Report on dose-effects relationships for reference (or related) Arctic biota. EPIC database “Radiation effects on biota”

A deliverable report for EPIC (Environmental Protection from Ionizing Contaminants)

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EXECUTIVE SUMMARY

The key issue in the assessment system for radiation protection of wildlife is the establishment of a set of dose-effects relationships for reference representatives of natural biota, based on scientific data from a range of doses and a range of radiation effects. Risks to natural populations in particular habitats can be evaluated from a comparison of estimated doses to biota with the scale of dose-effects relationships for different types of biota.

The main concern of environmental regulations is the development of safety standards for the conditions of routine operations in the industries dealing with authorized releases of technogenic or technologically enhanced natural radionuclides to the environment, which are normally associated with chronic exposures of flora and fauna at comparatively low dose rates (well below lethal dose levels). However, the effects of low-level radiation have never been analyzed on a systematic basis.

The key objective of this report within the EPIC project is to compile and analyze the published data relating to dose-effects relationships for flora and fauna in the Arctic and northern areas. The EPIC database on the effects of radiation exposure to wild organisms has been created as a tool to support this endeavour.

The general aim of the EPIC database “Radiation effects on biota” is to provide a basis for establishing criteria on the protection of wildlife from the effects of ionizing radiation. The EPIC database contains information based exclusively on Russian/FSU experimental and field studies of the radiation effects on flora and fauna of northern/Arctic climatic zone. Chronic/lifetime exposures were the focus of the work, owing to the fact that such exposures are the most typical in radiological assessments for biota. Data on radiobiological effects published in the world literature (in English) were compiled in the other EC project FASSET (FASSET Project, 2003).

In total, the EPIC database “Radiation effects on biota” contains about 1600 records from 435 papers and books. The database has been developed in the form of electronic EXCEL tables. Annexes to the report contain tables with database records, available in the accompanying CD.

The EPIC database consists of the following sub-databases:

- Radiation effects on terrestrial animals;
- Radiation effects on aquatic animals;
- Effects on terrestrial plants and herbaceous vegetation;
- Effects on soil fauna;
- Effects on microorganisms;
- Table of lethal doses.

The EPIC database information cover a very wide range of radiation dose rates to wild flora and fauna: from below 10^{-5} Gy d^{-1} up to more than 1 Gy d^{-1}. A great variety of radiation effects are registered in the EPIC database. These encompass effects from stimulation at low doses up to death from acute radiation syndrome at high doses. Background dose-rates were also considered in the report. From on information, compiled in the EPIC database, the preliminary dose-effects relationships were derived for terrestrial and aquatic animals, also for terrestrial plants. The dose-effects relationships provide the scale of severity of radiation effects at different levels of chronic radiation exposure.

The following pleliminary scale of dose-effects relationships can be suggested for northern organisms (low-LET radiation, chronic exposure) based on the EPIC database:

• 10^{-6} -10^{-5} Gy d^{-1}	Natural radiation background for Arctic/northern organisms
• 10^{-4} – $5x10^{-4}$ Gy d^{-1}	Minor cytogenetic effects. Stimulation of the most sensitive species.
• $5x10^{-4}$ - 10^{-3} Gy d^{-1}	Threshold for minor effects on morbidity in sensitive vertebrate animals.
• $(2\text{-}5)x10^{-3}$ Gy d^{-1}	Threshold for effects on reproductive organs of vertebrate animals, decrease of embryo's survival.
• $5x10^{-3}$ -10^{-2} Gy d^{-1}	Threshold for life shortening of vertebrate animals. Threshold for effects in invertebrate animals. Threshold for effects on growth of coniferous plants.
• 10^{-2} –10^{-1}Gy d^{-1}	Life shortening of vertebrate animals; chronic radiation sickness. Considerable damage to coniferous trees.
• 10^{-1} –1 Gy d^{-1}	Acute radiation sickness of vertebrate animals. Death of coniferous plants. Damage to eggs and larva of invertebrate animals.
• > 1Gy d^{-1}	Acute radiation sickness of vertebrate animals; lethal dose is received within several days. Increased mortality of eggs and larva of invertebrate animals. Death of coniferous plants, damage to decidous plants.

A general conclusion can be made, that the threshold for appearance of deterministic radiation effects in wildlife lay somewhere in the range 0.5-1 mGy d^{-1} of chronic low-LET radiation. In the same time, populations of highly productive vertebrate organisms (mice, some wide-spread fish species) were found to survive even at dose rates about 10 mGy d^{-1}, despite of radiation effects.

Effects of alpha-emitting radionuclides on natural biota were shown to be more severe than those from low-LET radiation; for some long-lived radionuclides (e.g. uranium), the effects were considerably aggravated by chemical toxicity of the radionuclide.

Dose-effects relationships for radioactive elements were compared with data pertaining to concentration-effects relationships for radioactive and non-radioactive contaminants.

The report consists of 11 chapters, two Supplements, and six Annexes with the data tables.

Chapter I outlines the objectives of the report in context of the radiation protection of natural flora and fauna.

Chapter 2 provides a brief summary of mechanisms of radiation damage to living organisms, and the variety of radiation effects, which were observed in humans and laboratory organisms. This chapter defines the categories of radiation effects, which can be expected in wild populations subjected to chronic/acute radiation exposure.

In the Chapter 3, the influence of severe climatic conditions on manifestation of radiation effects in natural biota is discussed. Chapter 4 contains the data on background radiation exposure of wild organisms in the Arctic.

Chapter 5 describes the structure and contents of the EPIC database “Radiation effects on biota”.

Chapters 6-8 contain the reviews of datasets and dose–effects relationships for the radiation effects on terrestrial animals (chapter 6), aquatic animals (chapter 7), terrestrial plants (chapter 8), soil fauna and microorganisms (chapter 9).

Chapter 10 considers the non- radioactive contaminants in the Arctic and provide the examples of concentration-effect relationships for harmful effects of non-radioactive and radioactive toxicants.

Chapter 11 contains the conclusions of the report and recommendations for future research.

With its focus on the effects of chronic exposure, the EPIC database of radiation effects provides a useful tool for scientists and decision-makers to establish safety standards for protection of natural biota from the harmful effects of ionizing radiation.

1. INTRODUCTION

In recent years, there has been a growing international demand to develop a systematic approach for the protection of the environment from the ionizing radiation, in addition to the system already in place for the protection of man. It has been previously assumed that by protecting man from the effects of ionizing radiation, the environment is automatically protected (ICRP, 1977, 1990; IAEA, 1996), and methodologies pertaining explicitly to environmental impact assessments, in the few instances where the environment has been examined have been conducted on an *ad hoc* basis only. The environment has mainly been considered as a pathway for radionuclide transfer to man. Furthermore, it has become evident that statements relating to the protection of the environment from contaminants (including radioactivity) generally, as enshrined in the international principles and conventions (e.g. UNCED, 1992), are rather uncertain and inadequate for the needs of regulators and decision-makers. This has further precipitated the requirement for the development of a concrete system addressing environmental protection from ionizing radiation.

It is pertinent to note that the human population represents only one biological species *Homo sapiens*, whereas the biosphere consists of millions of species, differing considerably from man by their size, lifespan, habitat, habits and radiosensitivity. The living conditions for non-human organisms in the natural ecosystems are not comparable with the conditions of human life, and the radiation dose rates to non-human organisms may be orders of magnitude different to those experienced by humans. Therefore, the protection of the biosphere from the detrimental effects of ionizing radiation cannot be based on the protection of only one biological species. However, up to now, no internationally agreed criteria, or guidance, exist for assessing the impact of environmental radiation on flora and fauna.

A key problem in developing an approach to ensure protection of wildlife from ionizing exposure is the construction of a set of dose-effects relationships for reference organisms[11], based on scientific data from a range of doses and a range of radiation effects.

The main concern of the environmental regulations is the development of safety standards that relate to normal operating conditions of industries discharging authorized levels of technogenic radionuclides or technologically-enhanced natural radionuclides to the environment and the concomitant chronic exposures of flora and fauna at comparatively low dose rates (well below levels of direct mortality) that arise from these releases (IAEA, 1976). Even in areas affected by radiation accidents, the lethal exposures of organisms were observed only within short periods immediately after the accidents. Unfortunately, in the existing reviews on the biological effects of radiation, most data refer to acute effects of short-term exposures at high doses. Rather limited datasets are published in the world literature on the effects of chronic exposure at relatively low dose rates (Polikarpov, 1966, 1977, 1998; Turner, 1975; Blaylock & Trabalka, 1978; IAEA, 1976, 1979; Woodhead, 1984; NCRP, 1991; UNSCEAR, 1996).

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[1] The term “reference organism” has been defined as : “a series of entities that provides a basis for the estimation of the radiation dose rate to a range of organisms that are typical, or representative, of a contaminated environment. These estimates, in turn, would provide a basis for assessing the likelihood and degree of radiation effects.” (Larsson *et al*., 2002).

The key objective of this report within the EPIC project is to compile and analyze the published and unpublished data relating to dose-effects relationships for flora and fauna in the Arctic and northern areas (EPIC Project, 2001, 2002). The EPIC database on the effects of radiation exposure to wild organisms has been created as a tool to support this endeavour. Presently, the EPIC database "Radiation effects on biota" contains information based exclusively on Russian/FSU experimental and field studies of the radiation effects on flora and fauna from the northern/Arctic climatic zone. Data collation has focused on wildlife; as a rule, domestic animals and agricultural plants have not been considered. Chronic/lifetime exposures were also selected as a focus of this work owing to the fact that this exposure type is the most useful in radiological assessments for biota, as discussed above. The unique feature of Russian data is the availability of long-term observations of radiobiological effects in natural conditions. For many years the radiobiological studies have being carried out in the following areas: Kyshtym radioactive trace in the Southern Urals (contaminated in 1957 as a result of the Kyshtym radiation accident); large territories in Ukraine, Belarus and Russia contaminated as a result of the Chernobyl accident of 1986; local areas with high natural radioactivity in Komi Autonomic Republic of Russian Federation. Beside this, great number of publications is available on the laboratory studies of radiation effects in non-human organisms.

