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Radiation Risk Estimates in Normal and Emergency Situations

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RADIOECOLOGY: HISTORY AND STATE-OF-THE-ART AT THE BEGINNING OF THE 21st CENTURY

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Abstract. The history of radioecology is described from the end of the XIX - the beginning of the XX centuries till the present days with the indication of the major evolutionary stages of this area of knowledge. The ecological aspects of the use of nuclear power engineering for military purposes (global contamination of the environment after nuclear tests) in the 1960s-1980s are elucidated. The paper also touches upon the ecological problems of nuclear power engineering development. Some issues of the radiation protection of the environment are analysed (anthropocentric and ecocentric principles). The paper summarises the main tasks of radioecology at the present stage. The role is stressed of studying the importance of the elevating radiation background of the environment considering the ever-growing anthropogenic pressure to biota.

Keywords: radioecology, history, biosphere, radiation protection, radionuclides, migration, radiation effects, nuclear power

1. Introduction

Radioecology as a science originated at the very end of the XIX – the beginning of the XX centuries, immediately after the discovery of X-rays by W.K. Roentgen, radioactivity phenomena by A. Becquerel and discovery and identification of the first natural radioactive elements by M. Curie. The earliest experimental studies in the field of radioecology dealt with the dispersion and migration of natural radionuclides via the trophic chains in the environment and elucidation of the natural radiation background role in the evolution of biota on our planet. The term "radioecology" was introduced into the scientific vocabulary more than half a century later, in 1956, simultaneously in the USA (E. Odum) and USSR (A.M. Kuzin, A.A. Peredelsky).

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The first investigations into the ionizing radiation effects on biota date back to the experiments of I.R. Tarkhanov with aquatic plants and animals in 1896 (Tarkhanov, 1896), and in 1923 N.V. Gajewskaja published a paper on X-ray effects on *Artemia salina* (Gajewskaja, 1923).

In 1932, a book was published on the effects of the elevated natural radiation background on plant communities inhabiting the regions of uranium ores occurrence, near Iochimstahl (present Czech Republic) "Biologie des Radiums und Uraniums". This book written by M. Curie's pupils, J. Stoklasa and J. Penkava (1932) can actually be considered one of the first monographs on radioecology dealing with the ionizing radiation effects at the ecosystem level.

A notable role in the development of radioecology as an independent science belongs to an outstanding Russian natural scientist, V.I. Vernadsky (1863-1945). The keywords in his extensive creative work were biosphere (noosphere, according to Vernadsky, is the combination of biosphere and man's intellect) and radioactivity. Actually, these two notions reflect the essence of modern radioecology (Shaw, 2005).

Among the founders of radioecology necessary is to mention N.V. Timofeev-Resovsky (1900-1981), who preferred to use the term "radiation biogeocenology" for this scientific direction. The first works of N.V. Timofeev-Resovsky go back to the late 1940s, these were implemented in the vicinity of an atomic industry facility in the USSR (Laboratory "B", now the town of Snezhinsk). In 1949, a report was written by N.V. Timofeev-Resovsky, G.I. Born and K.G. Zimmer "Calculation of ionizing radiation doses forming in a living body from the incorporation of radioisotopes. 2. Preliminary dose calculation" (classified at that time), then (in the 1990s) followed a series of declassified reports on the radionuclide migration in the environment and ionizing radiation effects on biota (Emelianov & Gavrilchenko, 2000). In the 1970s, N.V. Timofeev-Resovsky actually formulated the tasks of modern radioecology.

2. Radioecology Development in the Context of Problems of Military Application of Nuclear Power

Radioecology in the existing infrastructure of this science began to outline in the 1950s (Van der Stricht & Kirchmann, 2001). Historically predetermined was that the development of this science was dictated by the solution of tasks connected with the military application of nuclear power (Woodwell, 1965; Whicker & Schultz, 1982; Cigna, 1996).

From the late 1950s-early 1960s, radioecology saw a new stage in its development related, primarily, to the impact of nuclear weapons tests (mainly in the atmosphere), which had resulted in a global radioactive contamination of the biosphere. The man-made radionuclides dispersed in

the environment (fission products, nuclides with induced activity, fissile radionuclides) were incorporated into the trophic chains of migration in the deposition-soil (water)-plant-animal-man system (Izrael, 1996). The experimental studies covered all the natural environments: atmosphere, agrosphere, terrestrial ecosystems, hydrobiocenoses. Numerous articles on dispersion of radionuclides from global fallout were published in a vast number of journals including the leading ones (Science, Nature, etc.). One of the objectives of the analysis of radionuclide accumulation in plants and animals were estimations of exposure doses to the world population from global radioactive fallout and associated health effects. The most detailed reviews on the global fallout levels were published in regular reports of the United Nations Committee on the Effects of Atomic Radiation established in 1955 and including currently 21 countries. In the family of UN organizations, UNSCEAR was one of the key institutions dealing with the acquisition and analysis of data on radioactivity levels in the natural environment from different sources of radionuclide release into the environment, and various radioecological situations (global fallout, operation of full nuclear fuel cycle facilities, radiation accidents with the release into the environment of radioactive substances, etc.) (UNSCEAR, 1996).

