Atomic Energy, Vol. 114, No. 5, September, 2013 (Russian Original Vol. 114, No. 5, May, 2013)

ARTICLES

TOPICAL ENVIRONMENTAL PROBLEMS OF NUCLEAR POWER

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UDC 612.014.481

A leading factor determining the prospects for nuclear power is an assessment of the radiation safety of the environment and people. The anthropocentric (public health) and ecocentric principles of radiation protection are singled out and the role of the natural radiation background is described. Key environmental problems in the development of nuclear power are handling radioactive wastes and spent nuclear fuel, radiation accidents with emission of radionuclides into the ambient environment and decommissioning of NFC enterprises. The importance of harmonizing the standards for admissible irradiation of man and biota is noted.

In the analysis of the factors determining the development of nuclear power – economic, socio-demographic, medical, political and others – there has emerged in the last 10–15 years the point of view that the ecological factor is decisive. The idea is that the effect of the entire complex of NFC enterprises on nature is under study [1, 2]. NFC enterprises have diverse effects on the environment ranging from exclusion of sites under construction to thermal emissions and discharges from NPP, change in the meteorological conditions near enterprises, withdrawal of large quantities of fresh water for technical needs, discharges of non-radioactive toxic wastes and others. However, it is generally recognized that the environmental effects of ionizing radiation associated with the emissions and discharges of radionuclides are regarded as an ecological factor that is both local and global [3, 4].

An environmental effect of elevated quantities of radionuclides is intrinsic not only to nuclear power enterprises. Among the unified views on the effect of the radiation factor associated with the operation of NFC enterprises on the biosphere, it is important to analyze numerous other sources of ionizing radiation occurring in nature. In this respect, the effect of an elevated concentration of radioactive materials used in construction and as fertilizers and ameliorants in agriculture on biota and people's health is important in itself. Determining the effect of a naturally occurring radionuclide on health is an important biological problem – radon (^{222}Rn) in homes and the environment. The emissions of radionuclides into the atmosphere are significant for not only the NFC but also, for example, the emissions due to coal, which are characterized by flow in the environment of naturally occurring heavy radionuclides from the ^{232}Th and ^{238}U families.

In summary, on the one hand any assessment of the effect of the radioecological factor associated with nuclear power must harmonize with taking account of the role of all other sources of radiation effect on the biota and man. On the other hand, there is another important criterion in determining the significance of the radioecological factor in the development of nuclear power – its comparison with other components of technogenesis in today's world (chemical and thermal pollution, global climate change), for which an adverse effect on the environment is characteristic. Ecologically, nuclear power has obvious advantages, since, for example, unlike power generation using fossil fuel, first and foremost, coal, it is not associated with emissions of greenhouse gases and the associated global warming.

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1063-4258/13/11405-0301

Analysis of the effect of nuclear power enterprises on live organisms in their habitat leads to the conclusion that two problems are determining in the ecological perspective – handling radioactive wastes and the consequences of accidents in which radioactive substances are emitted. The study of the effect of ionizing radiation on biota during regular operations of NFC enterprises and radiation monitoring on adjoining territories as well as decommissioning of enterprises are still classed as real ecological problems.

General Tenets of Radiological Protection of the Environment. Ecologically, the consequences of radioactive contamination of the environment can be evaluated, in the first place, by determining and comparing the concentrations of radionuclides in environmental objects, first and foremost, in agricultural production, with the maximum admissible concentrations established by the health norms and, in the second place, in terms of the radiation damage in biota (plants and animals). According to the main, extant, radioecological paradigm, the area of visible radiation damage occurring in biota due to radioactive contamination is much smaller than the natural habitat where the radionuclide concentration in the objects in the environment exceeds the health norms and therefore man's agricultural activity is limited, right up to exclusion of human habitation. This paradigm is the basis for rehabilitation of contaminated ground and is reflected in the conceptual tenets concerning the radiological protection of nature.

This paradigm dates back to the classic work by V. M. Klechkovskii, who in the 1950s showed that the accumulation of technogenic radionuclides in plants can reach a concentration where eating the plants becomes dangerous but at the same time no radiation damage is observed [5]. Subsequently, the validity of this postulate was confirmed during cleanup after accidents with emission of radioactive substances into the environment – accidents at the Industrial Association Mayak in 1957, the Chernobyl NPP in 1986, and the Fukushima NPP in 2011 [6–8].

