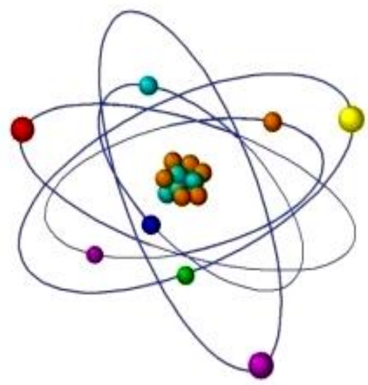
CHALLENGES IN MODERN RADIOECOLOGY FOLLOWING THE CHERNOBYL DISASTER



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ABSTRACT*: The Chernobyl disaster remains a key factor shaping modern radioecology even decades after the event. The scale of radiation impact on ecosystems, human populations, and biota has led to a wide range of theoretical and applied research challenges. One of the central issues remains the reconstruction of radiation doses received by the population, particularly during the acute phase of 1986, when a significant portion of the total lifetime dose was accumulated. Radiation exposure caused pronounced changes in ecosystems, including the death of radiosensitive species, the formation of the “Red Forest” and the initiation of successional processes whose consequences continue to evolve. Contemporary studies emphasize the need for systematic monitoring of biota conditions, radionuclide migration, and dose assessment within ecosystems. Particular importance is attached to the long-term storage of radioactive waste, environmental risk assessment, the development of dosimetric methods, and ecological standards that consider not only humans but also the biotic components of ecosystems. The importance of studying ecosystem self-remediation processes, adaptation mechanisms, and the possible effects of low (quasi-background) radiation doses is also highlighted. Special attention is given to the development of effective countermeasures, including biodecontamination technologies and approaches to ecosystem “therapy.” The exclusion zone is regarded as a unique natural testing ground for investigating long-term radioecological and evolutionary processes, as well as for conducting integrated environmental experiments. Overall, the outlined challenges reflect the formative stage of modern radioecology as an interdisciplinary field of fundamental importance for the advancement of general ecology and for managing the consequences of technological disasters.*

Keywords: radioecology, Chernobyl exclusion zone, ecosystem resilience, radionuclide migration

Although it has been forty years since the Chernobyl nuclear power plant accident, it remains an important impetus for analyzing the state of radioecology. The Chernobyl accident and its consequences sharply defined and presented radioecology with a whole range of theoretical and applied problems that required and to a large extent still require solutions. The main feature of this accident lies in its scale and the extent of its impact on the environment, the population, and personnel working within the 30-km Exclusion zone and beyond. Of course, the main problem that Ukraine has never fully managed to resolve is the assessment and reconstruction of radiation doses received by the population in the area affected by the Chernobyl accident during the most dangerous year of the acute phase of the accident –1986. According to various estimates, the radiation dose received by people in 1986 may range from 60 to 99% of the total lifetime dose received in an environment with elevated background radiation. As a result of the Chernobyl accident, the biotic component of ecosystems has been and continues to be subjected to significant radiation exposure – ranging from cGy to tens of grays. This has led, in particular, to the emergence of the "red forest" phenomenon due to the death of the most radiation-sensitive coniferous tree species. Noticeable succession processes have occurred and continue to occur in the Exclusion zone and surrounding territories. It is evident that other consequences should be expected, as the time elapsed since the accident is insufficient for long-term ecological consequences (particularly population-genetic ones) to manifest. Furthermore, due to the ongoing processes of radionuclide redistribution through food chains and ecosystem components (biota, bottom sediments, forest litter, etc.), further changes in absorbed doses within the biotic components of ecosystems are to be expected, and thus new consequences as well.

During the cleanup following the Chernobyl disaster, more than 200 different mitigation measures were implemented, resulting in a wide range of impacts that varied in both effectiveness and consequences. These efforts warrant a thorough analysis to assess their effectiveness and to develop a universal system of mitigation measures suitable for use in other environmental disasters and situations.

The main objectives of this article are:

- to propose a list of current unresolved problems in radioecology;
- to outline the current state of research on the most pressing radioecological issues;
- to discuss unresolved problems that require urgent research.

