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OVERVIEW OF THE COOPERATION BETWEEN THE CHERNOBYL CENTER'S INTERNATIONAL RADIOECOLOGY LABORATORY IN SLAVUTYCH, UKRAINE AND U.S. RESEARCH CENTERS BETWEEN 2000 - 2010

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ABSTRACT

The International Radioecology Laboratory (IRL) located in Slavutych, Ukraine was created in 1999 under the initiative of the United States Government and the Government of Ukraine in the framework of international cooperation on evaluation and minimization of consequences of the Chernobyl nuclear power plant (ChNPP) accident. Since the time the IRL was founded, it has participated in a large number of projects, including the following: 1) study of radionuclide accumulation, distribution, and migration in components of various ecological systems of the Chernobyl Exclusion Zone (ChEZ); 2) radiation dose assessments; 3) study of the effects of radiation influence on biological systems; 4) expert analysis of isotopic and quantitative composition of radioactive contaminants; 5) development of new methods and technologies intended for radioecological research; 6) evaluation of future developments and pathways for potential remediation of the ChEZ areas; 7) assistance in provision of physical protection systems for ionizing irradiation sources at Ukrainian enterprises; 8) reviews of open Russian language publications on issues associated with consequences of the ChNPP accident, radioactive waste management, radioecological monitoring, and ChNPP decommissioning; 9) conduct of training courses on problems of radioecology, radiation safety, radioecological characterization of test sites and environmental media, and on research methods; 10) conduct of on-site scientific conferences and workshops on the ChEZ and radioecology problems; participation in off-site scientific conferences and meetings; and 11) preparation of scientific and popular science publications, and interactions with mass media representatives. This article provides a brief overview of the major achievements resulting from this cooperation between the IRL and U.S. research centers.

Key words: Chernobyl, radioecology, radiobiology, international cooperation.

INTRODUCTION

The 1986 Chernobyl Nuclear Power Plant (ChNPP) accident is known to have resulted in catastrophic consequences for the health, social, and economic spheres of many countries, primarily, Ukraine, Belarus, and Russia. However, apart from the urgent problems that humankind had to face and that had to be resolved as quickly as possible, the ChNPP accident provided one-of-a-kind opportunities for scientists of the entire world. The extent of radioactive contamination, levels and forms of contamination, diversity of the ecosystems involved in the radionuclide cycle did not have any precedents. Following the natural course of their development, populations of species and their communities found themselves in conditions of chronic radiation that exceeded the natural background by factors of hundreds and thousands. Anything similar would have been extremely difficult if not impossible to recreate in a scientific laboratory. The knowledge that humankind was able to obtain from the consequences of this accident had a tremendous importance; therefore, the “natural laboratory of Chernobyl” could not be ignored, but inevitably became a scientific asset for researchers from all over the world. Consequently, since the first few years after the accident, multiple teams of scientists visited the Chernobyl Exclusion Zone (ChEZ), and in 1995, the International ChNPP Center, an intergovernmental organization, was established to combine and coordinate global efforts on overcoming and assessing the consequences of the Chernobyl accident. In Ukraine, the International Chernobyl Center was represented by the Chernobyl Center on Problems of Nuclear Safety, Radioactive Waste, and Radioecology. In 1998, in association with this organization and according to the decision made by Mr. Leonid Kuchma, the President of Ukraine, and Mr. Albert Gore, the U.S. Vice-President, and the agreement signed by the United

States Government and the Government of Ukraine, the International Radioecology Laboratory (IRL) was founded to provide administrative, scientific and engineering support to international research projects in the ChEZ. By the year of 2000, with support from the U.S. Department of Energy and the ChNPP, major activities associated with providing necessary equipment and instrumentation to the IRL were completed.

The IRL acquired broad capabilities such as all necessary facilities for sampling, sample pretreatment and storage, various equipment for field measurements, modern certified systems for alpha, beta, and gamma spectrometry and analytical equipment for radiochemical pretreatment and analysis of samples. The IRL became certified according to ISO 9001:2000, obtained all required licenses and currently successfully undergoes IAEA inter-calibrations (IAEA-CU-2006-03; IAEA-CU-2007-03; IAEA-CU-2009-03). In addition, the IRL procured various types of equipment for biological studies, such as a vivarium, microscopes, incubators, various spectrophotometers, refrigerators, and other applicable laboratory equipment. A special pride of the IRL is a mobile gamma-beta-spectrometric complex installed in a van for in-situ measurements of ^{90}Sr and ^{137}Cs content in bodies of small animals. Apart from the major laboratory facility in the city of Slavutich (50 km east of the ChEZ), the IRL has an additional facility in the city of Chernobyl. In addition, the IRL has capabilities for hosting scientific conferences, meetings, and training courses.

