Radiation accidents: contribution to radioecological science and ecological lessons

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INTRODUCTION

It has been historically established that the development of nuclear power industry and engineering was accompanied by a number of radiation accidents and incidents, some of which resulted in a release of radioactive substances into the environment and formation of zones affected by radionuclides, Emergency Radioactive Zones (ERZ) (Table 1). The reasons of these radiation accidents and incidents associated with radioactive contamination of the environment were different – imperfection of nuclear technologies, human factor, political motivation of the accelerated development of nuclear industry.

Table 1. Characteristics of the major radiation accidents with subsequent radionuclide release into the environment (Alexakhin et al., 2004)

Location	Date	Main radionuclides	Total release, Bq	Area, km^2	Criteria for contaminated area identification
River Techa, PP “Mayak”, USSR	1949-1953	^{89}Sr, ^{90}Sr, ^{95}Zr, ^{103}Ru, ^{106}Ru, ^{137}Cs	$1.1 \cdot 10^{17}$	–	–
PP “Mayak”, (Kyshtym accident), USSR	29 September 1957	^{89}Sr, ^{90}Sr, ^{95}Zr, ^{106}Ru, ^{137}Cs, ^{144}Ce	$7.4 \cdot 10^{16}$	23 000	Density of ^{90}Sr contamination above 74 kBq/m^2
Windscale (Sellafield), United Kingdom	10 October 1957	^{89}Sr, ^{90}Sr, ^{131}I, ^{137}Cs, ^{210}Po	$7.7 \cdot 10^{14}$	518	Excess of ^{131}I concentration in milk 3700 Bq/l
Palomares, Spain	January 1966	Pu	-	2.6	Excess of density of soil Pu contamination 1.2 MBq/m^2
Chernobyl NPP, USSR	26 April 1986	^{90}Sr, ^{131}I, ^{137}Cs, mixture of fresh fission nuclides	$5.3 \cdot 10^{18}$ (without inert gases)	150 000	Density of ^{137}Cs contamination above 37 kBq/m^2
Goiania, Brazil	September 1987	^{137}Cs	$5.1\ 10^{13}$	-	Density of ^{137}Cs contamination above 37 kBq/m^2, dose rate above 0.5-1 μGy/h

ERZ were unique test sites for ecological studies that significantly enriched radioecological science with information of paramount importance.

The major advantage of ERZ radioecological investigations was the chance to study the following issues:

- Radionuclide migration in various ecosystems (terrestrial, aquatic, etc.) and landscapes (transecosystem transfer) and in a wide range of trophic chains in a long-term cycle;

- Radiation and post-radiation effects in biota in its habitat at different levels of organization of biological events (particularly emphasizing the organism, population and ecosystem levels);
- Radiation effects in different biota representatives in their natural environments in a wide range of dose rates and cumulative doses;
- Modifying effects of various natural and anthropogenic factors on biota exposed to ionizing radiations;
- Development of countermeasures to mitigate consequences of radioactive contamination of natural objects in real conditions.

RADIONUCLIDE MIGRATION IN THE ENVIRONMENT

The major results from studying radionuclide migration in ERZ are as follows:
- Determination of transport parameters for a large number of anthropogenic radionuclides (mainly ^{90}Sr and ^{137}Cs) via the main trophic chains in the environment to humans for different types of natural and agricultural ecosystems;
- Study of the role of different natural and anthropogenic factors in the radionuclide transfer via the trophic chains (biogeochemical conditions, meteorological conditions, etc.)

An essential phenomenon of the behavior of anthropogenic radionuclides in ERZ is changes in their species with time after their escape to the environment resulting in alteration of their mobility and biological availability on incorporation into the trophic chains.

The parameters of these changes have been estimated. Thus, the effective half-lives for some ecologically important chains (e.g., soil-milk) were shown to be 1.3-3 years for "fresh" ^{90}Sr and ^{137}Cs, which is significantly lower than their actual half-lives (about 30 years).

IONIZING RADIATION EFFECTS ON THE ENVIRONMENT (BIOTA)

Radioactive contamination of the environment following the two radiation events in the USSR, the Kyshtym (1957) and Chernobyl (1986) accidents, has resulted in the formation of radioactive trails with a vide variation in the fallout density, thereby causing irradiation of different natural and agricultural ecosystems in a wide range of dose rates and cumulative doses, including the exposure levels at which total destruction of some types of biogeocenoses was reported (Fesenko et al., 2007; Alexakhin, Prister, 2008). This permitted the establishment of dose dependences of radiation induced effects at different levels of biological organization, from molecular to (which is especially important) population and ecosystem.