The data on radiobiological effects published in the world literature (published in English) were compiled in the other current EC Project - FASSET (FASSET Project, 2003). Reference to information compiled within the FASSET database made it possible to avoid duplication of data within the frame of EPIC.

The report consists of 11 chapters, two supplements, and six Annexes with the data tables.

Chapter I outlines the objectives of the report in context of the radiation protection of natural flora and fauna.

Chapter 2 provides a brief summary of mechanisms of radiation damage to living organisms, and the variety of radiation effects, which were observed in humans and laboratory organisms. This chapter defines the categories of radiation effects, which can be expected in wild populations subjected to chronic/acute radiation exposure.

In the Chapter 3, the influence of severe climatic conditions on manifestation of radiation effects in natural biota is discussed.

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Chapter 11 contains the conclusions of the report and recommendations for future research.

Annexes to the report contain tables with database records available in the accompanying CD.

With its focus on the effects of chronic exposure of wildlife, the EPIC database provides a usefool tool for scientists and decision-makers to establish scientifically based safety standards for protection of natural biota from the harmful effects of ionizing radiation.

2. MECHANISMS OF THE RADIATION EFFECTS IN ORGANISMS

The first observations of radiation effects in living organisms were made at the end of 19th century. By the present time, the radiation effects in various biological objects are investigated for over 100 years. Extensive information on radiation effects in cells, organs and tissues of organisms has been obtained from experiments with laboratory mammals (mice, rats, dogs, pigs, monkeys), agricultural plants, insects, and many other organisms (see for example, Pizzarello & Witcofski, 1975; Yarmonenko, 1984; Moskalev, 1989; Rose, 1992; UNSCEAR, 1996). Numerous data are available on radiation health effects in humans, including professionals working with radiation, patients subjected to exposure for medical reasons, victims of nuclear tests and nuclear explosions (Pizzarello, 1982; Coggle, 1983; Mettler & Upton, 1995, Yarmonenko,1984; Moskalev, 1991; Nias, 1998; Hall, 2000).

In contrast, far fewer data in the world radiobiological literature refer to observations of radiation effects in wild nature (IAEA, 1976, 1992; Blaylock & Trabalka, 1978; Turner, 1975; NCRP, 1991; UNSCEAR, 1996).

In the following sections of this chapter, we provide a brief summary of radiation effects, which were observed in laboratory conditions, and are known in human radiology. This information provides a necessary background for understanding and correct interpreting the radiation effects observed in wild nature, which are compiled in the EPIC database. In this brief overview, the main attention is given to the effects, which are of vital importance for wild organisms, namely, effects on survival capacity, reproduction, and lifetime.

2.1. Ionization of matter by radiation

The fundamental property of ionizing radiation is the ability to produce electrically charged ions from neutral molecules and atoms (Bacq & Alexander, 1966; Alpen, 1990; Hall, 2000). There are different types of ionizing radiation (i) particles, represented by α-, β- particles, neutrons, multi-charged ions, and (ii) electromagnetic radiation, like γ- and X-rays.
Important parameter, characterizing the ionizing radiation quality is the linear transfer of energy (LET). LET characterizes the losses of energy by a particle (or electromagnetic radiation) along its track in a material. LET is the criterion of quality of ionizing radiation, i.e. its capacity to create ions in a material.

Heavy α- particles have short tracks in biological tissues with a dense ionization along the tracks; β- particles (electrons and positrons) having lower mass, produce more sparse ionization in larger volume; γ-rays cause a relatively small number of ionizations dispersed along an extensive track.

The magnitude of harmful effects, caused by ionizing radiation depends not only on absorbed dose, but also on the type of ionizing radiation. Emissions of α-, β-, and γ- particles and rays differ from each other by penetrating capacity, size and energy of particles/photons, and by their ability to produce ions in biological tissues. Alpha particles are known to have the highest non-reparable damage to biological tissues per unit of adsorbed dose.

To account for the different quality of radiation, the concept of relative biological effectiveness (RBE) is employed. The RBE is defined as the ratio of the absorbed dose required to cause a specific biological effect in a defined endpoint from a standard radiation to that required to produce the same effect for the same endpoint from test radiation (alpha particles, low energy beta radiation, etc.).

In radiobiology, the RBE values are determined experimentally, using different radiation effects as endpoints for comparison, e.g. death of cells, death of organisms, embryonic losses, etc. It is noteworthy that the RBE values obtained in this way often yield rather different values for various endpoints.

The RBE values greatly depend upon the chemical form, in which radionuclide enters the living organism. Under internal administration, different chemical forms of radionuclide demonstrate specific, sometimes non-uniform distributions within biological cells/ tissies; the accumulation of radionuclide in critical tissues may increase considerably the effectiveness of radiation. For example, the isotope ^{3}H (tritium) in the form of tritiated water (HTO), is distributed uniformly in living cells. In contrast, the same isotope in the form of tritiated thymidine, is accumulated specifically in DNA molecule as a nucleotide. Radioactive decay of ^{3}H isotopes located directly within DNA evidently produce greater damage to the vital component of the cell compared with the harm from tritiated water (Straume, Carsten, 1993; Balonov et al., 1993).

It is practically impossible to obtain experimental values of RBE for a large number of possible endpoints and every type of organisms. Furthermore, RBE is also dependent on dose and dose rate adding to the total number of possible experimental configurations.

For the purposes considering RBE within the framework of human radiological protection, a pragmatic approach was adopted which involved, invoking a simple set of radiation weighting factors. The radiation weighting factors (w_r) are defined as multipliers of adsorbed dose used to account for the relative effectiveness of different types of radiation in inducing health effects in humans (ICRP, 1990; IAEA, 1996). The value of w_r for a given type of radiation is derived from available experimental values of RBE, and a consideration of LET. The equivalent dose (in units of Sv) is calculated by multiplying the adsorbed dose to the radiation weighting factor. In human radiation protection, the following values of radiation weighting factors are accepted: for photons and electrons w_r=1; for alpha-particles w_r=20 (ICRP, 1990).

In the radiobiology of non-human organisms, the establishment of appropriate radiation weighting factors between equal absorbed doses of high-LET and low-LET radiation is still an un-solved problem. Up to now, there are no officially established values for the radiation weighting factors for organisms other than man.

UNSCEAR (1996) has proposed that a radiation weighting factor (w_r) of 5 for alpha particles is, perhaps, appropriate for non-human biota, based on the approach that deterministic effects are of greater importance for wildlife than stochastic effects. Based on experimental data, Kocher and Trabalka (2000) suggested that the weighting factors for deterministic effects of alpha radiation are within the range from 5 to 10. A weighting factor of 20 for alpha particles is suggested in a number of publications (e.g., Woodhead, 1984; Blaylock et al., 1993; Environment Agency, 2001). For beta radiation, a radiation weighting factor of 3 has been proposed for tritium (Environment Canada, 2000; Environment Agency, 2001); UNSCEAR (1996) has made a general recommendation to use a radiation weighting factor of 1 for all beta emitters.

The EPIC database includes datasets on the effects of both low-LET and high-LET radiations on wild organisms in the natural environment. The comparison of dose-effects relationships for these types of radiation makes it possible to derive some conclusions on the relative effectiveness of these types of radiation.

2.2. Effects of ionizing radiation at the molecular level

Transfer of energy from ionizing particle to molecules in cells and biological tissue causes changes in their chemical forms and biological functions.

The most critical target for ionizing radiation in living cells is DNA, containing the genetic code of the organism. Ionizing radiation, crossing DNA, causes direct DNA damage in the form of single and double strand breaks..

Ionizing radiation can also damage the membranes of living cells, both the outer membranes and membranes of the organelles (i.e. nucleus, mitochondria, etc.). Violations of membrane integrity lead to the following effects: (i) an increased permeability of membranes, (ii) loss of K^+ ions from, and simultaneous entry of excess Na^+ ions into the cell, and (iii) dislocation of enzyme complexes normally attached to membranes (Kudryashov & Berenfeld, 1982; Yarmonenko,1984; Alpen, 1990; Hall, 2000).

In the presence of water and oxygen in biological tissues, considerable contribution to radiation damage is caused by indirect effects of irradiation. These arise from the interaction of oxygen free radicals or reactive oxygen species (ROS) produced as a result of water radiolysis with biological material (Bacq & Alexander, 1966; Kudryashov & Berenfeld, 1982; Kuzin, 1986; Nias, 1998; Hall, 2000).

Products of water radiolysis and ROS are highly chemically active and initiate great number of chemical reactions with biomolecules and inorganic substances in the cells; most typical types of chemical reactions are oxidation and peroxidation. The content of water in biological tissues is usually very high, so the products of water radiolysis predominate in terms of the total number of ions produced by ionizing particles. Oxidation/peroxidation of enzymes, proteins, and lipids results in inactivation of biomolecules; they lose normal biological functions, and become waste substances for the living cells. Some products of peroxidation are toxic, such as lipidoperoxides, quinones, etc. Some reactions have a “cascade”, or “chain” character. Accumulation of electrically charged ions on biomembranes leads to a degradation of bioelectric potential between the outer and inner surfaces of the biomembranes. This, in turn, results in violation of the normal ion transport through the membrane (Kuzin & Kopylov, 1983; Kudryashov & Berenfeld, 1982).

The presence of ROS leads to an abnormal increase in oxidation processes within living cells. Normally, the intensity of oxidation processes is maintained at a low level. Although a limited stimulation of oxidation may give a positive effect, an abnormally high rate of oxidation is harmful and results in early ageing and death of cells.

Radiotoxins (like ROS) react also with nucleotides in the DNA molecules, as well as with nucleus-protein complex (Yarmonenko, 1984; Friedberg et al., 1995; Schmidt-Ullrich et al., 2000). The outcome of these reactions is peroxidation of cytosine and thymidine, denaturation (destruction of H-H- links), destruction of ATP, etc. Reactions of radiotoxins with DNA cause indirect damaging effects of radiation on DNA. Changes in DNA nucleotides lead to point mutations in the genetic code, which may appear even in some distant descendants of the exposed cell. Some contribution to the violation of DNA replication may be associated with the damage of nucleus membrane, and the nucleus-protein complex.