The fact that the creation of the IRL was timely and appropriate was confirmed by a large number of international projects, workshops and training courses conducted during the period of 2000 - 2010. The largest share of these activities was supported by such U.S. organizations as the Department of Energy (DOE), Texas Tech University, Pacific Northwest National Laboratory, Savannah River Ecology Laboratory, Savannah River National Laboratory, Universities of

Georgia, South Carolina and Florida. Some of the activities were funded by the Civilian Research & Development Foundation (CRDF) and the International Atomic Energy Agency (IAEA).

MAJOR ACTIVITIES

In spite of the name given to the IRL and its original mission, activities that the IRL performs and has performed with its Western partners go beyond just radioecological research. The IRL's activities can be divided into the following major categories:

- Study of radionuclide accumulation, distribution and migration in the components of ecological systems;
- Dose rate assessments;
- Study of radiation effects on the biological systems;
- Expert analysis of isotopic and quantitative composition of radioactive contaminants;
- Development of new methods and technologies intended for radioecological studies;
- Evaluation of future developments and pathways for a potential remediation of the ChEZ areas;
- Assistance in provision of physical protection systems for ionizing irradiation sources at Ukrainian enterprises;
- Reviews of open Russian language publications on issues associated with consequences of the ChNPP accident, radioactive waste management, radioecological monitoring, and ChNPP decommissioning;

- Conduct of training courses on problems of radioecology, radiation safety, radioecological characterization of test sites and environmental media, and research methods;
- Conduct of on-site scientific conferences and workshops on the ChEZ and radioecology problems; and
- Participation in off-site scientific conferences and meetings; preparation of scientific and popular science publications, and interactions with mass media representatives.

Since the time the IRL was founded, its specialists became authors and coauthors of over 200 scientific publications. This summary describes major scientific achievements resulting from the joint projects conducted with the U.S. research centers and/or with support of the U.S. government or other organizations.

Study of Contamination of the Ecosystems Located in an Immediate Proximity of the Chernobyl Nuclear Power Plant

Historically, the cooperation of future IRL employees and scientists from U.S. national laboratories and universities started in early 1990's, long before the IRL was founded. This early cooperation was devoted to studies of the radioecological situation in the most contaminated areas of the ChEZ, i.e., in the sites "Red Forest" and "Glubokoe Lake". Since these areas were located close to the destroyed ChNPP reactor and due to the weather conditions in late April of 1986, a large amount of radioactive fallout, primarily, finely dispersed particles of nuclear fuel and the reactor's construction materials, precipitated there. The resulting radiation conditions were so severe (the dose rate reached 0.1–1 Gy h^{-1}) that, in the "Red Forest", all coniferous plants died while other plants were either partially eliminated or their development and reproduction was inhibited, and many animal species either completely or partially ceased to exist. For a long time, high doses prevented scientists from conducting any research that would require a prolonged human presence in those areas. A possibility to conduct research there occurred only in mid-1990's when the radiation background decreased by a factor of 1000. Scientists from Savannah River Site and Texas Tech University, together with Ukrainian specialists, were among the first researchers who started systematic studies at those sites.