As a result of ERZ studies into ionizing radiation effects on ecosystems, the peculiar features of radiation damage processes and post-radiation recovery were described:
- Radiosensitivity of various natural ecosystems varies widely, least radiosensitive proved to be forest ecosystems (particularly coniferous forests);
- Radioactive damage and post-radiation recovery of ERZ ecosystems is of a phase nature, with time after radioactive fallout, as dose rate is declining after the first period dominated by processes of radiation injury, comes the period of repair processes;
- Radioactive damage and post-radiation recovery of ERZ ecosystems depend on a large number of natural (meteorological conditions, environmental peculiarities, etc.) and anthropogenic (human activity) factors.

It has been noted that in the head parts of ERZ (with the highest contamination densities) the influence of anthropogenic activity (agricultural practice, tourism, hunting, fishery, etc.) can significantly overlap the impacts for evolution of ecosystems connected with the radiation factor (at low doses).

During ERZ studies a concept of radiation damage to ecosystems has been developed according to which the severity of radiation induced damage is dependent on changes in the factors themselves – radiosensitivity and dose burdens. In the conditions when in contaminated ecosystems migrating radionuclides are a source of irradiation, the dose field proves to be very heterogeneous in both time and space, and in the ecosystem the so-called “hot niches” and biogeocenotic segments with increased irradiation are formed. These may be illustrated by crowns of “evergreen” coniferous trees, mesofauna of forest soils and litters, mesofauna of meadow root mat, part of roots and underground buds of plants in the top most affected soil horizons. In these conditions the maximum radiation damage occurs in the events when increased are doses to the most radiosensitive components of ecosystems (e.g., coniferous trees, invertebrates of forest soil and litter). For the ERZ conjugated data have been obtained on ionizing radiation effects on biota, on the one hand, and humans, on the other hand, which is crucial for the development of anthropocentric and ecocentric approaches. It has been found that irradiation of humans and non-human species is nonequidosal, with doses to humans being two orders of magnitude higher than to other biota representatives.

As a result of ERZ studies, a basic paradigm of modern radioecology has been formulated: in radioactive contamination of the environment, the area where direct radiation injury of biota is observed is considerably smaller than the zone where the human economic activity is restricted (including the residence), because radionuclide concentrations in environmental objects (primarily in farm products) exceed the permissible standards.

SYSTEM OF COUNTERMEASURES

In ERZ, in real conditions, the effectiveness of a system of different countermeasures to reduce radionuclide accumulation in products and exposure of the population has been studied, which is essential in the remediation works on radioactively contaminated territories (Tables 2 and 3).

Table 2. Effectiveness of the main countermeasures in plant production based on ERZ studies data, times (Prister et al., 2007)

Countermeasures		^{137}Cs		^{90}Sr	
		Soils			
		mineral	organic	mineral	organic
Liming, 4-6 t/ha		1.5-3.0	1.5-2.0	1.5-2.6	-
NPK application		1.5-2.0	1.5-3.0	0.8-1.2	-
Manure, 50 t/ha		1.5-3.0	-	1.2-1.5	-
Liming + NPK		1.8-2.7	2.5-4.0	-	-
Zeolites		1.5-2.5	-	1.5-1.8	-
Plowing		8.0-12	10-16	2.0-3.0	-
Pasture and meadow improvement	radical	1.5-9.0	4.0-16	1.5-3.5	3.0-5.3
	surface	2.0-3.0	2.0-14	2.0-2.5	3.0-5.0

Table 3. Effectiveness of the main countermeasures in animal production based on ERZ studies data, times (Prister et al., 2007)

Countermeasures	^{137}Cs		^{90}Sr
	milk	meat	milk
Veterinary			
Cs binders application	1.5-6.0	1.5-2.1	
Sorbents application	5.0	4.5	1.5
Zootechnical			
Preslaughter feeding with "clean" feeds	-	2.0-15	
Fodder additives	1.2-1.5	1.5-3.1	1.3-1.5
Rational use of haylands and pastures	1.5-15	3.0-4.0	
Fodder selection	2.0	30	

CONCLUSION

The radiation accidents with the release of radionuclides into the environment and mitigation of their consequences required the solution of serious social problems. However, the formation of ERZ had become a unique site for radioecological investigations, which enriched this scientific discipline with the results of primary importance.

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