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MUTUAL INFLUENCE OF NON-HUMAN BIOTA AND RADIOACTIVE WASTE DISPOSAL FACILITIES: ENVIRONMENTAL AND ENGINEERING SAFETY

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For a long time, radioactive waste management, including RW temporary storage or disposal, has been considered as one of the main factors producing negative impact on present and future generations. Development of new recommendations under the international system of radiological protection, including those associated with additional consideration of the impact of ionizing radiation on non-human biota and relevant ethical aspects, has required certain approaches to be developed enabling to assess the long-term safety of nuclear facilities not only for humans but also for non-human species. In addition, decision making regarding the use of particular safety barriers for radioactive waste (RW) storage facilities and relevant justifications shall also consider biological impact that can negatively affect the isolation of radioactive waste from the environment. The article overviews the aspects associated with the interaction of anthropogenic facilities, namely RW disposal facilities, and biota species.

Keywords: *biota, biological impacts, radioactive waste, disposal, long-term safety, radiological protection, environmental radiation damage.*

Throughout the XX century the society has been developing a common perception of the negative impact of RW on the environment and on public. Such a point of view was supported by events associated with discharges of process waste to Techa River, explosion of a HLW storage tank at PA "Mayak", which lead to extensive contamination and formation of the so-called East Urals radioactive trace, large scale efforts on RW handling at Chernobyl NPP site and beyond it [1]. On the other hand, evolution and development of nuclear technologies was assosiated to continuous improvements in the safety of facilities and development of environment monitoring networks, large-scale studies of the impact of nuclear facilities on human and non-human biota, development of a robust system of regulatory safety requirements. The overall system of listed measures allows now to make more realistic assessments of the environmental damage associated with RW management activities and to analyze the problems of current and long-term environmental and technical safety of disposal facilities, as well as mutual influence of biota and anthropogenic facilities. The latter task is currently of special importance due to the construction of radioactive waste disposal facilities (RWDF), which shall assure radiation safety of the environment for the period of RW potential hazard, which may last for several hundreds or thousands years. In the long-term, the issues of adequate environmental and technical safety require correct consideration and scientific solution. The goal of this article is to evaluate the possible damage for biota based on the current level of safety of nuclear technologies and to analyze the dominant pathways of biological impact on natural and engineered RWDF barriers.

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Development of a radiological protection system and assessment of radiation impact on the environment in process of RW management

Anthropocentric paradigm of radiation protection was accepted at the international level for most of the previous century. The main goal of both the international recommendations and safety standards, including ICRP and IAEA documents, and the national regulatory documents, was radiation protection of current and future generations of people from the harmful effect of ionizing radiation on their health.

Large-scale fundamental radiobiological studies aimed at investigation of radiation effects at various levels of living matter organization, ranging from molecular to organisms and populations, have found their applied application in data extrapolation to human [2]. Even the investigations carried out in the USSR after the accident PA "Mayak" aimed at studying the laws of radionuclides uptake by agricultural products and development of tools and methods for agricultural plants and animals protection, were aimed at survival of human under the condition of nuclear weapons use [3].

By the start of the XXI century, attention to environmental safety has increased. Data accumulated during long-term studies of radiation effects on biota have led to a confirmation at the international level of a number of scenarios "*where humans are absent, and other exposure situations will arise where environmental consequences may need to be taken into account*" (ICRP Publication 103[1]). Environment protection was defined as an activity aimed at "*preventing or reducing the frequency of deleterious radiation effects on biota to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems*" (ICRP Publication 124[2]).

Due to enormous variability of biota and its assumed response to exposure, an effective environment protection system requires a number of simplifications and generalizations. Therefore, ICRP has adopted a concept of Reference Animals and Plants (RAP) — a representative selection of animals and plants living in various environments (terrestrial, freshwater, marine). The set of 12 RAPs was described by ICRP with account for taxonomic level of the "family" as this is the highest rank level where radiobiological response of animals or plants of the family to radiation impact may be considered to be fairly constant. Concept and use of RAPs were described in detail in ICRP Publication 108[3], which also included information with regards to practical assessment of doses to RAPs. Derived Consideration Reference Levels specific for various types of RAPs have been suggested. DCRLs are ranges of dose rate spanning for an order of magnitude indicating a certain amount of probability of harmful ionizing radiation effects for a specific RAP. Thus, DCRLs may be used as reference values in assessment of environmental protection costs in various exposure situations (planned, emergency, existing). It is important to note that DCRLs are recommended for use if additional environmental effect substantially exceeds the natural radiation background for the biota in question.