One of the major achievements of this cooperation was the first detailed study of spatial distribution of the fallout (in 435 points) in the "Red Forest" area (Bondarkov et al. 2003b). The measurements showed that, in 2001, the radionuclide content ranged as follows (MBq m^{-2}): ^{90}Sr: 1.20 x 10^{0}– 3.58 x 10^{2}; ^{134}Cs: 3.00 x 10^{-3} – 3.0 x 10^{0}; ^{137}Cs: 1.4 x 10^{0} – 7.47 x 10^{2}; ^{154}Eu: 2.00 x 10^{-3} – 5.30 x 10^{0}; ^{155}Eu: 4.00 x 10^{-3} – 2.9 x 10^{0}; ^{241}Am: 7.00 x 10^{-3} – 1.32 x 10^{1}; $^{238, 239, 240}$Pu: 6.00 x 10^{-2} – 4.17 x 10^{1}. These values were significantly higher than those predicted earlier and based on random sampling data and remote surveys. The assessment of the radionuclide distribution in the soil profiles showed that a large fraction of transuranic elements were still located in the top soil layer, while the major ^{137}Cs and, especially, ^{90}Sr inventories penetrated much deeper. Specifically, up to 97% of the total inventory of Pu, 93% of the ^{137}Cs inventory, and 90% of the ^{90}Sr inventory were found in the upper 0 – 10 cm deep soil layer. Based on the studied soil characteristics and radionuclides ratios in various soil layers, the IRL identified causes for the existing vertical distribution of the radionuclides and calculated parameters of the radionuclide migration (Bondarkov et al. 2006). The migration capabilities of the radionuclides were shown to depend on the form of the fallout and their ratio in a specific area, as well as on the agro-chemical characteristics of the soil. Regarding their migration capabilities, the radionuclides were placed in the following sequence for automorphous mineral soils with a normal aqueous mode: $^{90}Sr > ^{137}Cs > ^{241}Am > ^{154}Eu \sim ^{239,240}Pu$. In hydromorphous organogenic soils, the ^{137}Cs mobility was found to be comparable or greater than the ^{90}Sr mobility. At the same time, the velocity of destruction of the fallout particles, in composition of which the radionuclides precipitated, as well as life activity of animals and plants were likely to also significantly modify redistribution of radionuclides. The calculations showed that the period of ecological half-life of these radionuclides in the 0 – 5 cm deep soil layer ranged from 21 – 230 years for ^{90}Sr and from 25 to 650 years for ^{241}Am, depending on the characteristics of the soils and the fallout (Bondarkov et al. 2009).

Additional dose rate measurements and calculations made it possible to reconstruct the travel scenario for the radioactive cloud in those areas in April of 1986. According to the proposed models, the cloud that moved west of the ChNPP during the first day after the accident and north of the ChNPP during the second day had a different nature of origin, different composition and quality of the released particles and these clouds were affected by different meteorological conditions (Chesser et al. 2004; Chesser and Rodgers 2008), thereby affecting the pattern of the fallout distribution and generation of the dose fields along the clouds' trajectories. Some characteristics of the fallout along the northern plume were shown to indicate that throwing various materials from helicopters into the crater of the reactor caused an additional contamination of the adjacent territories.

Savannah River Ecology Laboratory participated in another set of radioecological studies focused on surveys of terrestrial areas of the ChNPP Cooling Pond shoreline. These studies were supported by the Civilian Research and Development Foundation (UKB1-2884-KV-07). The purpose of these studies was to obtain initial data on radioactive contamination of the components of the ChNPP Cooling Pond shoreline ecosystems required to assess the situation during and after the ChNPP Cooling Pond decommissioning (drawdown). Those were the first studies of that kind related to the ChNPP Cooling Pond. The major focus was given to assessments of the ^{90}Sr and ^{137}Cs content because they were key radionuclides found in the soil, herbaceous and arboreal vegetation, small mammals and birds, and, selectively, in amphibians and reptilians (Gaschak et al. 2008c). These studies used a method for live counting of the radionuclide content and were performed at three sites for which detailed descriptions of their terrain conditions, biocenosis conditions and distributions of the radiation fields were generated (Gashchak et al. 2009e). Using experimental and literature data, the IRL performed an overall assessment of consequences of the cooling pond drawdown (Oskolkov et al. 2010), calculated dose rates for a series of reference species currently inhabiting the area and even predicted potential doses if species inhabited the exposed ChNPP Cooling Pond bottom (Oskolkov et al. 2011a); denoting that the predicted doses can exceed the maximum doses recommended for the wild biota (IAEA 1992; UNSCEAR 1996; DOE-STD-1153 2002; ICRP 2009).

Another set of studies was related to issues of radioactive contamination of an urban system for which the ChEZ has unique conditions. The city of Pripyat, with the area of about 4 km^2 and primarily multi-storied residential and industrial buildings, is located in the immediate proximity of the destructed ChNPP reactor. The ChNPP accident caused significant radioactive contamination of the city and its population was evacuated. Currently, the city of Pripyat appears to be a natural laboratory where scientists can study processes of distribution and redistribution of radionuclides in an urban environment, develop and verify models for these processes, as well as test and improve methods for characterization and decontamination of the contaminated urban areas (Gashchak et al. 2009c).