The environmental protection doctrine is based on the need to secure the radiological safety of man and biota (plants, animals and other live organisms) simultaneously. According to the current concepts, the radiological protection of the environment can be guaranteed under conditions where peoples' safety during exposure to ionizing radiation is secured. The essence of this approach is actually anthropocentric. In other words, aphoristically, this reads as follows: if the standards secure radiological safety of humans, then the biota are also protected from radiation. The main prerequisite for this principle to be correct is that man is one of the most radiosensitive live organisms in the biosphere. In addition, radiation hygienic standards determining the limits on radiation exposure provide multiple safety factors for the admissible radiation dose for man. The world experience with nuclear power over almost 60 years has proved convincingly that this fundamental principle is correct and pragmatic.

We note that this paradigm was formulated mainly on ideas based on an analysis of situations where β- and γ-emitting nuclides determined the irradiation dose. Now there is a need to carefully analyze situations where α-radiation plays an important role (the early stages of the NFC, handling radwastes and spent nuclear fuel), when the formation of the absorbed dose in biota due to α-radiation becomes relatively more important biologically than for man.

The anthropocentric views indicated above concerning the radiological protection of the environment were, specifically, the fruit of development work done over a period of many years by the International Commission on Radiological Protection. The anthropocentric approach in solving the problems of protecting the environment from ionizing radiation was first formulated in ICRP Publication No. 26, and then confirmed in Publications 60 and 103 [9–11].

The theoretical basis for the anthropocentric view of the protection of biota and humans is the linear zero-threshold theory (concept) of the biological action of ionizing radiation, according to which the effect of irradiation is proportional to the dose, covering the entire range of possible dose effects – from small to lethal values. The validity of these ideas has been a subject of discussion in radiobiology for the last one hundred years, and the positions indicated are embedded in the base provisions of all official national and international documents pertaining to radiological safety.

At the same time, in recent years, the ecocentric views, according to which attention should be focused mainly on the direct protection of biota or, at least, the radiological protection of man and biota simultaneously, are being development more and more as a contrast to the anthropocentric views. The substantiation for the ecocentric postulate and some limitations of anthropocentrism are related with the fact that the supporters of anthropocentrism believe it necessary to study the consequences of irradiation of live organisms, something that is not done when using the anthropocentric thesis, which focuses solely on man and only indirectly assessing the safety of biota. The ecocentric views can be formulated as follows: man can be healthy only in a healthy environment.

The strengthening of the exocentric positions in the assessment of the effect of ionizing radiation on nature was a reflection of growing public concerns worldwide associated with the adverse effect of industrialization and urbanization on the Earth's biosphere and the acknowledgement of the fact that the preservation of the environment is becoming a problem of primary importance [12].

In regard to the views of the above-indicated principle of the radiological protection of man (based on the linear zero-threshold dose–effect concept), on the basis of the threshold effect of ionizing radiation the methodology of studying the consequences of the irradiation of biota (ecosystem) is polar. The justification for such an approach is that deterministic effects are of paramount importance in the effect of ionizing radiation on the population and community of live organisms (with respect to survival, morbidity, and fertility) while stochastic effects play the dominant role in the irradiation of humans. International (ICRP, IAEA, UNSCEAR) and national organizations are expressing the point of view that the threshold dose rate in chronic radiation exposure of live organisms lies in the range 1–10 mGy/day [13].

The ecocentric views of the radiological protection of nature are reflected in, specifically, the use of live organisms as references. Specifically, these views are developed in ICRP publications [14–16]. Some types of plants and animals are used as reference representatives of live nature. These references are chosen using certain criteria, the main ones being abundance, economic and ecological significance in world flora and fauna, radiosensitivity, amount of radiobiological and radioecological information, dose-forming characteristics in the ecosystem and others.

The main international document on radiological safety – the IAEA document "Basic Principles of Radiological Safety" – was adopted in 2011 [17] and once again confirmed the validity and correctness of the operative concept where people and nature are protected from ionizing radiation, though it does mention the importance of intensifying the search for direct proof of the protection of biota in different radioecological situations.

The development of conceptual views on the system for radiological protection of biota (environment) inevitably touches upon the assessment of the biological role of the Earth's natural background radiation. It is logical to infer that the natural radioactivity is an important ecological factor affecting all live organisms. Modern science has not formulated unified ideas about the biological significance of the natural background radiation. Moreover, there are diametrically opposite points of view on this. Ionizing radiation can be regarded as an important mutagen, which was proved back in the 1920s. The carcinogenic significance of ionizing radiation is acknowledged axiomatically.

One point of view on the biological role of natural radioactivity is the assertion that it is necessary for live organisms. Attempts have been made to prove experimentally the positive effect of the natural background radiation on different representatives of the living world (microorganism, plants and animals).