Highly reactive ions, free radicals and radiotoxins represent chemical products, created by irradiation in a biological tissue. Transfer of such products to un-exposed tissues (by diffusion, flow of blood and lymph, etc.) may cause the same chemical effects, as radiation itself. The abscopal/bystander effects of radiation were discovered more than 40 years ago (Kuzin, 1986; Mothersill & Seymour, 2001). During recent years, new experiments with microbeams of ionizing particles have provided new knowledge on these effects (Mothersill & Seymour, 2001; Little, 2002; Morgan, 2003).

2.3. Effects of radiation at the cellular level

Radiobiological effects of radiation in cells and biological tissues are not finalized at the moment of energy absorption. Living cells have developed several reparation mechanisms, which are specialized to counteract the deleterious effects of any harmful agent, including radiation (Kuzin, 1986; Friedberg et al., 1995; Nias, 1998; Schmidt-Ullrich et al., 2000). On the cellular level, these mechanisms include cell cycle control systems, signal transduction control in the cell, DNA damage repair systems, and some others. All these mechanisms interplay with one another.

Special enzyme complexes can repair many of DNA strand breaks, and restore the integrity of DNA. Limited damage to biomembranes can also be repaired, and normal ion transport restored. Several natural antioxidant systems, both enzymatic and non-enzymatic (like thiols, vitamins, etc.) can inactivate, at least partially, the free radicals and radiotoxins (Kuzin, 1986; Nias, 1998).

Even at low doses of radiation, damage to some cells is un-repairable. Such cells die and are eliminated from tissues. Some damaged cells with unrepaired or mis-repaired DNA or other structures, die at some later stage, even several divisions after the time of the original exposure.

Some subtle DNA injuries are not recognized by the reparation systems, and they pass through the “control mechanisms” in the form of mutations, which may be expressed in future generations of cells or organisms. These effects of genomic instability caused by radiation are intensively investigated in the recent years (Little, 2002; Morgan, 2003).

In biological cells, the reparation systems are more effective at low-to-moderate levels of injury. Furthermore, the injuries from γ-rays and β-particles are more easily repaired than damage caused by α-particles.

As a whole, the development of radiobiological effect is a complex process involving contradictory processes of destruction and reparation; the realization of the radiobiological effect is prolonged in time, sometimes it have several stages where different characteristics of the effect predominate. The effect of reparations explains the well-known phenomenon that the same dose produces a greater damage in the case of acute as oppose to protracted exposures (Bacq & Alexander, 1966;Yarmonenko, 1984).

The radiation effects on the cellular level in the EPIC database are placed under the category (umbrella endpoint) “Cytogenetic effects”.

In the wild nature, negative cytogenetic changes caused by radiation, are controlled by the process of natural selection. Organisms with genetically-reduced fitness, anable to struggle for existence effectively, are discarded from population by natural selection.

2.4. Factors modifying the radiation effects in living tissues

Chemical reactions of ions, radicals, and radiotoxins, created by radiation, with biomolecules in living tissues can be modified by certain chemical and physical agents.

Oxygen effect
Oxygen, which is normally present in living cells and tissues, can significantly intensify the radiation effects. This “oxygen effect” is well known in radiobiology and was demonstrated in a number of experiments (Bacq & Alexander, 1966; Kudryashov & Berenfeld, 1982; Kuzin, 1986; Nias, 1998; Hall, 2000).

Natural radioprotecting and sensibilizing agents
Natural anioxidants, normally present in the organism (e.g. some vitamins) can scavenge reactive oxygen species (ROS) like oxygen free radicals and peroxides and transform them to non-active forms, preventing their further reactions with other biomolecules (Kuzin, 1986; Mettler & Upton, 1995; Nias, 1998). However, the reserves of antioxidants in an organism are limited. Some natural chemical compounds, which are present in biological tissues, may increase the indirect effects of radiation, acting as radio-sensibilizing agents. For example, the increased concentrations of lipids or phenolic compounds in living tissues provoke an increased creation of radiotoxins (lipidoperoxides and quinines) in irradiated organism (Kuzin & Kopulov, 1983; Kudryashov & Berenfeld, 1982; Zhuravlev, 1990).

Temperature effect
Increase in temperature, as follows from the Arrenius’s Law, increases the rates of biochemical reactions within the biological range of temperatures. The temperature affects both the reactions of radiotoxins with biomolecules, as well as diffusion of toxic compounds to neighboring tissues. Lowering the temperature of biological tissues/organisms, helps to prevent the development of radiation effects. For example, in the radiobiological experiments the survival time of fish (*Carassius* sp.) kept at different temperatures between 3 and 25 ^{0}C after an exposure of 18 Gy was very much longer at low temperatures and seemed to follow the decrease of oxygen consumption; i.e. time of survival was inversely proportional to metabolic rate (Keiling et al., 1958).

However, at low temperatures the intensity of reparation processes also decreased. At temperatures of approximately 2-4 ^{0}C, the reparation is practically non-effective (Kudryashov & Berenfeld, 1982; Kuzin, 1986; Mettler &Upton, 1995).

2.5. Effects of radiation at the level of the organism

2.5.1. Restoration after acute exposure

If the dose of acute radiation exposure is not too high, reparation of the radiation damage starts immediately following irradiation (Kuzin, 1986; Mettler &Upton, 1995; Nias, 1998). The restoration involves the following processes:

- Neutralization of ions and radicals by natural antioxidants;
- Intracellular repair by re-synthesis of destroyed or inactivated molecules;
- Removal of killed cells, destroyed biomolecules, and radiotoxines from the organism;
- Recovery of organs or tissues by proliferation of cells to replace those that have been killed.

Some lesions caused by radiation exposure, are reparable, others cause permanent damage. At low-dose exposure by low-LET radiation, most lesions are of the reparable type and cause very little, if any, change in the health of organism. In the case of massive damage arising from high doses of radiation, the percentage of non-reparable lesions can be very high and, the result might be either death of organism or radiation sickness followed by a long recovery process.

“Split-dose” experiments have demonstrated that two irradiations, punctuated to give time for recovery do less harm than the same total dose given at once.

2.5.2. Effects on the immune system of animals

Defense mechanisms in organisms are of complex character. In a broad sense, they include the barrier properties of tissues, different cellular defense reactions, natural bactericidal properties of blood, lymphoid cells and tissues associated with innate and acquired immunity.

The immune system is a specialized system protecting the organism from any alien bio-substance of exogenous or endogenous origin. The immune system provides protection from bacterial/viral/parasitic infections; this system is responsible for elimination of dead/modified/forein cells, and elimination of foreign biomolecules from the cells.

In vertebrate organisms, the components of the immune system are lymphoid and myeloid tissues, lymph and it’s cell components – lymphocytes of different types. Among vertebrate animals, mammals have the most complicated and sensitive immune system. In invertebrate animals, immune system is more simple than that of vertebrate organisms; the main mechanism of immune response is phagocytosis (Gilyarov (Ed.), 1986).

Lymphoid and myeloid tissues of mammals are markedly radiosensitive. For example, acute dose of 1.2-1.8 Gy is enough to kill about 70% of human B-lymphocytes (Zherbin & Chukhlovin, 1989).

Due to a limited capacity to remove radiotoxins, broken biomolecules, and dead cells from irradiated organism, lymphocytes can be effectively restricted from doing their normal work of protecting from various infections, which permanently attack the organism. The situation is aggravated by the direct radiation damage to lymphoid tissues and lymphocytes; also the lymphocyte activity is depressed by radiotoxins circulating in the blood and lymph. In addition, the increased permeability of cell membranes in the exposed tissues is conductive to the easy entry of microbial/viral/parasite infections into the organism.

The whole-body effects of radiation on the immunity can be summarized in the following way (Klemparskaya, Ed., 1972; Shubik, 1977; Pizzarello, 1982; Yarmonenko, 1984; Kuzin, 1986; Mettler & Upton, 1995):

- General increase in the susceptibility of irradiated organisms to various infections;
- Increase of endogenous infections produced by normal intestinal microbial flora, to which un-exposed animals are normally resistant;
- Weakening and delay in antibody formation to infective agents;
- Increased probability of development of allergic reactions in exposed animals resulting from frequent triggering of the immune system by the excess of waste biomolecules.

As a result of weakening the immune system, the irradiated organisms may die, not directly from radiation itself, but from various infections; thus, radiation effects may appear in form of "natural death".

In the EPIC database, the radiation effects, associated with weakening of the immune system are placed under the category (umbrella endpoint) "Morbidity effects".

2.5.3. Effects on specialized organs and tissues

In organisms, the behavior of radionuclides follows the biochemical pathways of stable analogous elements. Thus, the radioactive iodine is accumulated in the thyroid glands, radioactive isotopes of strontium and calcium – in bones; radioactive cesium – in muscles, etc.

Non-uniform distrubution of certain radionuclides in the body is resulted in non-uniform distribution of dose loads. Increased exposure of individual organs leads to dysfunctions of these organs, which manifest themselves in form of specific diseases (Moskalev, 1989).

In the EPIC database, the radiation effects, associated with radiation damages to specialized organs/tissues of wild organisms (thyroid, liver, kidney, etc.) are placed under the category (umbrella endpoint) "Morbidity effects".

2.5.4. Effects on reproduction and embryos

Reproduction is a vitally important function of organisms. Reproductive organs are known to be sensitive to radiation exposure. Irradiation of testes and ovaries may cause complete sterility at doses, which produce only minor changes in hematological or gastrointerstinal systems. Although damage to gonads has not much influence on the survival of an adult organism, the temporary or complete loss of reproductive capacity by many organisms in a population leads to a gradual decrease in the population size and finally to total extinction.

Embryos of animals are known to be very sensitive to radiation. In vertebrate organisms, the effects on embryos include (Piontkovsky, Ed., 1961; Kudryashov & Berenfeld, 1982; Yarmonenko, 1984; Mettler & Upton, 1995; Brent, 1999; Hall, 2000):

- Pre-implantational and implantational death of embryos;
- Reduction of brood size;

- Deformations of skeleton;
- Undevelopment/deformity of organs and tissues;
- Decreased weight of new-born organisms;
- Decreased survival potential, etc.