In 2004, with support from the Pacific Northwest National Laboratory (PNNL), the IRL performed studies on penetration of radionuclides into construction materials (two types of bricks and two types of ceramic tiles) under natural conditions (Bondarkov et al. 2005). Using ^{90}Sr and ^{137}Cs as the examples, the studies showed that, in the absence of the initial decontamination, the radionuclides penetrated a few millimeters of the materials, depending on their characteristics, and ^{90}Sr penetrated deeper than ^{137}Cs. Consequently, the total inventory of the radionuclide per unit of area of such surfaces was only slightly lower than the contamination of the adjacent territory (especially in red bricks). Later on, with support from Savannah River National Laboratory, the similar issue was studied for reinforced concrete (Farfán et al. 2011a). Both ^{137}Cs and ^{90}Sr were detected up to 50 mm deep in the reinforced concrete structures, however, the major radionuclide inventory (over 90% of ^{137}Cs and 70% of ^{90}Sr) was found to be in the subsurface 0 – 5 mm deep layer. Also it was found that ^{90}Sr penetrated deeper under more humid conditions. The joint studies also showed that upper floors of the multi-storied buildings could be more contaminated than lower floors (either due to the characteristics of the initial fallout or due to an inadequate decontamination of the upper floors). This conclusion shows that upper floors of the buildings may require special attention if airborne contamination of the urban environment occurs (Farfán et al. 2011b).

In 2003 – 2008, with support from the IAEA and the Center for Risk Analysis (SENES Oak Ridge Inc. – Center for Risk Analysis, TN 37830, USA), the IRL participated in the IAEA EMRAS - Urban Remediation Work Group that applied the results of the ChEZ studies to validation of the models describing a long-term dynamics of the radiation situation in the urban environment affected by accidental or intentional (as a result of a terrorist attack) contamination. The results of these activities were presented in a report to the IAEA (available at: http://wwwns.iaea.org/downloads/rw/projects/emras/final-reports/urban-tecdoc-final.pdf) and two publications (Thiessen et al. 2008, 2009).

Radioecology of Animals in the Chernobyl Exclusion Zone

Study of radioactive contamination of animals inhabiting the ChEZ was one of the priority areas of cooperation of the IRL and U.S. scientists. This knowledge did not only reveal processes showing how animals participated in the turnover of the radionuclides that entered the ecosystem of the region, but also provided key information for an adequate assessment of biological effects in species exposed to chronic high intensity radiation.

The largest number of publications was devoted to radioecology of small mammals, such as murine rodents and shrews. The studies that had started before the IRL was established successfully continued in the subsequent years and resulted in detailed data on the ^{90}Sr and ^{137}Cs accumulation in the bodies of these animals, depending on trophic specialization of the species, radioecological characteristics of their habitat and season (Chesser et al. 2000; Oleksyk et al. 2002a; Baryakhtar et al. 2003). The combined information made it possible to describe long-term trends in radioactive contamination of the animals (Maklyuk et al. 2007c). In particular, the IRL showed that the average contamination value for different species in the given area was affected by significant seasonal changes that depended on changes in their food supply and territorial behavior. To a lesser extent, it was affected by changes in the gender and age structure of the local population, or, more precisely, by changes in composition of individuals differing by physiology and parameters of radionuclide exchange in tissues. Therefore, long-term trends expressing a gradual decrease of the average contamination became nearly visible, mainly reflecting the dynamics of the ^{90}Sr and ^{137}Cs decays.

Based on the data on radioactive contamination of the animals and radiation conditions of their habitat, values and structures of the dose burdens that the animals received were assessed (Chesser et al. 2000; Bondarkov et al. 2003a; Maklyuk et al. 2007b). It was determined that, 20 years after the accident, the largest contribution (up to 55%) to the total absorbed dose was provided by ^{90}Sr and ^{137}Cs incorporated into the body tissues while the external beta- and gamma-radiation, on the average, contributed up to 21 and 23% of the total dose, respectively. In spite of a significant improvement of the radiation situation, some animal species on certain areas could still receive up to 1 – 50 mGy d^{-1}, which exceed the level of 1 mGy d^{-1} recommended by international organizations as the upper allowable level for wild animals (IAEA 1992, UNSCEAR 1996).