In 1960-1980, of fundamental importance for the development of radioecology were the studies at the largest atomic industry facilities of the leading nuclear powers in the world (mainly the USSR and USA). Technical irregularities at the enterprises with reactor and radiochemical plants for the production of nuclear weapons components caused contamination with radioactive substances of the nearby territories. On the resulting test grounds, long-time comprehensive radioecological investigations were performed to study the radionuclide migration in various natural environments and ionizing radiation effects on natural communities of plants and animals.

A retrospective comparison of programs for radioecological studies near the nuclear facilities in the USA and USSR in 1950-1985 (Hanford, Oak Ridge, Savannah River Plant laboratories in the USA and SPA “Mayak”, Chelyabinsk-40, now Ozersk in the USSR) indicate virtually complete symmetric development of these programs. These radioecological studies were focused on the solution of the two main problems – study of the radionuclide migration in various natural and agricultural biogeocenoses and ionizing radiation effects on plant/animal populations and ecosystems as a whole.

Yet other regions of active radioecological studies associated with the military use of atomic energy, in addition to the areas near the nuclear facilities, have become the test sites for the development and testing of nuclear weapons (Semipalatinsk and Novaya Zemlya test sites in the USSR,

Nevada test site in the USA, Marshall Islands in the Pacific Ocean, Maralinga area in Australia, etc.). The studies at these military test grounds significantly supplemented radioecological information obtained in regions with the elevated radiation background (examples of such studies may be regions in the Komi Republic, Russia) (Titaeva & Tskev, 1983).

In the USA and West Europe countries, the major contributors to the radioecological studies in the vicinities of nuclear facilities and nuclear research centers were Sparrow A.H., Auerbach S.I., Woodwell G.M., Trabalka J.P., Platt R.B., Eyman L.D. (USA) and Bovard P., Foulquier L. (France).

For a more accurate quantitative estimation of ionizing radiation effects on natural ecosystems, the experimental works in the contaminated regions were supplemented with trials on the irradiation of large natural zones from powerful and point sources and the reactor without a biological shield (experiments in forests and meadows in the USA - University of Emory, Brookhaven National Laboratory, in the Wisconsin state; Puerto-Rico, in France – Cadarache, in the USSR – at the SPA "Mayak").

A big impetus for the development of radioecology was overcoming of the consequences of the radiation accidents accompanied by the radioactivity release into the environment. Among the first were the accident in the South Urals in September, 1957, at a radiochemical military plant "Mayak" in the USSR and not so heavy but also connected with malfunctions at a nuclear reactor for weapon grade plutonium production also in 1957, Windscale accident (Sellafield, UK). The 1957 accident in the USSR gave rise to the formation of the East Urals radioactive trail (EURT), whose area within the ^{90}Sr (the main dose forming radionuclide) isoline (2 Ci/km^2 or 74 kBq/m^2) was 23000 km^2.

The EURT has become a test site for extensive long-time studies into radionuclide migration in various natural environments and accumulation of activity by a wide range of plants and animals. A particular place at this test site is occupied by the studies on agricultural radioecology, headed by an outstanding radioecologist V.M. Klechkovsky (1900-1972). Together with R.S. Russell (1966), the author and editor of the monograph "Radioactivity and Human Diet" he may be considered the founder of agricultural radioecology. Within the EURT the various countermeasures have been tested on the return to the economic use of contaminated agricultural lands. This area itself has become the first region in the world where extensive rehabilitation works were performed on the return of these lands to the economic use (Alexakhin *et al.*, 2001).

High densities of radioactive contamination in the EURT head have caused radiation damage and death of pine and birch-pine woods, which was one of the first observations of the radiation effects at the ecosystem level in the situation of radioactive contamination of nature. The research

and experimental station founded on the basis of the SPA "Mayak" was fated to play the role of the *alma mater* of radioecology in the USSR. The greatest contributors to the radioecological studies in the region of the South Urals accident in 1957-1980 were V.M. Klechkovsky, N.P. Arkhipov, A.I. Ilienko, D.A. Krivolutsky, G.N. Romanov, A.N. Sirotkin, F.A. Tikhomirov, Ye.A. Fedorov, V.A. Shevchenko*, B.S. Prister, R.M. Alexakhin, N.A. Korneyev. In 1990-2005 in the far parts of EURT actively worked I.V. Molchanova, M.Ya. Chebotina, A.V. Trapeznikov.