For the existing exposure situations, which include management of special RW (storage, conservation, disposal), DCRLs may be considered as additional criteria for reducing the impact on the environment.

Another area of development of the international radiation protection system is aimed at propaganda and introduction of an ethical codex based on four key ethical values (ICRP Publication 138[4]):

beneficence/non-maleficence, which corresponds to the main goal of the radiation protection system: attaining an acceptable level of protection without imposing unjustified limitations on beneficial activities;

prudence: informed and thorough selection of activities in consideration of radiation risks indeterminacies both for human and and environment;

justice in distribution of benefits and drawbacks, for example, by limiting the individual dose and respective level of socially acceptable risk;

dignity including unconditional respect for every human regardless of his personal qualities or circumstances.

The listed ethical values support the goals of the radiation protection system and its three basic principles: justification, optimization and limitation of individual doses, but add a greater social aspect to the life sciences fundamentals of the radiation protection system.

Western developed countries (who initiated the above evolutionary additions) see the mechanism of practical implementation of the human and

[1] ICRP, 2007. 2007 Recommendations of the International Commission on Radiological Protection (Users Edition). ICRP Publication 103 (Users Edition). Ann. ICRP 37 (2–4).

[2] ICRP, 2014. Protection of the Environment under Different Exposure Situations. ICRP Publication 124. Ann. ICRP 43(1).

[3] ICRP, 2008. Environmental Protection – the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4–6).

[4] ICRP, 2018. Ethical Foundations of the System of Radiological Protection. ICRP Publication 138. Ann. ICRP 47 (1).

environment radiation protection concept as observance of the three procedural requirements: responsibility, transparency and informational involvement (stakeholder involvement) in the decision-making processes, and reflect these requirements in national laws and regulations.

In Russian law, environmental impact assessment (EIA) is stipulated for all planned economic and other types of activities by the Federal law "On environmental expertise".

With respect to RW storage facilities, which are predominantly located at the sites of organizations, risk of radiation impact for the population under normal operating conditions is less than the negligible risk level (10^{-6} $year^{-1}$). There is a legal requirement for "measures to be taken to ensure complete radiation safety of the environment"[5], which is reflected in a regulatory requirement for "assuring reliable RW isolation from environment"[6].

Therefore, the presence of natural and engineered safety barriers at the storage facilities and RWDF under construction shall, provided the design solutions were duly implemented, assure nearly complete lack of additional radiation impact both on humans and biota outside the facilities.

Response to the novel ICRP radiological and ethical requirements on assessment of environmental impact included introduction of a requirement of an environmental impact assessment in process of justification of the possibility of RW storage facility transition to a disposal facility[7]. Under these circumstances, within a limited timeframe, an approach for economic assessment of radiological environmental damage (Fig. 1) for the first time was developed, tested and applied.

The approach was based on extremely conservative assumptions. Threshold (reference) dose levels — fatal dose levels for biota — were selected at the level of chronic exposure dose rate values, which assure radiation safety of biota — a criterion of acceptable radiation impact on biota [4]. E.g., the allowed radiation impact level for an earthworm[8] was set at the level of 10 mGy/day. At the same time, biological effects even for the most radiation-susceptible development stage — the stage of cocoon, are observed only starting from the dose rates of 264 mGy/day (reduction of cocoon leave rate), while 50 % death rate for adult specimen $LD_{50/30}$ is 650—680 Gy (ICRP Publication 108),

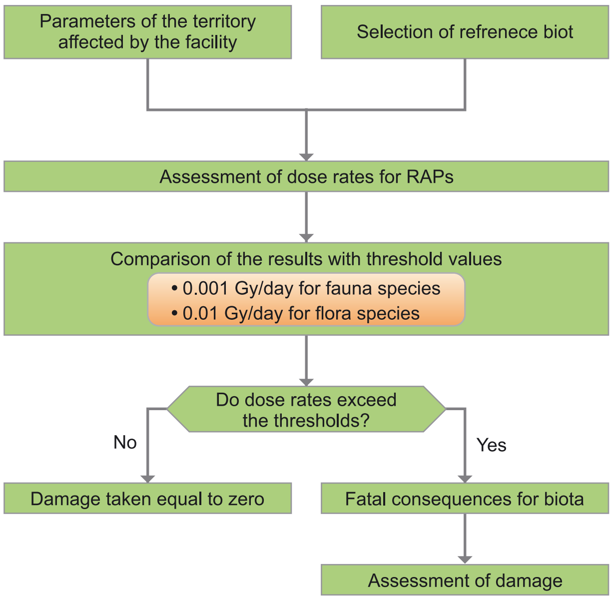

Fig. 1. Flowchart of environmental impact assessment

The developed approach has been implemented in the recommendations of Roshydromet on environment monitoring (Table 1) [5, 6].