Aside from the above-noted particulars of the effect of the natural background radiation on the growth and development of live organisms, positive stimulating shifts in these processes have been found with some, on the whole negligible, increase in the background ionizing radiation near the so-called stimulation dose. Together with the information on the necessity of the natural background radiation and even increasing growth rates and development of live organisms in the presence of low dose irradiation (stimulation), it has been observed that the action of radiation in the linear dose–effect relation is not proportional at low dose and low dose rate. Nevertheless, in evaluating the effect of irradiation on natural ecosystems, apparently, it will be rational to rely on concepts attesting that ionizing radiation is one of many ecological factors. Like for any ecological factor, depending on the intensity of its effect, there are three main responses. In the first zone, the response is to background and low-background action, which is required for growth and development of live organisms or, to a lesser extent, the live organisms have adapted to such action over many centuries of evolution. In the second zone, a region of higher dose loads with insignificant excursion above the background, the response of live systems can be such that an adverse influence is not seen – the ecosystem actively overcomes adverse consequences. Finally, in the third zone of action of the ecological factor above a threshold dose restoration from damage does not start and an adverse effect of the irradiation right up to complete degradation of the ecosystem starts.

In radioecological probing of the environment, depending on the irradiation dose rate ranging from the natural background to lethal, six such zones can be identified: uncertainty (below the natural background), radiological well-being (background), physiological (0.005–0.1 Gy/yr), ecological masking (0.1–0.4 Gy/yr), injury to communities and ecosystems (>0.4 Gy/yr), and lethal outcome for the biosphere (≫ MGy/yr) [18]. The ecological risk should probably be evaluated in this system of dose coordinates of the action of environmental factors, including ionizing radiation. In this scientific-methodological approach, the estimated natural radiation background is the reference point.

Extensive radioecological studies to determine the natural radiation background have been performed in a global context. According to UNSCEAR data, the present-day average radiation background on the Earth is 2.4 mSv/yr. Obviously, it can fluctuate. Thus, in separate regions of the world it can reach 10 mSv/yr or more. It is important to note that many radioecological studies on biota and epidemiological studies on man have not shown any consistent adverse changes in such zones.

Radioecological Problems of Handling Radwastes. The formation of radwastes is an unavoidable attribute of a large number of production processes at all stages of the NFC. In consequence, they enter the environment and become part of the biological migration chains, leading to man and man's subsequent irradiation. A biota is exposed to ionizing radiation at the same time. The main problems from the ecological standpoint are a reduction in the amount of wastes and a search for methods for lowering their chemical mobility and biological accessibility to the repository, which eliminate or at least minimize the entry of radionuclides into the biological migration chains and the associated irradiation of man and other live organisms. The program of the development of nuclear power into the near- and far-term futures must certainly include handling wastes.

The intensity of the action of radioactive substances entering the environment on man and biota is different in different links of the NFC. It depends on many factors, the main ones being the amount and composition of the radionuclides released into the environment, dynamics of the flow of radioactive substances into the environment, transport paths to man and others [4]. Thus, at the first stage of the NFC – the production and processing of the uranium raw material – the products of decay of the radionuclides in the ^{232}Th and ^{238}U families make the main contribution to environmental contamination. A feature of these families from the ecological standpoint is the presence of α-emitting nuclides with high biological effectiveness. One consequence of this is a higher irradiation dose to biota relative to man (α-emitters play a relatively small role in man's food chain). The main radionuclides produced during the operation of NPPs and entering the environment are fission products and nuclides with induced activity, mainly, β- and γ-emitting nuclides. Among these, mainly the relatively long-lived ^{90}Sr and ^{137}Cs are of biological interest. At the stage of handling spent nuclear fuel, belonging to, apparently, the most radio-ecologically stressed link of the NFC, the long-lived transuranium radionuclides are of greatest importance. There are other nuclear production operations where individual biologically important radionuclides – ^{3}H, ^{14}C, and others – play an important role.

A concept for protecting the environment and people's health from ionizing radiation was developed within the framework of the base ideas indicated above concerning the biological role of the natural radiation background. It is called radiation equivalence [19]. The crux consists in the need to attain equality between the possible biological dangers of buried wastes, on the one hand, and the naturally occurring uranium as nuclear fuel extracted from the deep interior of the Earth, on the other. The concept of the biological (potential) danger of the effect of the radiation factor is estimated only for evaluating the harmful effect of ionizing radiation on man. Analysis of the effect of ionizing radiation on live organisms other than man – biota – is not part of the concept.

The basis for implementing this principle – confining the analysis of the effect of irradiation solely to man – is the thesis noted above: if radiation standards protect man, then in this situation all other live organisms (the environment) are automatically protected from radiation. This limitation of the concept of radiation equivalence requires provisos, and in the future, undoubtedly, responses to the irradiation of live organisms other than man will have to be in included in the analysis.