3. Radioecology Development and Problems of Nuclear Power Engineering

From the late 1950s the range of radioecological problems has expanded to include these of the environmental safety of nuclear power engineering. Since that moment growing in importance has become an idea that, on the one hand, the ever-increasing energy demands of the humankind were impossible without nuclear power engineering and, on the other hand, its development was fundamentally dependent on the environmental safety of this industry.

The range of radioecological problems connected with the nuclear power engineering included issues concerning releases of radioactive substances into the environment and their migration via the trophic chains, radionuclide accumulation by living organisms and transfer to humans. A special topicality has assumed a study into the management of radioactive wastes (their burial in various natural environments). In recent years these were added by the issues of transportation and reprocessing of spent nuclear fuel (Luycks and Frissel, 1996). Radioecology has become a scientific basis for the radiation monitoring of the environment, *de facto* being carried out around each even of low significance facility containing radionuclides or another source of ionizing radiation. Of paramount importance are now aspects of low-level ionizing radiation effects – a sacramental problem of radiobiology and radioecology since the moment of their origination. A program was completed with the participation of 15 organizations from 9 European countries on the estimation of ionizing radiation effects from different radionuclides on plants and animals, FASSET (framework for assessment of the environmental impact of ionizing radiation in European ecosystems) (Williams, 2004).

As is the case with the military aspects of nuclear power engineering, a noticeable milestone in the history of this science was the accident in the USSR at the Chernobyl NPP in 1986, which had provided further powerful

* See obituary in this issue.

impetus to the progress of the science on radioactivity of the biosphere. The Chernobyl accident was classified as the most severe one in the history of nuclear power engineering. Radioactive depositions covered not only the USSR territory but also some other European countries, with the "Chernobyl radionuclides" being registered outside Europe (Alexakhin *et al.*, 2001; Smith & Beresford, 2005). Thus, the total area affected by the accident with a deposition density of the main dose forming radionuclide, ^{137}Cs, of 1 Ci/km^2 (37 kBq/m^2), which is about 6-7 times higher than the background global fallout in the middle latitudes of the Northern Hemisphere, amounted to 150 000 km^2.

The influence of the Chernobyl accident on the development of radioecology has become significant to an extent that it is conventional to divide its history into the "pre- and post-Chernobyl" periods. The overcoming of health and ecological impacts, recognized as the leading ones in this accident, has given rise to the development of comprehensive and diverse projects on medical and radioecological studies and implementation of many national and international research programs. Among these, worth special noting is the IAEA Chernobyl project and a number of investigations initiated by the European Commission.

As a result of radioecological investigations in a large Chernobyl NPP region, diverse data were collected on the behavior of some biologically important radionuclides in terrestrial and aquatic biogeocenoses for a wide spectrum of environmental conditions, long-time dynamics was assessed of the radionuclide cycling in ecosystems. An independent group of reseat were the works on the study of ionizing radiation effects on natural communities of animals and plants in a wide range of dose rates and cumulative doses. As in the South Urals accident in 1957, in the Chernobyl affected area in its near (10-30 km) zone the radiation damage was more severe, whole ecosystems (for instance pine forests) were destructed.

Radioecological Chernobyl investigations brought into existence new radioecological schools in many European countries (Great Britain – B. Howard, N. Beresford; France – G. Deville-Cavellin, Italy – L. Cigna Rossi , A. Antonelli and, more recently, M. Belli, U. Sansone; Germany – G. Voigt, H. Biezold, P. Jacob; G. Prohl, Spain – G. Rauret; Norway – K. Hove, P. Strand, B. Salbu; Sweden – L. Moberg; Ireland – B. Rafferty; Belgium – G. Desmet, Ch. Vandecasteele). Among the USSR-CIS specialists, great contributors to the experimental radioecological studies in the Chernobyl affected region were: Russia – I.N. Ryabov, F.A. Tikhomirov, V.A. Shevchenko, G.N. Romanov, I.I. Kryshev, S.V. Fesenko, A.I. Taskaev, R.M. Alexakhin, N.I. Sanzharova; Ukraine – Yu. A. Kutlakhmedov, B.S. Prister, V.A. Kashparov, I.N. Gudkov, G.G. Polikarpov; Belarus – I.M. Bogdevich, S.K. Firsakova.