In a set of experiments the parameters that characterized rates of accumulation and excretion of ^{90}Sr and ^{137}Cs in bodies of bank voles and house mice were estimated (Bondarkov et al. 2002d; Maklyuk et al. 2007c). In particular, 99.3% of the initial ^{137}Cs content was excreted with the half-life period of 2.18 days in bank voles (*Myodes glareolus*) and 4.4 days (99%) in house mice (*Mus musculus*). The ^{90}Sr excretion took a longer period of half-time: 11.7 days (56%) for bank voles and 49.9 days (87%) for house mice, with ^{137}Cs being excreted mostly with urine (74.7%) and ^{90}Sr being excreted equally with urine and feces. These circumstances directly explained why the contamination of individual species was so unstable and why it changed so rapidly with changes in the radionuclide intake with food. In this connection, the results of a field experiment were demonstrable when the fact was found that wild bank voles received up to 8 – 66% of their total ^{90}Sr and ^{137}Cs intake from soil particles, but not with food (Chesser et al. 2001).

The IRL experiments also made it possible to assess parameters of radionuclide transfer from nursing females to their off-spring (Bondarkov et al. 2002c), perform a detailed evaluation of ^{90}Sr and ^{137}Cs distribution in various tissues of murine rodents (Maklyuk et al. 2006) and complete many other studies. For the most part, these were unique studies that provided a large amount of new data on radiation ecology of animals inhabiting the ChEZ. It should be noted that a significant part of the research was conducted using a specially developed gamma-beta-spectrometric system for live counts of the total ^{90}Sr and ^{137}Cs content in bodies of animals, including measurements in-situ at ChEZ sites (the description of this system is provided in a separate article of this Supplement – Bondarkov et al. 2011).

Small mammals were the most, but not the only, radioecologically studied group of animals. In the late 1990's, the IRL jointly with the Savannah River Ecology Laboratory started activities that, among other things, included evaluation of radioactive contamination of amphibians. For the first time for the ChEZ, these studies analyzed inter-species differences in contamination of frogs and toads, as well as radionuclide accumulation parameters as a function of an ecological form of the animals and radioecological characteristics of their habitat (Jagoe et al. 2002; Bondarkov et al. 2002b; Gashchak et al. 2009d).

More detailed radioecological studies of birds were also conducted. Birds are one of the largest groups of vertebrates inhabiting the ChEZ regarding the total biomass. Moreover, most of them migrate seasonally, acting as a regular mechanism for biogenic transfer of radionuclides outside the region. However, until the year of 2003, only preliminary estimates were available on a potential role of birds in radionuclide transfer and practically no data existed on any other aspect. The IRL started the bird studies with the University of South Carolina and this work was funded by the Civilian Research and Development Foundation (UB1-2507-KV-03). The analysis was based on live counts of ^{90}Sr and ^{137}Cs content in birds with body size no more 70–100 g using a mobile laboratory. The obtained data showed inter-species and sex/age differences, seasonal dynamics of the bird contamination and impact of radioecological characteristics of the bird habitat on their radionuclide intake (Gaschak et al. 2005; Gashchak et al. 2008a). Using this newly obtained data and data on the bird distribution in various biocenoses of the ChEZ and landscape structure of the region, the values characterizing the total ^{90}Sr and ^{137}Cs inventory in the biomass of local birds and a scope of a potential radionuclides transfer by birds outside the ChEZ were calculated (Gashchak et al. 2009a, b). According to the estimations, as of in 2004, local birds were able to annually transfer about 45 MBq of ^{90}Sr and 11 MBq of ^{137}Cs, and all migrants crossing the ChEZ border were able to transfer 3,800 and 2,470 MBq, respectively. These values were tens and hundreds times less than the total cumulative activity transferred outside the ChEZ with groundwater and surface water (Kholosha et al. 2002).