Examples of maximum dose rates assessments for some of biota species in the vicinity of special RW storage facilities are given in Fig. 2 and 3.

For most species, the exposure dose rate assessments turned out to be substantially lower than the criteria of allowed radiation impact (see Table 1). Therefore, monetary assessments of damage of biota species in RW management demonstrate that there is no harm whatsoever for these species caused by RW storage [4].

Nevertheless, a requirement on conduct of radiation impact assessments in process RWDF operation and after their closure is in place (SanPiN, FNP, GOST, and other documents), including a requirement for an environmental impact assessment[9]. At the same time, the dose rate assessments for biota species should conservatively be performed for the immediate vicinity of the facility.

General parameters of 3 and 4 class RW and RWDF were assigned for calculations. It was assumed that the waste was immobilized by cementation and located in NZK type containers (3 class). Assuming that NZK is also used as a transport container, it

[5] Federal law No. 7-FA of 10.01.2002 "On protection of the environment"

[6] Disposal of radioactive waste. Principles, criteria and main safety requirements (NP-055-14).

[7] Decree of the Government of the Russian Federation of 19 November 2012 No.1069 "On the criteria of designation of solid, liquid and gaseous waste as radioactive waste, criteria of radioactive waste designation as special radioactive waste and removable radioactive waste and criteria of classification of removable radioactive waste".

[8] Reference biota species most relevant with respect to RWDF safety case.

[9] Disposal of radioactive waste. Principles, criteria and main safety requirements" (NP-055-14).

Table 1. Criteria of radiation impact on reference biota species [5]

Biota group (reference biota species)	Criteria of environmentally safe impact on biota species (for screening assessment), mGy/day	Criteria of allowed radiation impact on biota species, mGy/day
Mammals (deer, mouse, etc)	0.1	1
Vertebrates (snake, fish, frog, etc.)	0.1	1
Scotch pine (Pinus sylvestris)	0.1	1
Plants (grass, lichen, bushes, tree, water plants, etc.)	1	10
Invertebrates (earthworm, bee, mollusks, snail, etc.)	1	10

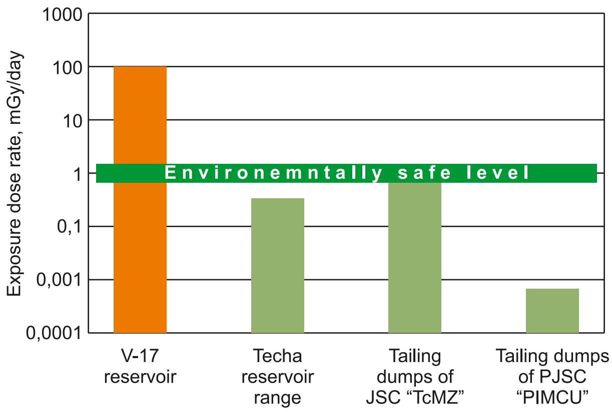

Fig. 2. Assessment of maximum dose rates for plants and invertebrates in the vicinity of special RW storage facilities

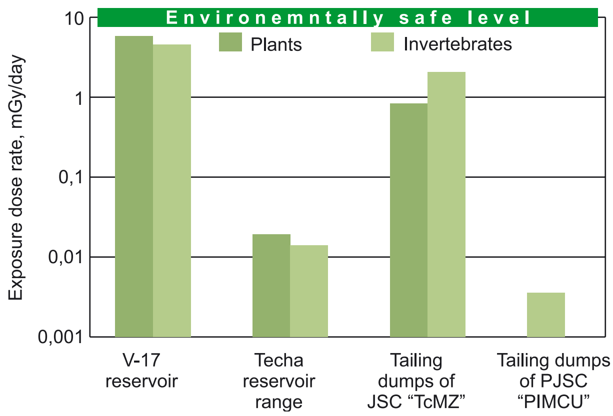

Fig. 3. Assessment of maximum dose rates for vertebrates in the vicinity of special RW storage facilities

shall conform to the requirements of GOST[10], specifically: "equivalent dose rate at any point of external surface shall not exceed 2.0 mSv/h, and shall not exceed 0.1 mSv/h at the distance of 1 m from the surface". Thickness of reinforced concrete wall of RWDF is 40 cm. For environmental impact assessment purposes, it was assumed that for VLLW (4 class) disposal the waste was packed in drums and the thickness of compacted soil screen was equal to 15 cm. RW packages contained ^{60}Co and ^{137}Cs containing waste with maximum specific activities for relevant classes of RW according to RW categorization criteria (see reference 7). Table 2 shows assessments of daily absorbed dose in the soil at the external surface of RWDF engineered barriers.