4. Radioecology and Environmental Protection from Ionizing Radiation

A growing societal concern over human-driven impacts on the environment (including radiation) has drastically exacerbated the problem of the biosphere protection (sustainable development and biodiversity). In this context the problem of biota protection from ionizing radiation is currently receiving increasing attention.

In 1978, an international professional organization of radioecologists was founded, the International Union of Radioecology, whose objective is coordination of a variety of research works on environmental radioactivity and organization of international conferences. Currently the UIR numbers nearly 600 members representing some 40 countries. In different years the UIR presidents were famous radioecologists (S. Myttenaere, A.A. Cigna, G. Desmet.). Since 2001, the UIR president is P. Strand and General Secretary is F. Brechignac. A special UIR (2003) declaration is being published on the principles of environmental protection against ionizing radiation at the beginning of the XXI century.

Among the most authoritative international institutions whose terms of reference include the analysis of radionuclide migration in the environment is the International Commission on Radiological Protection established in 1928. The main aim of the ICRP is radiation protection of humans, and from this point of view transport of radioactive substances in the environment via the trophic chains leading to man is considered in the aspect of formation of internal exposure dose, a crucial contributor to the overall dose burden to humans in many radioecological situations. At the same time, it is exactly the ICRP that formulated in 1977 a postulate on the principles of environmental protection (ICRP, 1977) according to which “if radiation standards protect man from ionizing radiation, then biota are also adequately protected in the same conditions”, this thesis was subsequently confirmed in the ICRP recommendations on radiation protection that are now in force (ICRP, 1991).

At the same time, in recent years, the ICRP interest in problems of radiation protection of the environment has noticeably increased (separate Committee 5 has been created within the ICRP structure dealing with the problems of environmental protection against ionizing radiations). It has issued Publication 91 (ICRO, 2003), which raises a problem of changing from the mentioned above anthropocentric principle of biota protection to the ecocentric paradigm. According to the latter, the basis of the radiation protection should be that of plants and animals proper. An importance is stressed of the development of general principles of environmental protection from ionizing radiation, pollutants and agent of non-radiation nature, strengthened is the viewpoint of the importance of ecocentric

approaches to the radiation protection of biota (Pentreath, 2002; Brechignac, 2003; Brechignac & Desmet, 2005).

5. State-of-the-art and Problems of Radioecology at the Beginning of the XXI Century

The major challenges of radioecology at the end of the XX – beginning of the XXI centuries are problems focused around the environmental safety and ecological advantages of a full nuclear fuel cycle. It is more and more actively stressed that along with the proper radiation safety of nuclear power engineering, increasing in importance becomes its advantage compared with power engineering on fossil fuel that the former is lacking releases of greenhouse gases. The latter becomes extremely important in the light of the solution of the problem of global warming due to the greenhouse effect.

Modern radioecology is a comprehensive scientific discipline that occupies a highly important place in the system of natural sciences and interacts with different fields of knowledge on the Earth's biosphere. It acts as the most advanced branch of ecology due to the use of highly precise techniques for determination of specific pollutants – radionuclides – in various environments and foundation on the reliable methodological basis for quantification of the acting factor – ionizing radiations (classical triangle: pollutant migration - dose from exposure to living organisms (their populations) - exposure effect). The development of nuclear power engineering, which currently continues to be considered as an alternative-free source to meet the increasing energy demands of the humankind, predetermines the development of the radioecological science, since radiation safety of the environment and human health is a necessary condition of progress in nuclear engineering.

In our opinion, among the priorities of modern radioecology are the following ones:

- Study into the ionizing radiation effects at low doses and dose rates at the levels of individuals, plant and animal populations and whole ecosystems (considering enhancement of the biosphere radiation background due to anthropogenic activity);
- Study into the combined effects of ionizing radiation, pollutants and agents of non-radiation nature (particularly at low concentrations and doses) on plant and animal communities and ecosystems as a whole;
- Development of a system of radiation protection of the environment and humans based on the integration of the anthropocentric (protected is man, protected are biota) and

ecocentric (biota protection from ionizing radiation is the focus of attention) principles;

- Introduction of the methodology of radioecology as the most advanced branch of ecology when studying the influence of different anthropogenic factors on the environment;
- Study into the applied ecological problems of the development of full nuclear fuel cycle (management of radioactive wastes, reprocessing of spent nuclear fuel, decommissioning of nuclear facilities, etc.);
- Solution of problems connected with the "radiation legacy" (rehabilitation of territories previously affected by radioactive contamination).

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