Initially, the concept of radiation equivalence did not take account of the fact that there is a certain probability for the radionuclides in buried wastes to act on man, since these nuclides spread with different rates in the engineered safety barriers protecting the environment. For this reason, the concept was modified taking account of the migration properties of the radionuclides and its name was changed to the concept of radiation-migration equivalence. For example, calculations of the time to radiation-migration equivalence were performed at the All-Russia Research Institute of Agricultural Radiology and Agroecology (VNIISKhRAE) and the Institute of Problems in the Safe Development of Nuclear Energy, Russian Academy of Sciences (IBRAE RAN) for uranium ore bodies located deep inside the Earth and on the surface [20]. The principle of radiation-migration equivalence makes it possible to solve in the ecological aspect in a general formulation the problems of handling nuclear materials in the fuel cycle, first and foremost, long-lived high-level wastes. Moreover situations in which mountain massifs, characterized by low migration intensity of the main radionuclides, are used for burying wastes, could be more realistic.

Adherence to the principle of radiation-migration equivalence presupposes the possibility of transmutation of wastes. The conditions indicated above cannot be satisfied in an open nuclear fuel cycle; they can be satisfied only in a closed cycle. It is thought that at some point in time the radioecological danger of burying wastes will not exceed the danger from the radionuclides extracted from deep within the Earth and this will make a definite contribution to the assessment of the long-term prospects for the development of nuclear power.

Ecological Problems of Accidents with Emission of Radionuclides into the Environment. The development of nuclear power in the long term presupposes the elimination of all accidents at NPP and other enterprises of the full NFC, especially with emissions of radioactive substances. History shows that such accidents cause serious delays in the development of nuclear power primarily because of the negative attitude of the public and growth of a wave of protests by environmental activists. Unfortunately, often, it cannot be ruled out that in reality the physical and moral damage from the consequences of radiation accidents and contamination of the environment are much smaller than in reality [6]. An example of the development of events in this key is the accident at the Chernobyl NPP, which seriously slowed the growth of nuclear power in the world, including in our country. As a result of the cleanup after the accident measures were taken to strengthen the nuclear and radiation safety of NPP and other NFC enterprises, which made it possible to restore confidence in nuclear power to a significant degree and restore its rates of growth. However, the accident at the Fukushima accident in 2011, which led to radioactive contamination of large territories, once again showed the importance of the problem of radiation accidents. One to two years after the accident, its effect on the slowing of the rates of growth of nuclear power was less pronounced than after the Chernobyl accident, but for some countries this effect was significant.

Analysis shows that even though efforts are being made to increase the nuclear and radiation safety at NFC enterprises it would be imprudent to eliminate the possibility of emergency situations. In consequence, there arises the need to develop plans for protective measures for different radioecological situations associated with different variants of anticipated and unanticipated accidents, leading to radioactive contamination of the environment. Thus, the section which can be named the radioecology of radiation accidents must be a separate component in the strategy for the development of nuclear power in the near- and long-term future.

As experience in cleaning up after the accidents in the Southern Urals and the Chernobyl and Fukushima NPPs shows, the ecological and medical aspects take a leading place in radiation accidents. The ecological consequences of radioactive contamination of the environment during accidents can be divided into two categories – radiation changes in the biota (different degrees, right up to complete destruction of plants and animals and entire ecosystems) and its radioactive contamination, in which the indications of radiation changes in the biota are weakly expressed and the main danger comes from the use of radioactively contaminated products, first and foremost, the consumption of agricultural products.

At the post-accident response level, the problems of limiting the intensity of radionuclide migration along trophic chains leading to man must be addressed first [6, 21]. In our country, extensive experience has been accumulated in cleaning up after radiation accidents and in the rehabilitation of radioactively contaminated territories [4]. Such accidents can be treated as communal, mainly, agricultural.

The basis for such a classification is as follows:

1) the use of agricultural products, first and foremost, food products, containing radionuclides is one of the main and sometimes also the dominant path for irradiation of man;

2) a reduction of the irradiation dose to the population is accomplished economically and technologically more efficiently for internal action (owing to regulation of the intensity of the migration of radionuclides along trophic agricultural chains);

3) the main contingent of the population on the territories subjected to radioactive emissions is, as a rule, rural;

4) the irradiation dose to rural inhabitants is as a rule higher than to urban dwellers (type of food, weaker protective role of homes and more time spent in the open air);

5) the important psychological and social significance of the production of products, first and foremost, food, with higher than the admissible concentration of radionuclides (keeping in mind stopping of the production of such products); and

6) the agro industry is one of the most important sectors of the economy in the regions which are contaminated due to an accident.