Data of Table 2 demonstrate that the in-force requirements applicable to RW containers and RWDF ensure protection of not only humans, but also the environment.

Requirements to container lifetime (300 years for NZK, at least 50 years for special drums, etc.), lifetime of RWDF engineered barriers (the whole period RW remains potentially hazardous), and the relatively short potential hazard period for the considered classes of waste suggest that criteria of

[10] GOST R 51824-2001. Single-use protective containers for radioactive waste made of concrete-based materials.. General technical requirements.

Table 2. Example of exposure dose assessment at the external surface of RWDF engineered barrier for near-surface RWDF

RW category	Radionuclide	Maximum value of radionuclide specific activity, Bq/g	Absorbed dose rate, mGy/day
LLW and ILW	^{137}Cs	$2.7 \cdot 10^4$	0.01
	^{60}Co	$3.64 \cdot 10^3$	0.03
VLLW	^{137}Cs	$1 \cdot 10^3$	0.2
	^{60}Co	$1 \cdot 10^3$	2.0

allowed radiation impact on biota species will not be exceeded in long-term perspective.

Today, the most important issue is coordination of international recommendations with documents of Ministry of Natural Resources and Environment of Russia, Rospotrebnadzor, Rostechnadzor, and Roshydromet. At the same time, the issue of environmental damage for the case of due handling of RW may be considered as a resolved one.

Biological interference

Speaking of environmental impact of nuclear facilities operation, one should remember the second face of the coin — impact of living organisms on safe functioning of man-made facility.

The term "biological interference" (hence called biointerference) is generally applied to biological organism affecting the sanitary condition of water bodies, water pipelines, irrigation system, hydroelectric power plants, nuclear power plants and other technical facilities [8]. Main sources of biointerference include aquatic organisms, water plants and microflora. For example, increased annual production of macrophytes and zebra mussels in NPP cooling ponds exceeds 6 kg/m^2 and 0.4 kg/m^2 respectively, leading to progressing overgrowing and shallowing [9]. A system of regulatory and technical requirements (sanitary, hygienic, fire, etc) aimed at safe operation of industrial facilities is already in place in Russia. Biota inhabiting the facilities (water bodies, pools, hydrotechnical structures) is either technologically regulated, or eliminated. Regulations on allowed distance of trees and bushes from industrial buildings are in place for industrial sites, there are requirements for establishment of mineralized lanes, chopping of bushes, grass mowing, etc. For sites located in forests, special attention is paid to protection from certain types of mammals, such as beavers, who create dams leading to damage of hydrotechnical structures and roads. In the framework of the current work, we will consider impact of biological organisms on the special RW storage facilities and RWDF, where potential hazard period may range from hundreds to thousands of years.

LRW storage facilities, near-surface and subsurface SRW storage facilities and tailing dumps are typical examples of special RW storage facilities.

Operation of such unique legacy sites as water bodies of FSUE "PA "Mayak" is accompanied by regular systematic studies of the local flora and fauna [10, 11]. Biogenic transport of activity has been studied, including in complex chains: by mosquitoes [12], bats [13], ducks, etc.

A seemingly minor process of radionuclide migration by Chironomidae mosquitoes turned out to be a serious pathway for radionuclide transport. According to the performed assessments, annual removal of activity only from V-10 water pond of FSUE "PA "Mayak" was up to $2.8 \cdot 10^9$ Bq of ^{90}Sr and up to $2.4 \cdot 10^8$ Bq of ^{137}Cs [12], which was nearly 0.001 % of radionuclide activity accumulated in this pond. In their turn, the insects are an intermediate link between water bodies and other species, such as bats. Levels of radionuclide activity in the bodies of Myotis dasycneme bats at the recreation camp "Zvezdochka" located at a distance of 20 km from LRW storage ponds of FSUE "PA "Mayak" were in average 200 Bq/g of ^{90}Sr and 10 Bq/g of ^{137}Cs [13].

In addition to activity transport out of the open water storage facilities (Techa range of reservoirs, V-6, and V-2), processes of natural water cleaning (sedimentation, etc. [14]) have been studied and received positive reviews. One of the considered options was the process of sedimentation of suspended particles to natural bottom sediments leading to removal of contaminants from the water environment. For example, self-cleaning of V-10 and V-11 reservoirs takes place both due to radioactive decay, and due to natural sedimentation processes (sedimentation rate reaches 8 mm/year [15]). In this sphere water species are considered to be an additional instrument of bringing the facilities into a safe condition.

