Methodology for assessing the adverse effects of the use of nuclear energy on agricultural land

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Abstract. The article discusses a new methodology for assessing the negative impact of nuclear energy on agricultural land. The necessity of assessing from a financial point of view the negative impact of nuclear energy on agricultural land and the environment is substantiated. Methods are proposed for assessing the financial damage of the negative impact of nuclear energy based on an analysis of the state of the soil and the living world. Examples of calculations of damage in monetary terms for the Russian Federation from the negative impact on the basis of studies of the state of the environment on agricultural land are presented.

1 Introduction

Currently, for the sustainable development of the economy, trade and other areas, human activity is developing in various directions [1-5]. One of which is the production of energy in the volume necessary for the state [6-14]. One of the perspective areas of energy for a number of reasons (for example, large capacities, etc.) is nuclear energy [6-8, 15-19]. It also, like other types of energy, requires the adoption of measures to ensure the safety of nuclear power plants (NPPs). The main objective of safety during the operation of nuclear power plants is to prevent negative effects on human health, the environment, agricultural land, etc. The main safety objective during the operation of nuclear power plants is to prevent negative effects on human health and the environment. The provisions of a large number of international conventions, documents of the IAEA and other organizations are oriented toward solving this problem. In the Russian Federation, ensuring the solution of this problem is based on the norms of domestic laws, including “On the Use of Atomic Energy”, “On Environmental Protection”, and also land, water and forest codes. Moreover, regulation is carried out at the level of not only principles and approaches, but also liability for harm and damage. Responsibility measures currently in force are developed using special procedures.

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In most cases, they spell out general principles. In some cases, they lack specifics, especially with regard to agricultural land. For example, in the field of environmental protection, in contrast to human radiation safety, where regulatory documents that determine the acceptable levels of radiation exposure for workers and the public have been established, there is no such regulatory framework, despite articles 21 and 22 of the Law on Environmental Protection. These articles provide for the establishment of quality standards and permissible effects on it, including standards for the maximum permissible concentration of radioactive substances, the level of radioactivity and permissible exposure to ionizing radiation. However, the articles with the exception of emission standards and discharges of radioactive substances have not been implemented yet. There are no problems with measuring the level of pollution, as well as its effect on changes in the state of the aquatic environment, plant structure and soil. Now, a large number of different devices have been developed, both for express control [20–25], and for conducting complete laboratory studies based on various physical principles [26–31].

The main reasons that impede the practical implementation of these articles are the methodological difficulties of creating such a system with respect to all the factors indicated in them, not just radiation, as well as the practical unpreparedness of certain sectors of the economy for environmental restrictions, even in cases where damage can be reasonably linked to source of pollution. Regarding the radiation factor, legal regulation is hindered to some extent by the unresolved issue of what approach the environmental protection system should be based on - anthropo- or ecocentric [27, 32]. This significantly hinders the development of methods for assessing damage from the harmful effects of nuclear energy on the environment, agricultural land, etc.

Our work describes a methodological approach based on regulatory documents in the field of environmental protection. Its use allows us to offer a number of methods for assessing possible environmental damage in monetary terms.

2 The Methods of analysis of the state of radiation safety of the environment

Our various studies of the state of the environment [23, 24, 28–31], as well as the results of studies by other scientists [9, 14, 27, 32–36], allowed us to propose the following methodology for assessing damage from the negative impact of nuclear energy on the environment. It is proposed to assess damage based on an analysis of the state of the environment in the area where the radiation object is located. Analysis of the environment, as demonstrated by the results of measurements and research, should be divided into the following stages:

- Identification of sources of radiation and environmental impact and possible pathways of pollution of environmental components (soil, surface and groundwater, atmospheric air, flora and fauna);
- Monitoring of the radiation situation and model estimates of the transfer of radionuclides;
- Selection of representative objects of the natural environment and determination of the dose rate of their exposure;
- Comparison of the calculated dose rate with environmentally friendly exposure for representative objects of the natural environment, justification of the appropriateness of assessing damage to flora and fauna.
At the stage of identification of sources of radiation and environmental impacts, it is necessary to consider possible ways of irradiating plant and animal objects. Currently, due to the onset of a man-made disaster, there are various methods for the release of radionuclides into the components of the environment from a radiation facility, from radioactive contamination of the components of the environment as a result of the previous operation of radiation accidents or emissions from other objects.

At the stage of radiation monitoring, observations of the external dose rate and of specific and volumetric radionuclide activity in the components of the environment in the area of the radiation object are analyzed and generalized. In the absence of data, the content of radionuclides in the components of the environment is estimated using radioecological models.