At a previous seminar of the International Union of Radioecologists, expert participants compiled a list of nearly one hundred unresolved problems in modern radioecology and ranked them by degree of importance and relevance, as we wrote about earlier [1]. In this article, we will focus on those issues that are directly or indirectly related to the impact of the Chernobyl accident on ecosystem biota; we have selected about two dozen issues from the previously proposed list, considering them the most important:

1. Monitoring the radioecological, phytosanitary, and zoosanitary status of biocenoses in the 30-km exclusion zone. Of course, individual studies on the phytosanitary and zoosanitary conditions of the 30-km zone are being conducted. However, these studies are irregular and selective in nature and address only certain aspects of this complex problem. These primarily involve investigating changes in the pathogenicity of certain plant and animal viruses, fungi (micromycetes), and others [2]. At the same time, increased genetic instability caused by elevated radiation doses in the 30-km zone may lead to intense succession processes, primarily in the microbiota of aquatic, soil, and forest ecosystems. High reproduction rates may also lead to microevolutionary changes in the biota of the 30-km zone. It cannot be ruled out that the 30-km zone may become a source of microorganisms dangerous to plants, animals, and perhaps even humans. Loss of control over the health status of the biota in the 30-km zone may also lead to the additional generation of dangerous or simply unknown mutations. All of this urgently requires systematic and regular research, which is absolutely essential to ensure the safe existence of biota and humans.

2. Long-term disposal of radioactive waste. The more than 800 temporary high-level radioactive waste disposal sites located within the 30-km zone pose a serious threat to the well-being of the biota. Destructive processes within these disposal sites will inevitably lead, sooner or later, to the contamination of the surrounding soil and groundwater. Furthermore, in areas with significant radiation levels, the altered activity of soil microorganisms and animals may affect the solubility and availability of radionuclides in the disposal sites and lead to their accelerated redistribution. Such processes may result in significant quantities of hazardous radionuclides entering the subsoil and surface water bodies via the hydrological network and groundwater discharge pathways, posing a danger to biota and humans. On the other hand, high-level radioactive waste disposal sites can be used as radioecological mini-test sites, a kind of “gamma-ray field”.

3. Radioecological Monitoring. The radioecological situation that has developed since the Chernobyl accident, due to its unique characteristics, offers more opportunities than ever before to study virtually all aspects of radioecology. This applies particularly to the radiation monitoring system, which, in our view, should be strengthened to focus on the study of succession processes induced primarily by a reduction in anthropogenic pressure on natural ecosystems at various levels of integration. To this end, the development and practical implementation of generalized parameters for assessing the state of ecosystems under conditions of elevated levels of radionuclide contamination should be continued. Extensive laboratory studies of the stress resistance of various representatives of the flora and fauna would be useful in this regard. We consider it particularly necessary to organize continuous monitoring of the cytogenetic status of natural populations and, especially, of changes in microsatellite DNA sequences, which reflect the influence of a radiation stressor at doses close to background levels.

Given that radiation doses to biota in the Chernobyl zone are close to background levels but still exceed them, we consider it necessary to direct certain experimental and theoretical efforts toward the development of new bioassay methods, in particular, methods using presensitized test organisms, which will allow for the detection of the effects of quasi-background doses of ionizing radiation.

4. Environmental regulation of radiation exposure to biota and humans. The current global system for regulating radiation exposure is strictly human-centered and is limited to radiation hygiene standards. At the same time, experimental studies and theoretical calculations show that the biota of ecosystems in the accident zone is subjected to significant radiation doses ranging from one to tens of Gy/year [3]. It has been shown that doses as low as 0.4-4.0 Gy/year can lead to stunted growth and the death of certain biota species. This indicates the need to supplement the system of health-based standardization with the theory and practice of ecological standardization of permissible levels of contamination of ecosystem biota. It is possible that in a number of situations, environmental regulation of permissible levels of contamination of ecosystem components may be stricter than health-based regulation, due to the dynamics of radionuclide redistribution among ecosystem components and their concentration in biota.