Ecotoxicological Studies

Negative consequences for animals and plants species associated with radioactive contamination of the environment were undoubtedly one of the top priority areas of joint studies between the IRL and U.S. scientific laboratories. By the year of 2000, the IRL accumulated data confirming that, in spite of very high doses of complex radiation exposure (on the average, about 30 - 40 mGy d^{-1}), small mammals that had been inhabiting the most contaminated areas of the ChEZ for tens of generations did not show any signs of depression and, in comparison with related populations from the control areas, had a higher, but not lower genetic diversity (Matson et al. 2000; Baker et al. 2001). At the same time, the radiation exposure that exceeded the recommended maximum allowable level of 1 mGy d^{-1} (IAEA 1992) for the wild fauna by factors of ten caused an increase in heteroplasmy of mitophondrial DNA, but this increase was insignificant relative to a spontaneous natural radiation level (Wickliffe et al. 2002). It would be logical to assume that either wild animal species (specifically, *Myodes glareolus*) acquired certain mechanisms of an adaptive response, successfully compensating a toxic impact of radiation, or they had an evolutionally preconditioned increased radioresistivity. However, using in similar experiments a laboratory mice strain with an increased radiosensitivity provided the same result (Wickliffe et al. 2003b). In addition, the laboratory mice as a well-studied test system of genotoxicological impact of radiation did not show a high frequency of point mutations being exposed to 3 Gy during 90 days under the conditions of the "Red Forest", the most contaminated area of the ChEZ (unlike an acute irradiation of the same dose) and did not differ from the control group (Wickliffe et al. 2003a).

A parallel assessment of cytogenic effects of *Myodes glareolus* species inhabiting the "Red Forest" showed that the frequency of micronuclei in their blood cells did not differ from that in a control group (Rodgers, Baker 2000). However, this fact did not result from any special mechanisms of reparation that this sub-population could have developed during tens of generations because an introduction of bank voles into the "Red Forest" did not cause any cytogenetic effects that would have exceeded the effects caused by natural spontaneous radiation levels (Rodgers et al. 2001b). Only an insignificant reaction of the adaptive response was detected, indicating an impact of the radiation stress, and that the body systems were being overcome by it. Similarly, exposure of a radiosensitive strain of laboratory mice under the conditions of the "Red Forest" during 30 – 40 days showed that the existing doses (up to 40 mGy d^{-1}) did not cause any unequivocal impact on the chromosomes and only resulted in an insignificant increase of frequency of the micronuclei (Rodgers et al. 2001a). In addition, no dependence between variations in the heterochromatin position and radiation levels was detected (Wiggins et al. 2002).

One more area of the studies devoted to the consequences of radiation influence was the assessment of an epigenetic indicator of development instability, i.e., a value of the fluctuating asymmetry (FA) for bilateral organisms. Since the FA is often used in ecotoxicological studies, it was decided to determine to what extent the development of small mammals deviated from the symmetrical one under the conditions of the ChEZ. Study of *Myodes glareolus* and *Sylvaemus flavicollis* species as examples showed that, although deviation from a stable bilateral development took place in the entire territory of Ukraine, the FA values were significantly higher in those areas of the ChEZ where the radiation doses exceeded 3 – 7 mGy d^{-1} (Oleksyk et al. 2002b, 2004). However, on other areas of ChEZ the FA values did not differ from the natural level. Since these two species were shown to have differences in their responses to the radioactive contamination of the environment, the contamination was unlikely the dominant factor causing an increase of the FA values.

Frequency of DNA strand breakage in amphibians (*Rana terrestris)* inhabiting areas with various radioactive contaminations also appeared to be inconsistent (Jagoe et al. 2002). If short DNA strand breakage fragments prevailed in animals on the most contaminated areas, long fragments were found to prevail in relatively “clean” areas.

Since, on the one hand, the above mentioned studies did not meet wide spread expectations and did not demonstrate an unambiguous dependence of the frequency and type of genetic effects on the radiation conditions, it was decided to verify a hypothesis that the identified effects resulted from some other non-radiation ecological factors and/or the legacy of an earlier natural historical development of these populations; specifically, whether a higher level of the genetic diversity found in bank voles (*Myodes glareolus)* in the “Red Forest”, resulted from their long-term immigration from the adjacent territories to the area where the original population had died due to a severe radiation exposure. In addition, the patterns of changes of their genetic diversity in a larger area were evaluated. It was indeed determined that indicators of the genetic diversity (frequency and uniqueness of haplotypes and frequency of nucleotides) were not a function of the radioactive contamination of the area, but they depended on a distance between subpopulations, geographic barriers and time of sampling of the genetic material during cycles of the population “life waves” (Meeks et al. 2007). The indicators of the genetic diversity reflected some intra-population processes and natural history of each population. Moreover, the genetic diversity of the *Myodes glareolus* species in Ukraine also appeared to vary significantly, and, consequently, genetic features of the vole’s sub-population in the ChEZ do not differ from those attributed to this species overall (Meeks et al. 2009).