In accordance with the recommendations of the ICRP [35], representative objects of the environment for assessing the radiation-ecological impact are selected from different types of biota: soil invertebrates, terrestrial mammals (mice, deer / roe deer), herbaceous plant, trees (pine), birds (duck), amphibians (frog), macro-algae, fish (pelagic and benthic), benthos (mollusks, crustaceans), aquatic mammals. The sources that led to the exposure, the duration of exposure, the parameters of the models for estimating the absorbed dose rate are determined, the dose rate is calculated taking into account the multiple routes of exposure. When assessing radiation exposure, external and internal exposure is taken into account. If the monitoring data are insufficient, we propose using NMR relaxometers and EPR spectrometers to estimate the absorbed dose rate of representative radiation in soil and biological organisms based on scenarios that are a combination of facts, assumptions, and expert opinions on how radiation exposure occurs [28-31, 37-39]. The methods for calculating the dose rate should be adapted to the conditions of the terrain and the natural background radiation.

It is extremely important to measure the dose rate of the most important biota objects for the living world and compare the data with environmental safety standards. In fig. Figure 1 shows the experimental and calculated dependences of the exposure dose rate, which is measured by a γ-ray dosimeter, in one of the directions of the territory under consideration. The calculation is made taking into account the characteristics of the terrain.

![Graph](image_url)

**Fig. 1.** The dependence of the change in the exposure dose rate $P_m$ on the distance $L$ in one of the areas of research. Graph 1, 2, 3 corresponds to the results of $P_m$ measurements in soil, in grass, and at a
Comparison of experimental results with calculation results confirmed the need for validation of our proposed methodology for assessing the state of the environment. Its application allows to define more accurately the category of danger of radiation exposure. The methodology for limiting the radiation effect on biota is based on the postulate of the threshold action of ionizing radiation, confirmed by experimental data [27, 35, 36, 40]. In accordance with world standards and control standards, in a new methodology developed by us, a dose rate of 1.5 mGy / day for the animal and 15 mGy / day for the plant world is proposed as an ecologically safe level of exposure to environmental objects.

Based on the results of various experiments proposed in the development of methods of assessing the damage to keep the value of the threshold of ionizing radiation to biota. In this case, we propose that if the dose rate of ionizing radiation is below an environmentally safe level, radiation damage is proposed to be considered equal to zero in this case, the calculation of possible harm to the ecological system is not carried out. If ecologically safe levels of exposure to fauna and flora are exceeded, damage is assessed. It is proposed to calculate this damage in accordance with the legislation on environmental protection and the rates established in regulatory documents.

3 Methods for assessing damage from harm caused by radiation exposure to the environment and agricultural land

In accordance with the legislation, harm is understood as a negative change in the environment as a result of pollution, resulting in the degradation of natural ecological systems and the depletion of natural resources. Damage from possible harm caused by radiation exposure is estimated on the basis of the above methodology according to the criterion of maintaining a favorable environment. The analysis is carried out on the territory of the completed or possible radiation exposure.

To calculate the damage, it is recommended to use the established rate, including for damage caused by the destruction of objects of flora and fauna. It is conservatively believed that when the environmentally safe dose rate of chronic exposure to representative biota objects is exceeded, a death of some of the organisms under consideration is observed, i.e. possible damage from radiation exposure is conservatively assessed as already held.

In this case, the radioecological situation in the areas of possible radioactive contamination is analyzed in detail not only for the considered representative biota objects, but also for other ecologically significant species of flora and fauna exposed to increased radiation exposure, and harm and damage are assessed.

To illustrate the methodology for assessing damage from harm to biota due to radioactive pollution of the environment, we consider a conditional example based on the following hypothetical scenario. Suppose, in the area where the radiation facility is located, there is a site of radioactive contamination of an area of 0.1 ha with increased impact on the biota. The territory of the site belongs to the zone of mixed forests. The site is the habitat of species representative of this natural and climatic zone. As a result of chronic radiation exposure to biota, the dose rate was, mGy / day: soil invertebrate organisms (worm) 6, reptiles and amphibians (lizards, snakes, frogs) 3, birds (piciformes order, order of passeriformes) 2, small mammals (family of muridae, family of hedgehogs) 4. The site is also the habitat of a species listed in the Red Book - large dragonflies, for the immature stages of development of which the dose rate is estimated at 5 mGy / day. In these groups, radiation exceeds an
ecologically safe level, below which radiation protection of biota is assumed at a population level. Thus, at the indicated dose rate, negative radiation effects can be expected. For the remaining biota groups, including plants, the calculated dose rate is below an environmentally friendly level.