It is important, that exposure of parents (males as well as females) is an essential factor of damage to embryos and new-born organisms. Some embryonic losses are caused by lethal mutations in the parent's genetic material; radiation sickness of females cause intoxication effects in embryos; decrease in immune status of parents leads to increased susceptibility of embryos and young organisms to various infections. Effects were observed even if parent organisms were exposed some time before mating, and embryos themselves did not receive any direct radiation exposure.

In the EPIC database, the radiation effects on fertility/ fecundity of organisms are placed under the category (umbrella endpoint) "Reproduction effects".

2.5.5. Life-shortening and early aging of organisms

The phenomenon of premature aging of irradiated organisms is known from 1939, when Russ and Scott (1939) noted that the irradiated rats "looked old and decrepit", they seemed to age more quickly than normal rats, and the death rate in chronically irradiated rats exceeded that of non-exposed animals. Observations of life-shortening and early aging of irradiated organisms have been discussed in numerous publications (Back & Alexander, 1966; Lindop, Sacher, Eds. 1966; Walburg, 1975; Casarett, 1981; Pizzarello, 1982; UNSCEAR, 1982; Coggle, 1983; Kuzin, 1986; Moskalev, 1991). However, it was found, that the processes of radiation aging are not exactly the same as the natural senescence. The effect of slight life shortening can be observed in organisms suffered from chronic radiation sickness, also in organisms survived the acute radiation sickness; irradiation at higher doses approaching the lethal doses, leads to a considerable decrease in lifetime.

The carcinogenic effects of ionizing radiation in humans and laboratory animals are studied for many years, a comprehensive review of these effects is given in (UNSCEAR, 2000). In wild nature, however, radiation-induced cancer in animals is of very rare occurrence because of rapid deletion of weakened animals by the process of natural selection.

The processes of life-shortening and earlier aging in wild populations can be revealed by comparison the health status and age-dependent survival in groups of irradiated animals with non-exposed control groups.

In the EPIC database, the radiation effects on lifetime of organisms are placed under the category (umbrella endpoint) "Mortality".

2.6. Radiation effects in populations and ecosystems

The ecosystem is a community where each species performs certain functions in ecosystem maintenance. Members of the ecosystem are dependent on each other, and sometimes cannot survive without one another (Odum, 1983; Ramade, 1994, 1995).

Different species of organisms demonstrate tremendous differences in radiosensitivity; the lethal doses (LD for adults) of acute exposure are ranging from few Grays (mammals) to thousands Grays (insects, microorganisms) (Odum, 1983; UNSCEAR, 1996). This results in higher vulnerability of particular groups of organisms to radiation exposure.

It should be noted, also, that radiosensitivity of many invertebrate organisms varies considerably at different stages of life cycle, e.g. young stages of some insects can be killed by few Grays of radiation exposure, whereas the adult insects of the same species are very radioresistant (Odum, 1983; Krivolutsky, 1983).

Beside the differences in radiosensitivity, there are many other factors, which directly or indirectly modify the radiation effects on individual population, and the ecosystem as a whole. Among these factors are the following: ecological differences in exposure, recovering capacity, type of reproduction, sensitivity at critical periods of onthogenesis, duration of lifespan, trophic relationships with other species, season of exposure, and some others.

Ecological differences in exposure

In an irradiated ecosystem, absorbed doses to different species of organisms may vary considerably as a result of differences in feeding habits, habitats and duration of lifespan and other factors. Species, which are sheltered from external irradiation, or species feeding on non-contaminated food items, receive lower doses than other members of biological community. Having minimal contact with ionizing radiation, these species take advantage in ecological competition over more damaged species..

In the conditions of chronic exposure, the total doses accumulated per lifetime of organisms can vary considerably between species. Species with relatively short lifespan accumulate lower lifetime doses, comparing with long-lived species. Therefore, short-lived species have better chances to survive in the irradiated ecosystem.

Beside the lifetime doses, radiation effects are determined also by doses accumulated during the most sensitive periods of development. In the conditions of radiation exposure, the preference in survival have species with short period of embryo's development.

On acute exposure of a natural ecosystem, the total radiation effect depends upon what proportion of each species were in radiologically sensitive stage of ontogenesis at the period of radiation exposure (Tikhomirov, 1972, Krivolutsky, 1983). An ecosystem might survive massive radiation during the winter, but suffer enormously if radiation is received in spring or early summer.

Recovering processes in wild populations

The survival of biological species, damaged by radiation, strongly depends on their capacity to restore rapidly the numbers of organisms in the population.

When irradiated, the unicell microorganisms may suffer much damage in form of individual cell deaths. However, on a statistical basis, some cells may escape entirely and give rise to a new population of descendants. The multi-cellular species may suffer an equal number of cell damages, but because of interdependence between cells and tissues, every individual multi-cellular organism may die. For example, if 99% of the cells in a bacterial colony are destroyed by irradiation, the bacterial population can survive and rapidly regenerate from the remaining 1% of cells. In contrast, if 99% of cells in a multi-cellular organism are killed by irradiation, the whole organism dies (Buchsbaum, 1958; Krivolutsky, 1983).

In the case of acute exposure, asexually reproducing organisms, being independent genetically, are more likely to restore their populations, than sexually reproducing species. In populations of sexually reproducing species, the decline in the total numbers of organisms makes lower also the probability of mating, which, in turn, leads to further decrease of the population size. From the other side, under the conditions of chronic exposure at low-to-moderate dose rates, the sexually- reproducing species produce organisms with more variable characteristics, and populations have better chances for rapid adaptation to radiation.

Highly productive and rapidly growing species (insects, fish, mice) have fair chances to restore the damaged populations. In contrast, long-lived species with low reproduction potential are very vulnerable to losses in population. The restoration of these species in irradiated ecosystems may occur due to migration of healthy organisms from the neighboring non-irradiated areas.

Non-direct ecological effects of radiation
Due to interactive relationships between populations, including competition, predation and mutualism, the radiation responses of individual populations cause indirect changes in the ecological balance between species in the ecosystem (Whicker, Schultz, 1982; IAEA, 1992). The ecological effects of radiation may manifest themselves in the following forms (IAEA 1992; Sazykina, 1996; UNSCEAR 1996):

- decline of sensitive species is accompanied by the increase in populations of similar, but less damaged species;
- increase in numbers of radiation-weakened preys stimulate the increase in populations of predators/parasites;
- radiation damage to predators is resulted in great increase in some of prey populations;
- decrease in population may be compensated by migration of organisms from neighboring non-exposed areas;
- chronic radiation exposure may lead to the decrease of biodiversity, etc.

In the EPIC database, the radiation effects, associated with changes in populations and ecosystems are placed under the category (umbrella endpoint) “Ecological effects of radiation”.

2.7. Other effects of radiation on organisms (stimulation, adaptation)

Stimulating effects of radiation at low doses on survival and health of organisms (radiation hormesis) are discussed for many years (see for example, Kuzin, 1986, Luckey, 1991). The stimulation effect is the result of activation of defense mechanisms in organisms, but without their exhaustion. Depending on radiosensitivity, the ranges of doses providing the stimulation effects to different types of organisms vary considerably, so doses lethal for sensitive organisms may be stimulating for radioresistant ones.

In the EPIC database, the stimulation effects of radiation are placed under the category (umbrella endpoint) “Stimulation effects of radiation”.

Some records in the EPIC database describe the specific adaptations of wild organisms to the conditions of chronic irradiation; these effects are placed under the category (umbrella endpoint) “Adaptation effects of radiation”.

2.8. Existing recommendations for protecting the wildlife from ionizing radiation

At present, no international agreed regulations exist for protecting the natural flora and fauna from detrimental effects of ionizing radiation.

There have been several review publications on radiobiological effects in wild nature (IAEA, 1976, 1992; Blaylock & Trabalka, 1978; NCRP, 1991; Polikarpov, 1977, 1998; Turner, 1975; Woodhead, 1984; UNSCEAR, 1996). In most cases, the intention of authors was to concentrate attention on the effects of chronic low-dose exposures, but these data were very limited. As a result, the existing reviews refer largely to studies of radiation effects from acute exposure at high doses, these data are not directly relevant to the environmental concerns.

In 1990s, the international reviews of radiation effects on flora and fauna have been published by IAEA (1992) and UNSCEAR (1996). Based on summaries of available radiobiological literature, these documents provide the following set of preliminary conclusions on the thresholds of radiation effects for terrestrial and aquatic biota:

> **IAEA report (1992, summary):**
> *"Chronic dose rates of 1 mGy d^{-1} to even the more radiosensitive species in terrestrial ecosystems are unlikely to cause measurable detrimental effects in populations and that up to this level adequate protection would therefore be provided".*
>
> *"In the aquatic environment it would appear that limiting chronic dose rates to 10 mGy d^{-1} or less to the maximally exposed individuals in a population would provide adequate protection for the population";*
>
> **UNSCEAR report (1996, para 264):**
> *"For the most sensitive animal species, mammals, there is little indication that dose rates of 10 mGy d^{-1} to the most exposed individual would seriously affect mortality in the population. For dose rates up to an order of magnitude less (1-2.4 mGy d^{-1}), the same statement could be made with respect to reproductive effects.*
>
> *"For aquatic organisms, the general conclusion was that maximum dose rates of 10 mGy d^{-1} to a small proportion of the individuals in aquatic populations and, therefore, lower average dose rates to the whole population would not have any detrimental effects at the population level".*
>
> *It was suggested that chronic dose rates less than 10 mGy d^{-1} would have effects, although slight, in sensitive plants but would be unlikely to have significant deleterious effects in the wider range of plants present in natural plant communities".*

The conclusions of the IAEA and UNSCEAR reports specify the ranges of chronic dose rates, which are of concern in the environmental protection of the flora and fauna. Non of these dose rate levels were intended as recommendations for radiation protection criteria, although they clearly could have implications for the development of such criteria.

With respect to environmental protection, however, it is important to derive dose-effects relationships for a large range of exposures, providing a scale of severity of radiation effects on natural biota following the increase in irradiation levels.