A similar conclusion that there was no unequivocal dependence on radiation exposure was made in the study of frequency of loci of microsatellite DNA in two types of cattail: *Typha angustifolia* and *Typha latifolia* (Tsyusko et al. 2006). The data collected in Ukraine, including the ChEZ, exhibited that variability of the genetic diversity of these plants was mostly due to the geographic latitude, characteristics of the region and their aqueous habitat, as well as the origin of the local population. However, the presence of a positive correlation between some genetic parameters (an effective quantity of alleles) and ^{90}Sr and ^{137}Cs specific activities in the plants tissues might imply an impact of the radiation related factors.

Therefore, the joint studies of the U.S. research laboratories and the IRL reinstated a conclusion that the international communities had to revise their approaches to risk assessment of low dose exposures. The linear dose effect model developed in the experiments with an acute irradiation and at usually high doses (> 0.1 Gy) does not appear to reflect processes that occur in those biological systems that exist in conditions of a chronic complex radiation exposure, which is especially true for the wild biota and doses that do not exceed the natural background by factors of 100 – 1000. However, the mechanisms that make it possible for the biological systems to successfully exist in the conditions of such radiation exposure require further studies to provide a baseline for the development of new approaches to the risk assessment for both wild biota and humans.

One more result of the joint studies of the genetic diversity was revealing consequences of those processes that had taken place on the area of ChEZ long before the ChNPP accident occurred. While studying the species diversity of the *Apodemus* (or *Sylvaemus*) genus, two genetic forms of the *Sylvauemus sylvaticus* species earlier described in Europe were found in Ukraine (Hoofer et al. 2007; Gashchak et al. 2008b). These forms originated thousand years ago in the glacial period due to a separation of the initially single species, and in Europe they can only be found allopatrically. However, in the northern Ukraine, not far from the ChEZ, a contact (sympatry) zone of these two forms was found, without any signs of cross-breeding. This interesting phylogenetic fact indicates that the genetic processes and characteristics observed in the ChEZ might have much older roots than the ChNPP accident.

Future Management of the Lands Affected by the ChNPP Accident

The cooperation between the IRL and U.S. research centers was not only associated with various research projects. In some cases, the projects provided practical applications of the accumulated knowledge and skills. In particular, the IRL conducted a number of international scientific workshops and training courses, provided assistance to the Ukrainian enterprises, and developed manuals to handle problems raised by the ChNPP accident.

Specifically, with support from the Pacific Northwest National Laboratory, the IRL developed a draft manual on remediation of lands contaminated after the Chernobyl accident. The manual described multiyear research efforts conducted by the Ukrainian scientists.

Large areas of Ukraine, Belarus, and Russia are significantly contaminated (with the population being evacuated) and they currently remain abandoned. Nevertheless, in the near future, some of these areas may potentially become available for the population and recovery of economic activities. However, to make reasonable decisions and assure safe conditions, it is necessary to have appropriate guidelines on remediation that will make it possible to identify those conditions under which the return of the population to the previously abandoned lands and its certain economic activity in those lands will be acceptable. To develop such guidelines is a challenging task because during 25 years following the ChNPP accident the abandoned lands have undergone significant changes. The draft remediation manual developed by the IRL included two parts: 1) methodological fundamentals of remediation of the abandoned lands; and 2) procedural aspects of remediation of the abandoned lands that included algorithms and examples of calculations.

The first part of the manual was based on the methodological recommendations entitled: Principles of Remediation of the Exclusion and Mandatory Evacuation Zones Contaminated after the ChNPP Accident (2000) and included the following sections: general provisions (legal issues, characteristics of the areas that potentially could be remediated, principles and criteria for conducting remediation activities), major concepts underlying the phenomenon of remediation according to the dose criteria, data required to substantiate the decision making process, criteria for the decision making on the land remediation, assessment of selected areas of the abandoned lands regarding their complete or partial (limited) remediation (environmental characteristics of the abandoned lands, identification of those areas where remediation activities might be feasible (identification of areas for complete and partial remediation), identification of the buffer zone and substantiation for its selection), identification of areas of the remediation activities and remediation scenarios for various activities (agricultural activities, forestry activities, etc.), comparison of effectiveness and feasibility of the selected scenarios for the remediation activities (reduction of risk of food production with contamination higher than the allowed, reduction of individual doses, collective exposure doses, diverted dose costs assessment, and the definition of the optimal scenario of remediation activity).