With respect to SRW storage facilities, there has been no special radiological studies performed and general rational requirements on maintaining the integrity of engineered barriers and counteraction to biointerference shall be applied. For example, a requirement on periodic chopping of trees and bushes growing on the cover screen to avoid its failure, etc.

Requirements on RW isolation from the environment for the whole period of its potential hazard lead to the need to assure functional capabilities of safety barriers for extended periods of time. In this connection, biota living outside the near-surface storage facilities of special SRW and RWDF (trees, bushes, animals, etc.) becomes a source of biointerference potentially leading to deterioration of safety barriers (covering screen compromise by roots), while biota living inside the facilities — a source of potential releases and increase of temperature inside the facility.

For example, the fact of earthworms inhabiting the vicinity of RW storage facility (earthworm is one of the referent biota species) was assessed for the first time in process of justification of RW designation as special waste [16]. On the other hand, this shall also be regarded as biointerference in development of long-term safety case for near surface RW disposal facilities. C. Darwin once said that not paying attention to the activities of worms was "an example of mans inability to sum up the effects of a continually recurring cause". Studies performed at the beginning of XX century demonstrated that from 0.5 % (desert-steppe heavy clay earth) up to 2 % (North-East Altay soils) of the soil volume may be taken up by earthworm pathways [17]. These pathways change the soil structure (increase air permeability, water permeability, change density) and are a required condition for plant roots growth both downward and sidewards. In turn, high population of worms leads to growth of populations of moles and other animals. In other words, taking into account this type of biointerference starts to become a practically important problem, as the above processes may cause deterioration of facility safety barriers in the long term period.

Impact of microorganisms on processes of biological conversion of metal structures and destruction of cement compound microstructure is an important factor for RWDF containing long-lived radionuclides.

Porous concrete structure promotes participation of thionic, nitrifying and tropholytic bacteria, mould and yeast in corrosion processes. These microorganisms produce aggressive chemical compounds: inorganic (nitric and sulphuric) and organic (gluconic, oxalic, succinic) acids, hydrogen sulphide, other sulphides, ammonia.

Microorganisms as biointerference may be located immediately on the surface, inside protective barriers or at a specific distance from them. Therefore, the rate and intensity of impact of microbially produced aggressive chemicals will be substantially different based on spatial position of the biotic objects. This is significant for optimization of measures on prolongation of their duration the natural and engineered safety barriers remain within the acceptable range of parameters.

The fastest propagation of concrete and reinforced concrete corrosion is observed in technogenic environments. High humidity, presence of organic matter, fats and their hydrolysis products, ammonia, salines, all make favorable conditions for intense growth of corrosive-active microorganisms. Observance of RW disposal acceptance criteria becomes an important factor of long-term safety in this connection.

Studies of microbial impact on the safety of liquid RW disposal in deep geological formations, on long-term near-surface storage of solid RW, and the impact of this waste on environmental safety, have been underway in Russia for several years [18].

Microbial effect on the rate of radionuclides migration, generation of complexing agents and aggressive compounds, production of new mineral phases, change of biogenic gas generation, etc. have also been studied [19]. Microbiologic study of underground waters in the vicinity of deep liquid RW disposal facilities is an important problem, aimed, among other things, at development of safety case for closure of the facilities [20].

This is the reason why studies of microorganisms present in geologic formations need to be performed, among other considerations, in process of siting long-lived RW disposal facilities.

Conclusion

Development of new approaches to radiation protection, including additional account for the impact of ionizing radiation on biota and ethical principles is appropriate and has specific features with respect to application to RWDF.

In the short-term “protection by distance” by establishment of control areas around major nuclear facilities guarantees safety of the population and environment. However, there remains the problem of long-term safety justification after RWDF closure and lifting of all institutional controls taking into account the possible scenarios of degradation of natural and engineered barriers. Concepts of reference animals and plants and derived consideration reference levels shall be duly developed in terms of adequate account for flora and fauna species at RWDF sites.

Account for negative and positive impact of biointerference on long-term RWDF safety is another aspect of mutual influence of anthropogenic facilities and nature. This factor shall be taken into account separately for the operational stage (licensed operation period) and post-institutional control stage. It is proposed to use a concept similar to RAPs, a limited subset of animals, plants and microorganisms affecting the containment of RWDF in various time periods.

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