5. Environmental radiation risks (genetic and somatic). The Chernobyl accident had (and has) several dose periods, distinguished by the main dose-forming radionuclides that predominantly constitute the radiation background. For example, the “iodine period,” caused by the decay of iodine-131, was followed by the “strontium-cesium” period (strontium-90 + cesium-137), in which we currently find ourselves, and which will be replaced in a hundred years by the “americium” period (americium-241). It follows that ecological systems have undergone and will continue to experience diverse dose loads, causing both deterministic (primarily during the “iodine period”) and stochastic (currently and, likely, in the future) effects. The deterministic effects observed during the “iodine period” were primarily somatic effects in the form of the death of coniferous trees in the immediate vicinity of the destroyed Unit 4 of the Chernobyl NPP (“the red forest”). In subsequent periods, stochastic effects have been and will continue to be observed, primarily in the form of changes in the genetic and/or epigenetic structure of natural populations. The observational data obtained to date on these types of responses allow for a significant refinement of previously existing assessments of somatic risks at the population level of ecosystem organization. It is becoming clear that such assessments should be made while taking into account other environmental stressors (primarily chemical ones). As for the risks associated with the possible genetic consequences of increased background radiation, the Chernobyl accident provided a unique opportunity to improve the quality of such assessments, since, compared to other nuclear incidents (e.g., the Kyshtym accident 1957 y.), the influence of the anthropogenic factor (“people left the Zone”) was virtually reduced to zero after this accident, and the impact of ionizing radiation on the biotic components of ecosystems occurred against the backdrop of other powerful succession processes that inevitably influenced the genetic and cytogenetic consequences of the accident.

6. Critical landscapes and components in ecosystems. Radioecological studies conducted in real landscapes within areas affected by radiation accidents demonstrate the decisive role of landscape structure in the distribution, redistribution, and deposition of radionuclides [4]. Landscape depressions are particularly important in this regard, as they are crucial for predicting the vertical and horizontal dynamics of radionuclide contamination, as well as for the potential use of natural and artificially created landscape depressions in phytodecontamination technology.

7. Radioactive capacity and ecological capacity of ecosystems. The question of methods for assessing the resilience of ecosystems to radiation loads remains unresolved. In particular, research must be intensified to identify the critical elements of ecosystems that primarily determine their response to irradiation. It is also important to study indirect, remote effects in irradiated systems. Ultimately, the results of such studies can serve as a foundation for studying ecosystems under normal conditions. In any case, stress ecology should be developed, and radioecology and radiobiology, with their arsenal of sufficiently accurate methods, will be a significant aid in this endeavor.

8. Equidoseimetry and dosimetry of radionuclide exposure to biota. Perhaps we should have started with this, but issues of radiation dosimetry in the case of ecosystem irradiation are particularly acute, since significant vertical and horizontal heterogeneity of radionuclide contamination is observed, which greatly complicates the estimation of integral doses to the biotic components of ecosystems. In addition, the task of dosimetry is complicated by the alternation of acute and chronic (prolonged) radiation exposures. Equally important are the problems of equidosimetry, the resolution of which has allowed for a more scientifically sound standardization of radiation and other exposures based on carcinogenic risks.

9. Determination of critical pathways for radionuclide migration beyond the boundaries of the Exclusion zone. This task is important and relevant in two respects. First, it requires an answer to the question of the structure of the radionuclide migration flux. To this end, it may be advisable to apply the theory of non-equilibrium (dissipative) structures, which would allow us to describe the origin (channelling) of such flows and their interaction with existing migration channels through which non-radioactive isotopes move. A very important aspect of this task is determining the ratios (proportions, shares) of the contributions of biotic (birds, fish, insects, etc.) and abiotic (water, air) components to the transport of radionuclides beyond the boundaries of the Exclusion zone. Second, monitoring the migration of radionuclides in natural and/or anthropogenically altered landscapes significantly simplifies the task of monitoring the migration of chemical non-radioactive analogs of radionuclides. In other words, it becomes possible to use radionuclide tracers to obtain an overall picture of geochemical migration within the Exclusion zone and beyond.