The EPIC database “Radiation effects on biota”, described in this report, provides the extensive sets of data from Russian/FSU publications, which may substantially enlarge the knowledge of radiobiological effects in the northern wildlife. These data were found sufficient to develop the preliminary dose-effects relationships for northern biota in the terrestrial and aquatic environment, see chapters 6-9 of this report.

3. THE INFLUENCE OF ENVIRONMENTAL CONDITIONS IN THE ARCTIC ON MANIFESTATION OF RADIATION EFFECTS IN BIOTA

Climatic conditions in the Arctic are, in general, unfavourable for organic life. Low temperatures, extreme seasonal variations in light are some of the physical and chemical characteristics which cause environmental stress to organisms in the Arctic and make them potentially more vulnerable to contaminants (AMAP, 1998).

Organisms, which are adapted to the extreme environment of the Arctic, exhibit the following peculiar features (Becker, 1994; Dayton et al., 1994; ANWAP, 1997; AMAP, 1998):

- The development and metabolism of poikilotherm (cold-blooded) organisms is considerably slower than that in warm climatic zones;
- Arctic species usually are longer lived, exhibit deferred age of first reproduction in females compared with similar species in temperate climate;
- Many arctic animals have high content of fat or fatty oils in their tissues, which prevent body from freezing and provide support during periods of starvation;
- Homoiothermic (warm-blooded) animals have special covers protecting them from freezing (fur, thick skin, down);
- Both accumulation and removal of toxicants by cold-blooded arctic organisms occurs slower at low temperatures;
- Many species of fish, sea mammals and birds accomplish long-distance annual migrations between feeding and spawning/reproduction areas;
- The development of phyto- and zooplankton in the Arctic Seas is restricted by very short spring-summer period, and by ice covering large marine areas.

Severe climatic conditions are factors of natural environmental stress, restricting the number of biological species, which are able to survive in the Arctic. Low biodiversity is a negative ecological factor associated with the low capacity of Arctic ecosystems to adapt in the case of any environmental changes.

Although the direct data on radiation effects in the Arctic are rather scarce, some peculiarities in manifestation of radiation effects can be expected in the Arctic organisms as oppose to organisms inhabiting the temperate environments.

The development of radiation effects in the Arctic poikilotermic (or hibernating) organisms is expected to occur more slowly, because of low environmental temperatures (see section 2.4, para “*Temperature effects*”). On the other hand, the repair of radiation damage in cells and tissues is not effective at very low temperatures. Lesions in the cooled organisms (e.g. poikilothermic or hibernating animals) are latent. However, if organisms become warm, lesions are rapidly revealed. As a result, radiation effects may not appear during the winter period, and manifest themselves intensively during the warm season.

Development of embryos and young poikilotermic organisms in the Arctic occurs slowly; for example, the development of roe of some Arctic fish species takes more than 200 days, whereas in the temperate climate fish eggs are developed usually during 8-10 days. At the same dose rate, the Arctic fish eggs receive much higher dose during the radiosensitive stages of ontogenesis when compared with fish eggs in the temperate climate. Long-lived species, depending on their reproductive strategy, may be more vulnerable to radioactivity because of the potential for integration of dose in the reproductive organs with time.

High concentrations of lipids in the Arctic animals may be expected to increase the radiosensitivity, since chemical products of lipidoperoxidation produced by irradiation are toxic for organisms (see section 2.4, para "*Natural radioprotecting and sensibilizing agents*").

Thick skin of Arctic animals can protect effectively not only from cold and ice, but also from external alpha - and beta radiation.

Long-distance migrations of Arctic animals, in general, are favourable for survival, since animals do not stay within any contaminated local area for a long time; thus accumulated doses to migratory animals are expected to be lower than those for sedentary organisms.

4. RADIATION BACKGROUND EXPOSURE OF ORGANISMS IN THE ARCTIC

In the Arctic, as everywhere on the Earth, terrestrial and aquatic organisms are exposed to natural sources of ionizing radiation, including cosmic rays, radionuclides produced by cosmic ray interactions in the atmosphere, and radiations from naturally-occurring radionuclides, which are ubiquitously distributed in all living and non-living components of the biosphere (Whicker & Schultz, 1982). Contemporary life forms are adjusted to the natural radiation background; the exposure from common levels of radiation background is considered to be not only harmless, but even health-giving for organisms. The typical dose rates of natural background exposure for different types of organisms in the Arctic are given in Tables 4.1-4.5.

The data on the activity concentrations of natural radionuclides in the Arctic aquatic ecosystems (see Supplement I) were used in the estimation of background radiation exposure to reference species of fish in the Arctic/Northern ecosystems. The doses have been estimated by the methods described in the earlier studies (IAEA, 1976, 1979; Kryshev & Sazykina, 1990,1995; Kryshev A. et al., 2001,2002), taking into account geometrical characteristics of organisms and ionizing radiation sources.

Annual doses from natural radiation sources, which are generally applicable to humans and most other terrestrial vertebrates, are listed in Table 4.5 (Whicker & Schultz, 1982).

Table 4.1. Summary of dose rates (Gy/day, weighted by w_r^*) to marine organisms from natural environmental radioactivity (compiled from IAEA, 1976; Woodhead, 1984; UNSCEAR, 1996; MARINA II, 2002)

Source	Molluscs (5 m depth, on the sea bed)	Crustaceans (10 m depth, on the sea bed)	Fish	
			(20 m depth, remote from sea bed)	(20 m depth, on the sea bed)
NATURAL BACKGROUND				
Cosmic radiation (low LET radiation only)	3.8x10^{-7}	2.6x10^{-7}	1.2x10^{-7}	1.2x10^{-7}
External radionuclides	(3.6-38.4) x10^{-7}	(3.6-38.4)x10^{-7}	2.4x10^{-8}	(3.6-38.4)x 10^{-7}
Internal radionuclides	(1.9-7.8)x10^{-5}	(1.2-34)x10^{-5}	(1.1-13)x10^{-6}	(1.1-13)x10^{-6}
TOTAL	(1.9-7.8)x10^{-5}	(1.2-34)x10^{-5}	(1.2-13)x10^{-6}	(1.6-16.8)x10^{-6}
*. W_r=20 for alpha-emitters				

Table 4.2. Assessments of the radiation background exposure to marine biota in the Kara Sea, 10^{-9} Gy/day (nGy/day)

Parameter	Natural background
Internal radiation	
Phytoplankton	500-2000
Zooplankton	600-4000
Crustaceans	2000-5000
Molluscs	2000-4000
Macrophytes	1000-3000
Fish	600-1000
Waterfowls	500-1500
External radiation	
From water	20-100
From sediments	700-9000

Table 4.3. Contribution of individual natural radionuclides to the background exposure of Arctic freshwater fish, 10^{-6} Gy/year (Kryshev, Kryshev A., 2003)

Reference species	Radio-nuclide	External dose from water	External dose from sediments	Internal dose	Sum
Shallow-water cisco	^{3}H	0	0	0.11	0.11
	^{40}K	0.038	0	242	242.038
	^{210}Pb	0	0	0.013	0.013
	^{210}Po	0	0	16.2 (324)	16.2 (324)
	^{232}Th	0.0036	0	3.7 (74)	3.704 (74)
	^{238}U	0.022	0	6 (120)	6.022 (120)
	Sum	0.066	0	268 (760)	268 (760)
Cisco	^{3}H	0	0	0.11	0.11
	^{40}K	0.036	71.4	253	324.436
	^{210}Pb	0	0	0.013	0.013
	^{210}Po	0	0	16.2 (324)	16.203 (324)
	^{232}Th	0.0033	108.6	3.6 (72)	112.2 (180.6)
	^{238}U	0.021	89.3	6 (120)	95.3 (209.3)
	Sum	*0.062*	*269.3*	*278.9 (769)*	*548 (1038)*
Pike	^{3}H	0	0	0.11	0.11
	^{40}K	0.036	31.4	253	284.4
	^{210}Pb	0	0	0.013	0.013
	^{210}Po	0	0	16.2 (324)	16.2 (324)
	^{232}Th	0.0036	48.6	3.6 (72)	52.204 (120.6)
	^{238}U	0.021	39.3	6 (120)	45.3 (159.3)
	Sum	*0.063*	*119.3*	*278.9 (769)*	*398 (888)*

Note. Assessments of exposure with w_r=20 for for α- radiation are given in brackets.

Table 4.4. Estimates of annual doses (mGy/year) to freshwater fish from natural sources of radiation in the Arctic and other regions

Source of radiation	Arctic	Other regions (Whicker, & Schultz, 1982)
Cosmic	0.24	0.19-0.24
Water	0.00006	0.00004-0.06
Sediments	0-0.27	0-3.2
Internal	0.28	0.32-0.42
Sum of natural sources	0.5-0.8	0.5-3.8

Table 4.5. Typical annual doses received by humans and terrestrial vertebrates from natural sources (Whicker & Schultz, 1982)

Source of irradiation	Dose rate, 10^{-5} Gy year^{-1}	% of total
External sources		
Cosmic rays	35	30
Terrestrial γ- rays	60	51
Internal sources		
^{40}K	19	16
^{14}C	1	1
^{226,228}Ra	1	1
^{3}H, ^{87}Rb, ^{210}Po, ^{220}Rn, ^{222}Rn, ^{238}U	1	1
Total	117	

5. THE EPIC DATABASE "RADIATION EFFECTS ON BIOTA"

5.1. Objectives and general information

The EPIC database on the effects of radiation exposure to natural biota has been created as a part of the EC EPIC project (Environmental Protection from Ionizing Contaminants in the Arctic).

The main objective of the database is to compile the available radiobiological information relating to northern organisms, determine the radiobiological endpoints, and construct dose-response relationships (EPIC project, 2001).

Early studies in radiobiology were concentrated on the determination of lethal dose values, i.e. acute doses, which lead to short term mortality of organisms. However, the radiation protection of the natural environment cannot be based on mortality as a sole endpoint of concern. Nevertheless, the effects of low-level radiation have never been analyzed on a systematic basis, and the EPIC database represents the first and unique collection of effects on natural biota at relatively low, non-lethal dose rates.

