 (0.10–1.0)
Grain	0.39 (0.23–0.54)	0.3 (0.1–0.7)	0.3 (0.1–0.7)	0.63 (0.36–0.94)

The contribution of food products to existing exposure doses varies from 14 to 64%, which is due to the local features of the formation of exposure pathways (Table 3). Public exposures in the Kursk NPP affected area are

Table 3. Radioecological characteristics of NPP locations (Tsygvintsev et al. 2020, Kuznetsov et al. 2020, Isamov et al. 2020, Panov et al. 2020, Doses of Radiation Exposure 2019)

Parameters	Beloyarsk NPP	Kursk NPP	Leningrad NPP	Rostov NPP
Existing exposure doses from technogenic radionuclides				
Total dose, mSv×yr^{-1}	1.52×10^{-1}	1.43×10^{-2}	9.1×10^{-2}	4.7×10^{-3}
Contribution of products, %	14	17	64	52
Doses from NPP emissions				
Total dose, µSv×yr^{-1}	16*) ($1,2\times10^{2}$)	1.5	4.1	7.1×10^{-2}
Total dose per 1 GW, µSv×yr^{-1}	15	0.5	1.5	2.9×10^{-2}
Contribution of products, %	85	12	86	17
Total dose, µSv×yr^{-1}	1.58×10^{-1}	6.25	5.2	6.8×10^{-2}
Total dose per 1 GW, µSv×yr^{-1}	1.5×10^{-1}	2.1	1.8	2.8×10^{-2}
Doses from natural background radiation (existing exposure)				
Total dose, mSv×yr^{-1}	3.98	3.13	3.31	4.16
Dose from products mSv×yr^{-1}	0.113	0.128	0.155	0.118

*) The annual dose from all the radiation objects on the site is 120 µSv×yr^{-1}

Table 4. Doses to the public due to gas-aerosol emissions from the Russian NPPs (Vasyanovich et al. 2019)

NPP	Dose, μSv yr^{-1}	Contribution to dose, %							
		IRG	^{3}H	^{14}C	^{60}Co	^{131}I	^{134}C	^{137}Cs	Others
Beloyarsk NPP	1.58×10^{-1}	31.3	7.5	32.6	2.8	< 0.1	2.0	23.8	< 0.1
Kursk NPP	6.25	22.3	1.1	31.0	27.0	0.8	1.1	14.4	2.3
Leningrad NPP	5.16	31.3	2.5	53.4	5.9	< 0.1	0.9	4.2	1.8
Rostov NPP	6.79×10^{-2}	20.5	57.8	20.4	0.1	< 0.1	0.5	0.5	0.2

largely related to the impact of Chernobyl fallout. The low values of the radionuclide-to-product transfer factors determine the dominance of the total dose for the Rostov NPP. When developing requirements for a monitoring program to identify factors that determine environmental contamination and human exposure it is necessary to consider regional specific parameters.

The doses from existing technogenic contamination vary over a wider range from 0.47 to 150 μSv×yr^{-1}, reflecting both the influence of natural and climatic conditions and differences in sources of environmental contamination specific for the monitoring region: Chernobyl fallout, emissions and discharges from other nuclear enterprises, and differences in the technologies used for electricity production (Table 3). The public exposure dose in the Beloyarsk NPP area, formed due to the technogenic radiation background, is 0.15 mSv×yr^{-1}: it is determined by environmental contamination as a result of previous activities (operations of the AMB-100 and AMB-200 reactors). In the areas of the Leningrad and Kursk NPPs, the public exposure doses are 9.1×10^{-2} and 1.4×10^{-2} mSv×yr^{-1}, while the main contamination source is Chernobyl fallout. The minimum dose due to the technogenic background is noted in the area of the Rostov NPP: it is 4.7×10^{-3} mSv×yr^{-1}.

The contribution of NPP emissions and discharges to the existing technogenic radiation background, calculated based on radioecological monitoring data, varies from 1% (Rostov NPP) to 10–11% (Kursk and Beloyarsk NPPs).

When comparing natural and technological factors that determine the contribution of NPPs to the total public exposure, it is necessary to take into account the plant capacity, and the exposure doses should be given per unit of electricity generated. The doses from NPP emissions calculated per 1 GW of electricity produced vary from 2.9×10^{-2} to 15 μSv×yr^{-1}, which is consistent with estimates for similar power plants located in other countries (UNSCEAR 2017).

The comparison of the estimates of human exposure doses based on the monitoring results with the data of (Vasyanovich et al. 2019) (Table 4) shows that they are close for the Leningrad and Rostov NPPs, up to two orders of magnitude lower than the data for the Beloyarsk NPP (Panov et al. 2020), and significantly exceed the dose estimates for the Kursk NPP (Kuznetsov et al. 2020). The noted differences can be associated both with an underestimation of local environmental factors, and with variations in the composition and volume of NPP emissions.

Another reason for the differences in assessing public exposures may be different accounting for the tritium dose. The models recommended by the IAEA (IAEA 2001) show that the contribution of tritium can be up to 95% of the dose. Additionally, dose estimates may differ significantly depending on the purpose of their use, for example, when assessments are based on conservative or realistic approaches. Therefore, the use of a tiered approach with a clear definition of which models and parameters can be used for a particular purpose is the most rational way to assess the safety of nuclear facilities. International approaches to the safety of NPPs involve the use of realistic dose models based on radioecological monitoring data and accounting of local conditions. It is fundamentally important to introduce the concept of a ‘reference person’ into the practice of radiation regulation, which will affect the assumptions when using radiation monitoring models.

Conclusion

One of the requirements of the IAEA International Safety Standards is to directly demonstrate the absence of the impact of nuclear enterprises on the environment and humans (IAEA 2014). Radioecological monitoring is the main tool that makes it possible to give this justification and, using the data obtained as a result of its implementation, we can adequately justify assessments of the radiological situation in the regions where the NPPs are located (IAEA 2010). At the same time, there are several problems to be addressed in assessing the safety of NPPs and other facilities of the nuclear power complex based on the data of radioecological monitoring and using dose quotas as the main criterion. Among the general issues, we should highlight the discrepancy between the legislation of the Russian Federation in the field of radiation safety and modern requirements and standards of the IAEA, which limits the spread of Russian technologies abroad.

Approaches to the classification of exposure situations, including existing exposure, planned exposure and emergency exposure, have not been introduced into the national regulatory radiation safety system.

The experience of using international calculation codes is not analyzed, while Russian codes for determining maximum admissible emissions from NPPs and public exposure doses are of a closed nature, which limits their use outside the Russian Federation.

The basic document currently regulating the radiation safety of NPPs, (SanPin 2.6.1.24-03 2003), declares that “the radiation safety of nuclear power plants is considered sufficient if technical means and organizational measures ensure ‘non-exceeding’ of the basic radiation dose limits established by NRB-99/2009 for staff, people...” At the same time, the assessment of ‘not exceeding’ the main dose limits cannot be considered correct if the main dose-forming radionuclides, such as ^{14}C and ^{3}H, are not considered when dose quotas and admissible releases are being set.

The role of radioecological monitoring of the environment in the whole radiation safety system has not been defined. There are no requirements for monitoring sources of radioactive descharges (IAEA 2010). In SanPiN 2.6.1.24-03, the term 'monitoring' is not mentioned. It is necessary to improve the methods for sampling and preparing samples for measurements in relation to a number of radionuclides that determine the public exposure doses, such as ^{14}C and ^{3}H.

The need to improve methodological approaches, regulatory and methodological support as well as to bring national requirements to conformity with international documents is an urgent problem of improving the regulatory system, including the system of radioecological monitoring.

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