10. Prevention and restoration of ecosystems under conditions of stressful radiation exposure. There is no doubt that the wide-ranging research currently being conducted on the adaptive and hyperadaptive capabilities of biological systems at various levels of integration must also find its place in the field of radioecology. From this perspective, the goal of reducing ecological (and, in particular, radioecological) risks can be achieved not only by minimizing the stresses on ecosystems caused by factors of various natures (physical, chemical, and/or biological), but also through the unique ability of ecosystems to "train" ("harden") themselves in response to stressors [5]. While the existence of such an ability in ecosystems is evident, the methods (pathways) by which ecosystems achieve a state of increased stability compared to their initial state are not so obvious. By analogy with the practice of adaptation (hyperadaptation) of systems at the organismal and sub-organismal levels, methods can be proposed for transitioning ecological systems into a state of increased resilience, the primary one of which will obviously be the stimulating (hormetic) effect of "stressors" on the biotic component of ecosystems (see item 18 for details). As for "therapy," i.e., the use of measures to restore ecosystem parameters altered by radiation loads, it should be noted that virtually no research has been conducted in this area, and solving this problem remains extremely urgent. We consider the comprehensive and simultaneous application of physical, chemical, and biological factors in appropriate dose and power regimes to be promising.

11. Self-purification of ecosystems from radionuclide contamination. The process of self-cleaning of ecosystems from radionuclide contamination, as applied to the Exclusion zone, has to date led to a significant reduction in the resulting background radiation level. However, the mere fact of such a reduction does not imply a specific mechanism or set of mechanisms "responsible" for this effect. It is evident that both biotic (migration of radionuclides through food chains) and abiotic components ("aging" of radionuclides due to their irreversible binding in the crystal lattices of clay minerals in the soil) of ecosystems are involved in this process. In this regard, theoretical and experimental studies of these processes – which ultimately determine (along with the initial stability of biotic components) radioecological risks – should be encouraged.

The study of ecosystem self-purification processes from radionuclide contamination and/or the minimization of the natural (spontaneous) availability of radionuclides to biota will help develop new or improve existing technologies for "forced" purification from radionuclide contamination in the form of various protective and decontamination measures.

12. The contribution of radioecology to resolving the "low-dose" dilemma of ionizing radiation. The concept of a "low dose" is, in fact, a metaphor that reflects the aspiration of radiobiologists and radioecologists to explore reactions at the most fundamental structural and functional level of biological systems. From this perspective, despite its vagueness, this concept serves an important function in uniting research efforts around such critical issues as the induction of new and modification of constitutive repair systems, mechanisms of radiation mutagenesis and carcinogenesis, and others. On the other hand, this concept has a negative impact on the distribution of research priorities among radiobiologists and radioecologists, diverting their attention from addressing no less important problems of radiobiology in biological entities at higher levels of integration (organisms, populations, communities, etc.). Regardless of the nature of the effect induced by ionizing radiation, i.e., regardless of whether it is stochastic or deterministic, from our point of view, it is appropriate to refer to the majority of doses absorbed by biological entities in the territories contaminated following the Chernobyl accident as “quasi-background doses,” emphasizing their quantitative and qualitative similarity to pre-accident parameters of the natural radiation background.

13. Development of a registry of preventive and therapeutic anti-radiation countermeasures with recommendations for their adaptation to specific conditions of radionuclide contamination. This position is consistent (and only) with what we mentioned in point 10, but with an emphasis on the need to adapt existing countermeasures to the specific characteristics of contamination (radionuclide spectrum, transport modes, etc.), as well as to soil and climatic characteristics. Furthermore, it is particularly important (and perhaps most important) that such an approach will enable the planning of radiation protection measures at the national level.

14. Adaptation of biota to radiation exposure under the influence of other environmental factors. Since ecosystem biota experiences radiation effects against the backdrop of other stressors, this raises the task, first, to quantitatively determine the degree of nonlinearity (non-additivity) in the interaction of stressors, and, second, to identify combinations of factors that minimize their negative impact on ecosystems. From our perspective, a study of the cross-resilience of the biotic component of ecological systems would also be entirely original. In “traditional” adaptology, cross-resilience is understood as a biological organism acquiring a broad spectrum of resilience under the influence of a specific (adaptive) level of one of these stressors. It is possible that under certain conditions and at certain doses of radiation exposure to ecosystems, they may acquire an increased level of resistance to the radiation stressor and other types of stressors.