The dose-effects relationships based on the EPIC database information cover a very wide range of radiation dose rates to natural biota from 10^{-5} Gy d^{-1} up to more than 1 Gy d^{-1}. Great variety of radiation effects is registered in the EPIC database. These encompass effects from stimulation at low doses up to death from acute radiation syndrome at high doses.

Presently, the EPIC database contains information based exclusively on Russian/FSU experimental and field studies of the radiation effects on representative non-human organisms. Chronic/lifetime exposure is the focus of the work owing to the fact that this regime is the most typical in radiological assessments for biota. The following general restrictions were made in the selection of information for inclusion in the EPIC database: (i) from a great number of available publications on the effects of acute exposure, only effects of organism's exposure in the field conditions were included in the database; (ii) since the analyses of radiation effects on domestic animals and agricultural plants were outside the scope of the project, data on these organisms, as a rule, were not considered; (iii) taking into account the general orientation of the EPIC project towards Northern/Arctic organisms, data relating to warm-climate organisms, with few exceptions, were not included in the database.

The available Russian/FSU publications on chronic effects in biota are plentiful, they can be subdivided into two major categories: 1) laboratory experiments, and 2) field studies in the areas with high levels of radioactivity.

At present, the database “Radiation effects on biota” includes the descriptions of radiobiological effects observed in the areas of great radiation catastrophes and historical releases of radionuclides. Effects of high levels of natural radiation (Ra, U, Th) observed in natural ecosystems are also included in the database. Description of the levels of radioactivity in these areas is given in Supplement II. Besides, the database includes results of radiobiological experiments conducted in the laboratory conditions.

In spite of great number of publications, not every result was eligible for inclusion within the database. Two basic criteria were employed in selecting the information for inclusion into the EPIC database “Radiation effects on biota”. First of all, the source of information (publication) had to include information on the dose rates/dose to organisms, or at least, information about the activity concentrations in the environment and tissues of organism to enable dose assessment. The second criterion was the availability of statistical information, moreover whether the effect was statistically significant comparing with the control. As a rule, effects, which were not statistically reliable, were not included within the database. Exceptions were made only for some effects of a qualitative nature, and field observations in the early periods after radiation disasters.

Dosimetric data in the database records are given in two forms: (i) estimations of doses as they were published in the original publications, (ii) dose reconstructions were made, in some cases, by the authors of the database using data on levels of radioactive contamination in the organism/environment.

5.2. Structure of the EPIC database “Radiation effects on biota”

The EPIC database has been developed in the form of electronic EXCEL tables. Annexes A, B, C, D, E, F containing the database tables, are available in the accompanying CD. The EPIC database consists of the following parts:

- SUB-DATABASE “**Radiation effects on terrestrial organisms”,** see Annex A;
- SUB-DATABASE “**Radiation effects on aquatic organisms**”, see Annex B;
- SUB-DATABASE “**Radiation effects on terrestrial plants**”, see Annex C;
- SUB-DATABASE “**Radiation effects on soil fauna” ,** see Annex D**;**
- SUB-DATABASE “**Radiation effects on microorganisms,** see Annex E;
- SUB-DATABASE “**Lethal doses of acute radiation exposure** ”, see Annex F.

5.3. Biological species represented in the EPIC database

Among terrestrial animals, the most extensive studies were carried out on small mammals, such as mice, voles and other mouse-like rodents. These species have numerous populations, and they can be easily caught from wild populations. The lifespan of mice/voles is about 1-1.5 years, so the investigations can be carried out over many generations of organisms. Mice are territorial animals, and they do not accomplish any distant migrations from contaminated areas. Because of these features, mice are often favorite test subjects for radiobiological investigations in all areas with high levels of radioactivity. Radiobiological information on effects in mice is available for the Chernobyl 30-km zone, Kyshtym area, as well as for Komi radioactive sites.

Among terrestrial plants, the most extensive studies were carried out on pine; fewer data are available for spruce, birch, also some widespread herbaceous plants (dandelion, ribwort, etc.).

Among aquatic organisms, the most extensive radiobiological studies have been carried out with fish and fish eggs. For a long time, fish eggs were favorite test subject for investigation, because the development of fish embryos could be easily observed. However, fish eggs were found to be sensitive to any defects in artificial incubation (deficiency of oxygen, non-optimal temperature conditions, etc.); which may have led to a misinterpretation of radiation effects reported in early publications. The results of modern radiobiological experiments with fish eggs are more reliable, because the technique of incubation has considerably improved.

Long-term observations of radiobiological effects on fish have being carried out in the most contaminated lakes of the Kyshtym radioactive trace (Lakes Berdenish, Uruskul and others), and in the highly contaminated cooling pond of the Chernobyl NPP. In the laboratory experiments, the typical test organisms were small aquarium fish or young fish of different species, which could be maintained under laboratory conditions.

5.4. Types of radiobiological effects in the EPIC database

Following the suggestions of the FASSET project (FASSET, 2001; 2003), various radiobiological effects presented in the database, were divided formally into several umbrella endpoints. In the EPIC database the following umbrella endpoints were considered:

- Morbidity (worsening of physiological characteristics of organisms; effects on immune system, blood system, nervous system, etc.);
- Reproduction (negative changes in fertility and fecundity, resulting in reduced reproductive success);
- Mortality (shortening of lifetime as a result of combined effects on different organs and tissues of the organism);
- Cytogenetic effects;
- Ecological effects (changes in biodiversity, ecological successions, predator-prey relationships);
- Stimulation effects;
- Adaptation effects.

It should be noted, that the last three categories listed above are additions to those defined within the FASSET project. The classification of radiation effects by categories is discussed in the Chapter 2 of this report.
It should also be understood, that the defined categories are mutually dependent, i.e. effects on morbidity can lead to worsening of reproduction success, to early death, etc. In the EPIC database, the categories of effects are included in the column ”Effect code”.

5.5. Format of records in the EPIC database

The special format of the EPIC database has been developed to provide a possibility for analyzing the “dose-effect” relationships by mapping the calculated dose onto a given effect.

The EXCEL tables with the database "Radiation effects on biota" have a unified format, consisting of 12 vertical columns and horizontal rows. The following information is given in each record:

- Record identification number;
- Type of organism;
- Latin and English name of organism;
- Impact (experiment or field study with indication of investigated area);
- Nuclide (or nuclides);
- Activity of radionuclide in soil, Bq m^{-2} (in the terrestrial sub-database) or activity in water, Bq L^{-1} (in the aquatic sub-database);
- Activity in tissues of organism, Bq kg^{-1} ;
- Dose rate, Gy day^{-1} (whole body or critical organ);
- Dose, Gy accumulated during the course of experiment of field observation;
- Description of radiobiological effect;
- Code of effect (MT-mortality; REPR-reproduction; MB-morbidity; NE-no effect; AD-adaptation to radiation; STIM – stimulation; ECOL – ecological effect);
- Reference (source of information).

The information in the database is arranged in such a way, that one item of effect (one record in the database) corresponds to one case of exposure.

The identification number of a record consists of a letter and number, e.g. A15-1; T40-7, etc. Records beginning with letter "**A**", refer to aquatic database; "**T**"- terrestrial database; "**P**" – plants; "**S**"- soil fauna; "**M**"-microorganisms. Numbers next to the letter, identify the record number in the specific EPIC base, e.g. **A15** is the identification of the 15th record in the aquatic database.

In cases, where a publication includes a batch of similar experiments differing by the levels of radiation exposure, records are identified by the number of the main record and additional extension (using a hyphen and extension number). For example, record T40-7 refers to the 40th main record in the terrestrial database (consisting of a series of exposure experiments) wherein the given record refers to exposure number 7 from the series.

5.6. Contents of the EPIC database

In total, the EPIC database "Radiation effects on biota" contains about 1600 records from 435 papers and books.

5.6.1. Sub-database "Radiation effects on terrestrial animds"

At present, the sub-database "Radiation effects on terrestrial animals" (see Annex A in accompanying CD) includes 429 records from 114 publications. Effects on the following types of terrestrial organisms are represented in this sub-database:

- Mammals – 362 records;
- Birds – 20 records;
- Insects – 28 records;
- Amphibia and reptilia – 19 records.

In the sub-database "Radiation effects on terrestrial animals", the largest amount of data pertain to the radiation effects from the Chernobyl accident (52% of records); 26% of records refer to the area contaminated as a result of the Kyshtym accident; 10% refer to the areas of high natural radioactivity in the Komi AR in Russia; laboratory and other studies comprise 12% of the sub-database.

Representation of different categories of effects in the sub-database “Radiation effects on terrestrial animals” is given in Table 5.1.

5.6.2. Sub-database “Radiation effects on aquatic organisms”

At present, the EPIC sub-database “Radiation effects on aquatic organisms” (see Annex B in accompanying CD) includes 520 records from 122 publications. The effects on the following aquatic organisms are represented in this sub-database:

- Fish and fish eggs – 65% of records;
- Molluscs and other benthos - 22% of records;
- Plankton – 13% of records.

Most of the records in the aquatic database pertain to laboratory experiments – 74%; data from the Chernobyl zone comprise about 11% of records; data from the Kyshtym contaminated area represent about 15% of records.

Representation of different categories of effects in the sub-database “Radiation effects on aquatic organisms” is given in Table 5.1.

5.6.3. Sub-database “Radiation effects on terrestrial plants”

At present, the EPIC sub-database “Radiation effects on terrestrial plants” includes 252 records from 106 publications (see Annex C in accompanying CD). The effects on the following terrestrial plants are represented in the database:

- Coniferous plants – 42% of records;
- Deciduous plants - 8% of records;
- Herbaceous plants – 50% of records.

Only plants, which represent the natural flora of northern/temperate regions, are included in the EPIC database.

Representation of different categories of effects in the sub-database “Radiation effects on plants” is given in Table 5.1 .

5.6.4. Sub-database “Radiation effects on soil fauna”

At present, the EPIC sub-database “Radiation effects in soil fauna” (see Annex D in accompanying CD) includes 180 records from 53 publications. This part of the EPIC database represents the radiation effects on soil mezofauna, and some species of soil microfauna. From the records on radiation effects in soil fauna, experimental studies represent 57% of records, observations in the Kyshtym contaminated area – 11%; Komi – 22%, Chernobyl – 10% of records.