After cleanup following radiation accidents, extensive experimental data were accumulated on the migration of radionuclides along food chains leading to man, a complex of protective measures on rehabilitation of the contaminated territories, which can be used as a basis for a response to the consequences of the radioactive contamination of a territory, was developed and tested on large scales. Unique experience in rehabilitating contaminated agricultural land is being accumulated after the accident at the Fukushima NPP, where the removal of radionuclides from the top layer of the soil formed the foundation for protective measures, i.e., the problem reduces to handling wastes [8].

Unfortunately, there are no fundamental documents, regulating the principles for the protection of the environment from ionizing radiation, in the domestic laws pertaining to the nuclear industry. The development of nuclear power requires systemic documentation that would harmonize the principles of the regulation of the admissible radiation effects in man on the one hand and the environment on the other. At the same time, such harmonization is necessary between national and international documents regulating the radiation protection of man and biota.

REFERENCES

1. *Conceptual Propositions of a Strategy for the Development of Nuclear Power in Russia in the 21st Century*, NIKIET, Moscow (2012).
2. *On a Strategy for Nuclear Power in Russian to 2050*, National Research Center – Kurchatov Institute, Moscow (2012).
3. R. M. Alexakhin, *Nuclear Power and the Biosphere*, Energoatomizdat, Moscow (1982).
4. I. I. Kryshev and E. P. Ryazantsev, *Ecological Safety and the Nuclear Power Complex in Russia*, IzdAT, Moscow (2010).
5. V. M. Klechkovskii (ed.), *On the Behavior of Radioactive Fission Products in Soils, Their Migration into Plants and Accumulation in Crops*, Akad. Nauk SSSR, Moscow (1956).
6. R. M. Alexakhin, L. A. Buldakov, V. A. Gubanov, et al., *Large Radiation Accidents: Consequences and Protective Measures*, edited by L. A. Il'in and V. A. Gubanov, IzdAT, Moscow (2001).
7. *Environmental Consequences of the Chernobyl Accident and Their Remediation: Twenty Years of Experience*, Report of the Chernobyl Forum Expert Group "Environment," IAEA, Vienna (2006).
8. *Final Report of the International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Dai-Ichi NPP*, Oct. 7–15, 2011, IAEA, Vienna.
9. *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, *Annals ICRP*, 1 (3), Pergamon Press, Oxford (1977).
10. *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, *Annals ICRP*, 21 (1–3), Elsevier, Amsterdam (1990).
11. *The 2007 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 103, *Annals ICRP*, 37 (2–4), Elsevier, Amsterdam (2007).
12. F. Brechignac, C. Bradshaw, S. Carroll, et al., *Towards an Ecosystem Approach for Environmental Protection with Emphasis on Radiological Hazards*, Intern. Union of Radioecology (2012).
13. T. G. Sazykina, A. I. Kryshev, and K. D. Sanina, "Nonparametric estimation of thresholds for radiation effects in vertebrate species under chronic low-LET exposures," *J. Environ. Biophys.*, **48**, No. 4, 391–404 (2009).
14. *A Framework for Assessment of the Impact of Ionizing Radiation on Non-Human Species*, ICRP Publication 91, *Annals ICRP*, 33 (3), Elsevier, Amsterdam (2003).
15. *Environmental Protection: the Concept and Use of Reference Animals and Plants*, ICRP Publication 108, *Annals ICRP*, Elsevier, Amsterdam (2009).
16. *Environmental Protection: Transfer Parameters for Reference Animals and Plants*, ICRP Publication 114, *Annals ICRP*, Elsevier, Amsterdam (2009).
17. *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*, No. GSR Part 3 (Interim), IAEA, Vienna (2011).

18. G. G. Polykarpov, "Conceptual model of responses of organisms, populations and ecosystems to all possible dose rates of ionizing radiation in the environment," *Rad. Prot. Dosim.*, **75**, 181–185 (1998).
19. E. O. Adamov and I. Kh. Ganev, *Ecologically Faultless Nuclear Power*, NIKIET im. N. A. Dollezhalya, Moscow (2007).
20. E. V. Spirin, S. I. Spiridonov, R. M. Alexakhin, and S. S. Utkin, "Radioecological evaluation of a uranium deposit for validating the radiation-migration balance of long-lived wastes," *At. Énerg.*, **114**, No. 1, 34–39 (2013).
21. G. Voigt and S. Fesenko (eds.), *Remediation of Contaminated Environments*, Elsevier, Amsterdam (2009).