The second part of the manual included algorithms and examples of calculations, specifically, assessment of the current radiological situation in abandoned lands (radionuclide composition, contamination density, physico-chemical forms of the fallout and dynamics of its transformation, assessment of potential contamination of food products (with and without countermeasures), assessment of potential doses for the population in case of the re-evacuation, categorization of the territories regarding the radiological situation, separation of those territories where partial remediation is possible, zoning), assessment, categorization and zoning of areas regarding their potential for the remediation.

Development of New Methods and Technologies for Radioecological Research

One of the scientific achievements of the IRL was associated with development of new methods and technologies on radioecological research. One of these methods was a method of live counts of ^{90}Sr and ^{137}Cs content in bodies of small animals. By mid-1990's, most radioactive isotopes released from the destroyed reactor were known to have decayed. Out of the remaining isotopes, only ^{90}Sr and ^{137}Cs had radioecological significance because they could easily enter biological chains and create an internal irradiation while also being the major contributors to the external irradiation in the contaminated areas. The ^{137}Cs content measurements were never technically difficult, while, for measuring the ^{90}Sr content, scientists had to either use radiochemical methods or radiometry of the pretreated samples, thereby making the process time-consuming and expensive and precluding a large number of studies associated with live animals.

The IRL, in cooperation with the Institute of Nuclear Research and with support from the U.S. DOE, developed a technology for measuring ^{90}Sr content in thick-layered objects in the presence of comparable ^{137}Cs quantities (Bondarkov et al. 2002a, e). For this purpose, the IRL developed a special beta-spectrometer and an associated software application. The method and equipment made it possible to measure the total ^{90}Sr content quickly and without having to resort to radiochemistry in such objects as mice and other small animals, as well as in minimally pretreated soil and vegetation samples. This technology was further enhanced by combining the beta-spectrometer with the gamma-spectrometer and their installation in a mobile laboratory for simultaneous ^{90}Sr and ^{137}Cs measurements in bodies of animals directly at the ChEZ experimental sites. This technique drastically improved the effectiveness of the measurements, and its application provided a significant fraction of the results in the joint IRL projects since 2001 and mentioned in this Supplement. A more detailed description of the method of live ^{90}Sr and ^{137}Cs counts in biological objects is provided in another article of this Supplement (Bondarkov et al. 2011).

Summary of Data on Radioecological Monitoring, NPP Decommissioning, and Methods of Radioecological Research

In 2006, the Chernobyl Center for Nuclear Safety, Radioactive Waste, and Radioecology and Savannah River National Laboratory operated by Washington Savannah River Company LLC (and later by Savannah River Nuclear Solutions, LLC) signed a contract shifting the ongoing cooperation from theoretical science to reviews of the expertise and knowledge available in Ukraine regarding minimization of the ChNPP accident consequences, remediation of the contaminated lands and the ChNPP decommissioning. The scope of work focused on colletion of data from open publications in Russian and Ukrainian languages that could have been beneficial for practical applications in other countries (including the U.S.) for activities on characterization of contaminated areas, risk assessments and predictions associated with the environmental contamination, radioecological monitoring of areas and facilities related to various types of their management or various phases of decommissioning. Under this contract, the IRL reviewed problems associated with decommissioning of the ChNPP and the ChNPP Cooling Pond, construction of a new safe confinement, radioecological processes occurring in various ecosystems of the Chernobyl Exclusion Zone, approaches to radiation risk assessment, environmental monitoring methods and many other issues. Some of the results of these activities are described in other articles of this special supplemental issue (Oskolkov et al 2011a,b).

CONCLUSION

Summarizing this overview, it can be stated that, apart from capabilities that became available for scientists of the entire world, the creation of the International Radioecology Laboratory significantly contributed to the world's knowledge on radioecology and radiation safety, expanded and strengthened cooperation among scientists from many countries and helped preserve and augment the scientific and research potential of Ukraine. The IRL continues to serve interests of safe and secure peace, providing assistance in assessing consequences of technogenic contamination of the environment, and identifying adequate solutions for minimizing these consequences.

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