Statistical information on the percentages of records referring to different umbrella endpoints in the sub-database “Radiation effects on soil fauna” is given in Table 5.1.

5.6.5. Sub-database "Radiation effects on microorganisms"

EPIC sub-database "Radiation effects in microorganisms" (see Annex E in accompanying CD) includes 42 records from 15 publications. This part of the EPIC database represents the radiation effects on those microorganisms, which inhabit both soils and aquatic systems. In general, experiments pertaining to radiation exposure of microorganisms were numerous. However, typical doses of exposure in the experiments were very high, far above values, which can be expected in the natural environment. For this reason, only data from field studies, and experiments with chronic exposure from radioactive solutions were included in the database. In the EPIC sub-database "Radiation effects on microorganisms" 19% of records represent field studies; 81% - laboratory experiments.

5.6.6. Sub-database "Lethal doses of radiation exposure to organisms"

The EPIC collection "Lethal doses of radiation exposure to organisms" (see Annex F in accompanying CD) includes 198 records from 62 publications. This part of the EPIC database represents data on relative radiosensitivity of different organisms.

Table 5.1. Representation of records in the EPIC database by categories of effects.

Types of biota in the EPIC sub-databases	Number of records in sub-database	Proportion of records representing the specific type of radiation effects						
		MB	REPR	MT	CG	NE	ECOL	Others (STIM, ADAP)
Terrestrial animals	429	13%	9%	9%	23%	37%	7%	2%
Plants	252	37%	7%	7%	34%	5%	6%	4%
Aquatic organisms	520	5%	35%	17%	5%	31%	-	7%
Soil fauna	180	1%	7%	51%	-	21%	17%	3%
Micro-organisms	42	7%	2%	17%	45%	17%	2%	10%
Code of effects: MB – effects on morbidity; REPR - effects on reproduction; MT – mortality; CG -cytogenetic effects; NE -no effects on exposure; ECOL-ecological effects; STIM- stimulation; ADAP - adaptation.								

6. EFFECTS OF RADIATION ON TERRESTRIAL ANIMALS

The EPIC sub-database "Radiation effects on terrestrial animals" is given in the ANNEX A (available in the accompanying CD).

In selecting data for inclusion in the EPIC database, the general attention was concentrated on field radiobiological studies of wild populations inhabiting areas with enhanced levels of radioactivity. As a rule, experiments with radiation exposure of laboratory animals were not included in the database; the exceptions were made for some special effects, which is difficult to observe directly in the field conditions.

The most extensive and long-term field studies of radiation effects on wildlife have been carried out in the following territories of Russia/FSU: Kyshtym radioactive trace, local "spots" of enhanced natural radioactivity in the Komi Autonomic Republic; territories contaminated as a result of the Chernobyl accident (30-km zone around the Chernobyl NPP and, also the contaminated areas in Ukraine, Belarus and Russia). Description of these areas is given in Supplement II.

6.1. Effects on terrestrial animals in the Kyshtym radioactive trace (area contaminated with 90Sr in 1957; Southern Urals, Russia)

Radiation effects on animals inhabiting the territory of the Kyshtym radioactive trace are described in the records from T1 to T14; from T23 to T32; T43; T45; T47; T50; T62; T63; from T104 to T107 (EPIC database bibliography: Ilyenko, 1971; 1974; Ilyenko, Krapivko, 1989; Burnazyan, 1990; Lebedeva, 1994; Piastolova, 1996; Sokolov, 1993; Kryshev, 1996; Ilyin, 2001).

6.1.1. Acute radiation syndrome in the early period after the Kyshtym accident

In the early period after the Kyshtym accident (autumn of 1957), the fallouts in the head part of the radioactive trace were very high (over 30 MBq m^{-2}), and were composed from several radionuclides. The long-term contamination was dominated by ^{90}Sr, and at much lesser extent by ^{137}Cs. More detailed description of the Kyshtym accident is given in Supplement II.

At the head of the trace, cows had received 1.4-3 Gy from external exposure within a few days following the accident. In addition, the estimated doses to large intestine of these mammals were from 4 to 23 Gy. As a result of these high exposures, cows began to die within 9-12 days following the accident from acute radiation sickness (records T106-1; T106-2). Sheep, in this period, received about 1.4-3 Gy from external exposure, and from 8-15 increasing to 30-54 Gy to the large intestine. These sheep died within 9-12 days from acute radiation syndrome (records T107-1, T107-2).

In the less contaminated part of the radioactive trace, with fallout levels of 4.5 MBq m^{-2}, cows and sheep received about 0.13 Gy from external exposure and 1-4 Gy to their large intestine. These animals did not die, although negative changes in their blood were observed. Following evacuation from the contaminated area, cows and sheep gradually regained their normal activity (records T106-3; T107-3).

In autumn of 1957 and also in 1958, a decrease in the numbers of elks and roe deer was observed in the Kyshtym radioactive trace at contamination levels of 3.7-37 MBq m^{-2}. Estimated dose rates to ungulates in autumn of 1957 were 0.1-1 Gy d^{-1} (also 10-30 Gy to intestines), see record T105-1. In the Spring of 1958, a decrease in numbers of wintering birds by a factor of 10 was observed in the most contaminated parts of the Kyshtym radioactive trace. In the subsequent years, the populations of wild animals gradually recovered due to the cessation of anthropogenic activity in the contaminated area and decay of shorter-lived radionuclides. Some animals probably migrated from the neighboring non-contaminated territories (T104-2; T105-2).

6.1.2. Long-term studies of radiation effects in mice-like rodents in the Kyshtym radioactive trace

Systematic observations of mouse-like rodents in the contaminated area started a few years after the accident, when the acute period had elapsed. For this reason, radiobiological effects produced by exposure doses in the "acute" period have been estimated on the basis of published information on the radiosensitivity of mammals and correlating these data with actual doses calculated for this period (Ilyenko, 1974). Based on dose reconstruction, it was concluded that in the autumn-winter period of 1957-1958, all species of mammals and birds had received lethal doses at a contamination density of 37 MBq^{90}Sr m^{-2} (1000 Ci^{90}Sr/km^2), and over. In the subsequent years, the numbers of forming populations in these areas were regained, probably following migration of animals from the neighboring non-contaminated areas.

Studies on mice in the Kyshtym contaminated area were carried out on a systematic basis for about 40 years. After the Chernobyl accident, field studies on mice were carried out in the Chernobyl zone, using the same methodology of radiobiological analyses.

The mice species studied were European wood mice *Apodemus sylvaticus*, short-tailed vole *Microtus agrestis*, northern red-baked mice *Clethrionomys rutilus*, and some others. Results of many-years investigations were published in numerous papers (see EPIC database bibliography: Ilyenko, 1967,1971, 1974; Krapivko, 1986; Ilyenko, Krapivko, 1983, 1988, 1989).

Radiobiological effects were studied in the highly contaminated "head" parts of the Kyshtym radioactive trace. Mice were caught from wild populations in spring, summer and autumn periods year-by-year; these mice were studied in the laboratory. The following parameters were studied: concentrations of ^{90}Sr in the body, morphometric and physiological parameters, blood, reproduction, infestation with parasites; duration of life and duration of reproduction period; radioresistance to test exposure; some ecological parameters, such as size of the individual feeding plots, etc.

Records from T1 to T14, from T23 to T32, and T63 (with sub-records) shows the radiation effects observed in about 50-60 generations of mice living in the area contaminated with ^{90}Sr.

In the early 1960s, dose rates to mice were about 0.06 Gy d^{-1} ; activities of ^{90}Sr in bones were up to 5x10^7 Bq kg^{-1} . At these dose levels, life shortening was observed (records T23, T24, T25); decrease in size of feeding plots (record T8); anomalous growth of upper teeth was revealed in 16% of analyzed adult voles, which prevented animals from normal feeding (record T6). However, osteosarcomas were not found in wild mice populations, possibly reflecting the short lifetime of animals (record T7).

In mid-1960s, dose rates to mice were about (1-3)x10^{-2} Gy d^{-1}. At these and higher exposure levels, negative changes in blood (chronic radiation sickness) were observed, high infestation with parasites, shortening of reproduction period and general shortening of life time (records T3, T4, T5, T8, T29, T30). With respect to reproduction, radiation effects were partially masked by compensatory increases in fertility of the mice, which was natural reaction of mice species to the decrease in population density (records T2, T26, T27, T28, T31). In the later periods, dose rates about (1-3)x10^{-2} Gy d^{-1} were persistent only in local area with the highest levels of contamination. In the neighboring less contaminated parts of the radioactive trace, dose rates to mice gradually decreased to a few mGy d^{-1}.

In the 1970s and early 1980s, some experiments were conducted to test the radio-adaptations of mice to the conditions of chronic low level radiation exposure following many generations of mice living in the contaminated area. Probing acute exposure by superlethal doses (8-11 Gy) of mice from the Kyshtym area revealed an increased radioresistance of these mice: field-exposed mice died at later periods compared with the control animals, and some mice survived over the 30-day period of observation. Experiments with progeny from exposed parent mice also demonstrated the increased radioresistance of progeny (records T9, T10, T11).

Among physiological changes, which were interpreted as adaptations to radiation, hypooxigenia was observed. In essence, chronically exposed mice from Kyshtym consumed less of oxygen from the breathing air; and the level of oxygen consumption was inversely correlated with the level contamination (record T12). As a result of such adaptation, mice from the Kyshtym area survived in respiration chambers at much lower atmospheric pressures compared with control mice (record T15). Moreover, in tests entitled "capacity for swimming", exposed mice could swim longer time compared with the control (Ilyenko, Krapivko, 1989). Average body temperatures of exposed mice were found reproducibly higher (36.8 ^{0}C) when compared with control mice temperature (36.1 ^{0}C), see record T13. Breathing rates of exposed mice were also higher than normal (record T14).