15. Radiation and Evolution. The Role of Radionuclide Anomalies in Ontogenesis and Phylogeny. Although the study of the role of natural background radiation (NBR) in the phylogeny and ontogeny of biological organisms has been ongoing for nearly a century, a definitive answer has yet to be reached. Nevertheless, it is clear that the radiation factor is not strictly essential (obligate) for the functioning of biological organisms. Nevertheless, the non-essential (facultative) nature of this factor does not guarantee its insignificance under conditions of elevated levels of radionuclide contamination caused by human technological activity. Data on the wide variability of the PRF level in different regions of the Earth (within approximately three orders of magnitude) suggest that any evolutionarily significant events (microevolutionary, for example) are unlikely in the conditions of the Exclusion zone; but, nevertheless, as we noted in the introduction, there is a continuous redistribution of radionuclides among ecosystem components, which can significantly affect the corresponding dose loads. It is now becoming clear that it is incorrect to rely solely on average background radiation values to assess dose loads on organisms. This is particularly true for aquatic and soil organisms. Actual dose loads may be significant enough for radiation to act either as a factor of organismal variability, a selection factor, or both simultaneously. In particular, the phenomenon known in radioecology of radionuclide concentration in critical ecosystem components can lead to the formation of extremely high local dose loads (for example, this is observed in some aquatic organisms), which, even if they do not exert a “microevolutionary” effect, will be sufficient to cause ontogenetic modifications (for the hormetic effect, see section 17).

16. Development of systems for the biodecontamination of ecosystems from radionuclide contamination. The problem of self-purification of ecosystems from radionuclide contamination, discussed in section 11, clearly has its continuation in the development of means and methods for the “forced” purification of natural and artificial (agro-) ecosystems. We are convinced that special attention in this area should be paid to the development of biological purification methods, which, in fact, are a continuation (enhancement) of the biotic component of natural (ecological) self-purification mechanisms.

Recently, there has been a significant increase in interest in technologies for purifying contaminated aquatic environments using the rhizofiltration method with plants. The use of aquatic vegetation itself, given the limited biomass and the complexity of cultivation, does not appear very promising for the purification of contaminated aquatic environments. The use of terrestrial plants, however, makes it possible to easily control their growth and development processes, yielding sufficiently large amounts of biomass. The results of our research on the biosorption properties of various plant tissues have allowed us to propose a fundamentally new method for the biological purification of natural and anthropogenic water bodies from radionuclides [6]. First and foremost, it is proposed to use intact terrestrial higher plants or their isolated parts (primarily leaves and stems) as biosorption material. The plant material serves as an element of a biofilter, which is a system consisting of two units: a rhizofiltration unit that utilizes the sorption properties of the plant root system, and a filtration unit in which the sorption capacity of the plant stem parts is utilized in the initial stage, and subsequently the sorption potential of secondary rhizogenesis. These units can be used independently of one another, sequentially, or in parallel. It is evident that the proposed approaches require adaptation to specific landscape conditions and characteristics of radionuclide contamination.

17. Radioecological hormesis (radioecostimulation). Radiation stimulation (radiation hormesis, radiogormesis) is a universal type of response exhibited by biological organisms to exposure to ionizing radiation within a certain dose range. Without delving into the details of this phenomenon—that is, without examining its transitive, “value-based,” and other properties—we would like to draw attention to its universality, by which we mean its manifestation at all levels of biological integration, including the hierarchical structures of numerous ecological systems, or, more precisely, their biotic components. The possibility of radiation stimulation at the ecosystem level was demonstrated more than 60 years ago. Typically, the mechanism of this phenomenon is associated with a shift in the populations of dominant species within communities, which evidently possess varying levels of radiation resistance. Unfortunately, under the real-world conditions of the Chernobyl nuclear power plant accident, it is very difficult to distinguish between the effects of direct and indirect hormetic effects of ionizing radiation. Thus, the increase in the population sizes of certain animal and plant species (e.g., wild boars) in the Exclusion Zone can most likely be explained by a reduction in “anthropogenic pressure” resulting from the Chernobyl accident. Nevertheless, radiation doses to the biota in the Zone may alter established relationships within communities and lead to noticeable hormetic effects.