For biota exposed to radiation above an ecologically safe level (1.5 mGy / day for fauna), a conservative assumption is made on the damage assessment of the destruction of these groups of organisms within the area of increased radioactive contamination. The amount of damage from harm to invertebrate animals caused by radioactive contamination of the soil (litter) and other habitats, with the exception of the dragonflies, is determined by the formula:

\[
D_{\text{soil}} = C_{r.w.} \times V + S V_{s.i} \times S \times K_i + S V_{n.g.i} \times S \times K_i,
\]

(1)

where \(D_{\text{soil}}\) is the amount of damage caused to the habitat of objects of the animal world, rubles; \(C_{r.w.} = 1000 \text{ rub.}/m^3\) - costs for the implementation of a range of works: acquisition, transportation and placement of plant soil to replace contaminated soil (litter); \(V = 500 m^3\) - volume of contaminated soil (litter); \(SV_{s.i} = 143 \text{ rubles }/ \text{ m}^2\) for the zone of mixed forests - the standard value of soil invertebrate animals living on 1 m\(^2\) of land; \(S = 1000 \text{ m}^2\) is the area of the land on which the soil, litter and other habitats of invertebrates are destroyed, with the exception of the large dragonflies; \(SV_{n.g.i} = 50 \text{ rubles }/ \text{ copy}\) - the standard value of objects of the animal world relating to other invertebrate animals (non-ground), excluding invertebrate animals listed in the Red Book; \(K_i = 1\) - an indicator that takes into account inflation, for assessment in the current year.

Thus, the damage from harm to invertebrate animals caused by radiation exposure from soil pollution (litter) and other habitats is 693 thousand rubles.

The amount of damage caused by radiation exposure to objects of the animal world, not related to invertebrate animals, and to the species of invertebrates listed in the Red Book – the large dragonflies, for example, is determined by the formula:

\[
D_{a.} = N_{r.n.} \times SV \times K_i \times K_{f.g.} + AC,
\]

(2)

where \(D_{a.}\) is the amount of damage caused by radiation exposure to objects of the animal world, except for soil invertebrates and other types of invertebrate animals; \(N_{r.n.}\) - reduction in the number of animals of one species, except soil invertebrates and other types of invertebrate animals, including a complete loss of numbers; \(SV\) - the standard value of the cost of the animal species of a given species, rubles / copy; \(K_i = 1\); \(K_{f.g.}\) - dimensionless coefficient of accounting for the value of future generations of animals; \(K_{f.g.} = 10\) for species of animals listed in the Red Book; \(K_{f.g.} = 1\) for other species (with the exception of objects of the animal world, referred to objects of hunting and fishing); \(AC\) - costs required to assess the damage are calculated on the basis of data on the cost of the main types of work and (or) on the basis of data on the necessary and actual costs.

In this method of calculating the damage, it is assumed that the reduction in the number of animals is 100% of the population, determined on the basis of the average biological density standards of each species, taking into account local conditions. To calculate the damage in monetary terms, using two methods (formulas (1) and (2)) we compiled table 1.

In this case, the total amount of damage calculated using the data of table 1 according to formula (2), taking into account the previously performed assessment for invertebrate organisms in the considered conditional example, is 827.5 thousand rubles.
Table 1. Assessment of damage from radiation exposure on invertebrate animals listed in the Red Book and objects of the animal world that are not related to invertebrate animals in the area where the radiation object is located.

| Type of animal                      | Number, copy | The standard value, rubles / copy | Coefficient of accounting for the value of future generations | Amount of damage, thousand rub. |
|-------------------------------------|--------------|----------------------------------|---------------------------------------------------------------|---------------------------------|
| Insects-butterflies, dragonflies, beetles | 1            | 3000                             | 10                                                            | 30                              |
| Lizards                             | 20           | 500                              | 1                                                             | 10                              |
| Snakes                              | 5            | 3000                             | 1                                                             | 15                              |
| Birds:                              |              |                                  |                                                               |                                 |
| Piciformes order                    | 1            | 3500                             | 1                                                             | 3,5                             |
| Passeriformes order                 | 50           | 1000                             | 1                                                             | 50                              |
| Mammals:                            |              |                                  |                                                               |                                 |
| Hedgehogs                           | 5            | 1000                             | 1                                                             | 5                               |
| Shrew                               | 10           | 100                              | 1                                                             | 1                               |
| Muridae                             | 200          | 100                              | 1                                                             | 20                              |

4 Conclusions

Studies and analysis of data on emissions and accidents at nuclear facilities showed the validity of the proposed methods for assessing environmental damage from radiation exposure.

In addition, the proposed methods can be used to assess the damage from radiation exposure to the environment when substantiating the classification of radioactive waste as special [41-43], as well as planning environmental measures for the management of radioactive waste. Moreover, the assessment of radiation damage is relevant for determining the environmental impact during the planning, construction, operation and decommissioning of nuclear facilities. The necessity for damage assessment also arises during the rehabilitation of territories exposed to radioactive contamination as a result of past activities or radiation accidents before carrying out construction work on them [42,43].

The variety of uses considered shows that for the practical implementation of the damage assessment methods we have proposed, it is necessary to develop environmental criteria and economic indicators of permissible radiation exposure to environmental objects, environmental standards for the content of radioactive substances in the components of the environment that ensure human and biosphere safety, and other normative and methodological documents. This will allow us, based on our proposed methodology, to develop new methods for assessing damage in monetary terms.

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