18. Remoteness in the spread of radioactivity at the transnational level. Although the bulk of the Chernobyl emissions fell on Ukraine, Belarus, and Russia, air masses and rain carried radioactive isotopes to the Black Sea coast of the Caucasus. For Georgia, the consequences of the Chernobyl accident manifested themselves in the form of localized radioactive contamination of certain western regions. [7]. One of the significant radioecological provisions that emerged after the Chernobyl disaster is the discreteness of the forms and scales of the spread of distant radionuclide contamination. In contrast to the repeatedly analyzed scenario of nuclear explosions, the experience of realizing the consequences of the Chernobyl accident revealed a number of important radioecological features. In particular: while during a nuclear explosion the height of the radioactive cloud reaches a level of 20 km, then in the case of an accident at a nuclear power plant this value does not exceed the level of 0.5-2 kilometers. Thus, if fate has it that during a nuclear explosion a smooth trace is formed in the general direction, then in the case of an accident at a nuclear power plant a tortuous "layer cake" is formed. Moreover, the duration of the process itself and the release of radionuclides creates a situation of discontinuity in the directions and forms of propagation, depending on the variability of numerous meteorological factors. For example, if in the initial period of the radionuclide release, their propagation vector was northern, then after a relatively short time this shifted to westerly. An even more complex nature of the remote propagation of radioactive contamination was recorded in the case of Georgia. A cloud containing radioactive elements bypassed the Black Sea and Turkey, and, after making a significant detour in the form of prolonged torrential rains, contaminated the entire territory of western Georgia. Moreover, the duration of precipitation in a specific area created a clearly demarcated zone of increased radioactivity. Thus, the experience of the Chernobyl accident demonstrated that when calculating radioecological risks for the possible contamination of remote areas, distance becomes a highly arbitrary criterion [8].

19. **Chernobyl radiation contamination in mountainous regions.** Given the Chernobyl footprint's widespread distribution and the diversity of landscapes, an uneven distribution of radioactive contamination often occurs. Two broad ecosystems can be roughly distinguished: mountain and lowland landscapes. While in lowland areas the leading factors are the horizontal spread of radionuclide contamination due to atmospheric transport and sorption, in mountainous regions these processes are supplemented by vertical landscape migration. Furthermore, the vertical zoning of mountainous regions determines not only landscape features but also temperature regimes, precipitation intensity and pattern, insolation, and gradual changes in phytocenosis. Naturally, given such a diversity of factors, studying the distribution of radioactive contamination requires an individual approach to adequate environmental monitoring of high-mountain regions. For example, heavy precipitation in Western Georgia (Adjara, Abkhazia, and Guria) resulted in intense surface runoff of radiocesium from slopes into lowlands and river floodplains. This resulted in an uneven distribution and formation of surface patchiness with a high level of radioactivity, many times higher than the average values for flat landscapes in the same zone.

20. The “Fate” of the Chernobyl exclusion zone. From all that has been said above, it follows that the Zone has enduring value, which determines its future fate. The appearance of “Red Book” species (e.g., the Black Stork) in the Zone indicates the need for even greater isolation from anthropogenic influence, with the exception of areas (territories) that are fully accessible (due to low levels of radionuclide contamination) for recreational visits.

We also consider it necessary to conduct a thorough radiation mapping of the Zone in order to clarify its boundaries and identify those areas that do not represent additional value from the standpoint of ecology and radioecology, and which it would be advisable to return to agricultural use and, possibly, for the re-evacuation of indigenous residents.

Of course, in the Exclusion zone, it is possible-and, we would say, extremely necessary-to conduct a whole range of not only radioecological but also ecological, botanical, zoological, and other diverse biological (including molecular biological) studies. We consider it particularly important to note the unique opportunity that the Zone “offers,” namely, the conduct of large-scale ecological experiments aimed at identifying means and methods for managing levels of ecological and radioecological parameters.

It should be emphasized that all the issues discussed received fairly high scores from the experts (in fact, the highest), which speaks to their importance and the need for close study. This means, in our view, that in addition to ongoing monitoring of the radioecological situation, most of the tasks and problems still require solutions. We are talking only about the beginning of the formation of modern radioecology. This is important because the experience of radioecology before Chernobyl, and especially after, forms the scientific basis for the development and establishment of modern general ecology in its theoretical and applied aspects. In fact, an entire research program has been formulated, the implementation of which will significantly advance the field of stress biology and ecological sciences.

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