In 1990s, a survey was carried out to investigate the current health status of wild mice living in the most contaminated "head" part of the Kyshtym radioactive trace. In 1990s, dose rates to wild mice in this local area were estimated to be about 1.1×10^{-2} Gy d^{-1}. Negative changes in blood characteristic for chronic radiation sickness were found in 50-60% of mice analysed; also shortening of lifetime, and shortening of reproductive periods were revealed (record T29). However, numbers of progeny per female did not differ from normal, and pre-implantation deaths of embryos were lower than those in the control (records T29, T30, T31, T32).

6.1.3. Radiation effects on birds in the Kyshtym radioactive trace

Studies on birds in the Kyshtym contaminated area were not as systematic as studies on mice. The EPIC collection contains two records, T43 and T45, describing the reproduction of birds in the contaminated area (see EPIC database bibliography: Ilyenko, 1971;Lebedeva, 1994; Ryabtsev, Lebedeva, 1999). The reproduction of birds was studied in the 1990s, using man-made nests distributed in the contaminated area (5.6×10^{7} Bq m^{-2} of ^{90}Sr in soil). Reproduction of flycatchers in man-made nests was unsuccessful – from 30 nests only 6 were occupied with one baby-bird developed, and even this baby-bird died at the age 11-12 days (in the control reproduction success was about 92%).

6.1.4. Radiation effects on frogs and lizards in the Kyshtym radioactive trace

The EPIC collection contains some field studies (in 1990s) of radiation effects in brown frog *Rana arvalis* and viviparous lizard *Lacerta vivipara* (see EPIC database bibliography: Piastolova, 1996; Semenov et al., 1999); Ivanova, Semenov, 1993).

The following effects were revealed in brown frogs inhabiting place near Lake Berdenish (5.6×10^{7} Bq m^{-2} of ^{90}Sr in soil): the sizes of frog's eggs were smaller than those in the control, total numbers of eggs laid by one female were close to the control numbers; forelarvae developed from only 10% of eggs (low reproductive success); among young frogs about 17% had morphological abnormalities (records T62-1, T62-2, T62-3). Young frogs in the contaminated area developed more rapidly compared with the control. However, adult frogs were smaller than normal size.

Specimens of viviparous lizard were caught in 1992-1995 at different places within the Kyshtym radioactive trace $(3.7\text{-}18.5) \times 10^{7}$ Bq m^{2} of ^{90}Sr in soil). From 43 specimens analyzed, sterile lizards were not found, although one specimen was hermaphrodite; from 42 embryos, 26.6% had morphological abnormalities (in normal conditions not more than 2.1%); see records T47-1, T47-2.

6.1.5. Insects in the Kyshtym area

The EPIC collection includes results from field studies on insect populations in the very contaminated local area near Metlino and Lezhnevka. Considerable decrease in biodiversity of flies was observed in the contaminated area. From 31 species typical for local ecological conditions, only 9 species were found (control plot – 29species). Absent were fly species, which are normally developed in ooze and near-water vegetation (record T50).

6.2. Radiation effects on terrestrial animals in the local areas with high natural radioactivity (Komi AR, Russia)

Effects of elevated levels of natural radioactivity on terrestrial animals were studied for many years in several local areas in Komi AR (Russia) characterized by enhanced concentrations of ^{226}Ra, ^{238}U, ^{232}Th, ^{210}Po, and other natural radioisotopes. Studies of radiation effects on natural fauna began in 1950s, and investigations have continued, for many years, up to the present time. The EPIC collection includes the results of long-term, complex and time-consuming investigations of animals living in these areas, see records from T17 to T22, and from T55 to T61 (with sub-records). The results were published in many papers, mainly in Russian (see EPIC database bibliography: Verhovskaya et al., 1965; Maslov et al., 1967; Maslov, Maslova, 1972; Maslov, 1972; Maslova, Verhovskaya, 1976; Maslova, 1980; Materij, Maslova, 1977, 1978; and many others).

6.2.1.Tundra voles

As usual in field radiobiological studies, the most extensive investigations were made on small mice-like rodents. The main objects for the studies were tundra voles *Microtus oeconomus*.

In the local areas with the highest levels of radioactivity, the external radiation background was about 8000 μR h^{-1} (80 μGy h^{-1}), concentrations of ^{226}Ra in soil were up to 70 kBq kg^{-1}. Estimated doses from external and internal exposure were about 350 mGy y^{-1}, in addition the animals were exposed to radon in their burrows. The chemical toxicity of heavy natural radioisotopes also contributed to the health effects in mice.

The following radiation effects on the morbidity of mice were observed:

- Changes in blood, indicated chronic radiation sickness (records T19,T55, T56, T57, T58);
- High (up to 100%) levels of infestation with parasites (record T21);
- Many low-fat (thin) animals in populations (record T22);
- Low weight of liver in young mice, abnormalities in liver of adult mice (record T18).

In the radioactive areas, serious problems with the reproduction of voles were revealed:

- Sexual maturity of many young males of voles was inhibited up to 9 months of age (control: maturity at 1-3 months of age; lifespan 1-1.5 years);
- Numbers of females involved in reproduction and numbers of embryos per female were about two times lower than those in the control (records T17, T20).

Vole populations were supported by migrations of healthy animals from neighboring areas. Numbers of recent migrants were found to be about 30% of the population; after 1 month, newcomers became as highly contaminated as residential animals (record T17).

6.2.2.Otters

Field studies on the health status of otters, *Lutra lutra*, living along the river in thorium-contaminated area (northern taiga of the Komi AR) have been carried out over several years. These studies started with long-term identifications of places permanently inhabited by otters, detection of their paths, living habits, radioactivity levels in living places, etc. Observations of otters in wild populations are very complicated and time-consuming, since the otters do not form compact populations. These animals are very careful and live in difficult-to-access places. The numbers of otters in the thorium-contaminated area were found to be about 33% lower than those associated with the control (record T59-4): 27 otters were identified as permanently inhabiting a 127 km stretch of the river in the thorium-contaminated area compared to 21 otters inhabiting a 67 km stretch of riverside in the control. The average weight of otter in the thorium-contaminated area was lower than that in the control (7.4 and 8.3 kg respectively, summer period); see record T58-1. Detailed recordings (on a whole-day-round basis) of otter's swimmings habits, revealed that otters from the thorium-contaminated area spent shorter periods in water (record T59-2). Consequently, the amount of food hunted was smaller compared with the control animals in the neighboring area with normal radiation conditions. The possible explanation of this effect was violation of thermoregulation in otters. To check the conditions of hair cover, detailed measurements of hair density were made in 4 otters. For one male from four animals, the hair density on the belly was about 2 times lower compared with the control. Hair cover on the backs and sides of animals did not differ statistically from the control (record T59-3).

6.2.3.Birds

Studies on the health status of grouse birds in the thorium-contaminated area (northern taiga of the Komi AR, radiation background about 1000 μR h^{-1}, or 10 μGy h^{-1}) were carried out over several years. Wild populations of great grouse *Tetrao urogalis*, black grouse *Lyrurus tetrix*, hazel grouse T*etrastes bonasia* and white grouse *Lagopus lagopus* were studied. The densities of bird populations were studied by direct counting for several years in both the thorium-contaminated and the control areas. Measurements of radionuclide concentrations in the hunted birds were made on a systematic basis. The populations of large grouse birds (great grouse and black grouse) within the thorium-contaminated area were found to be smaller than those associated with the control: numbers of great grouse per km^2 were by 13-25% lower, and black grouse by 14-35% lower than the control densities (record T60-3). Average weights of large grouse birds in the thorium-contaminated area were lower compared with the control (record T60-1), and exposed birds were more heavily infested with feather parasites and endoparasites (record T60-2). Populations of smaller grouse birds (hazel grouse and white grouse) in the thorium-contaminated area were found to be in better health: weight of birds did not differ statistically from the control T61-1); increased infestation with parasites was revealed in hazel grouse, but not in white grouse (record T61-2). The population density of white grouse in the thorium-contaminated area did not differ statistically from the control, whereas the population density of hazel grouse was by 12-14% lower compared with the control values (records T61-3, T61-4).

6.3. Radiation effects on terrestrial animals in the areas contaminated by the Chernobyl accident

The Chernobyl accident is among the most serious radiation accidents in the history of nuclear power engineering in terms of both the quantity of the released activity, and the extent of contaminated land.

Large amounts of data on radiation effects in wild animals have been collected in the areas of Ukraine, Belarus and Russia contaminated in 1986 as a result of the Chernobyl radiation accident. In the EPIC sub-database on radiation effects in terrestrial animals, the following records are concern with the radiobiological consequences of the Chernobyl accident: T15, T16, T39, T40, T42, T44, T48, T49, T52, T53, T54, from T70 to T131. The results were published in numerous papers and books (see EPIC database bibliography: Taskaev, 1988; Zaynullin, 1988; Kozubov & Taskaev, 1990; Sokolov et al., 1990; Kryshev et al., 1991,1992; Atlas, 1994; Eliseeva et al., 1994; Kryshev & Sazykina, 1995, 1998; Kudyasheva, 1997; Ryabtsev & Lebedeva, 1999; Ilyin, 2001; Voitovich, 2002, and many others).

6.3.1 .Mouse-type rodent populations in the Chernobyl zone

In the areas affected by the Chernobyl accident, the pathways of rodent's exposure included: external irradiation from radionuclides deposited on soil and vegetation; alpha- and beta-irradiation of animals from radionuclides adsorbed on skin hair, and internal irradiation from incorporated radionuclides. Population-averaged doses at different observational sites were primarily estimated based on the external irradiation from the soil.

Several mice species were studied, which differed by their habitat and feeding habits: house mice *Mus musculus*, striped field mice *Apodemis agraris*, common vole *Microtus arvalis*, root vole(or tundra vole) *Microtus oeconomus*, common red-baked vole *Clethrionomus glareolus*, and some others.

The studies of mice populations within the 30-km zone of the Chernobyl NPP have shown a significant reduction in the number of animals in 1986 in the most of the contaminated areas. During the early period following the accident, the monthly absorbed doses reached 22 Gy for gamma irradiation and 860 Gy for beta irradiation in the areas within a few km to the west of the reactor's buildings (Testov & Taskaev, 1990). High doses caused an increase in deaths of animals by autumn of 1986. In the subsequent period, the number of rodents increased due to migration from adjacent, uncontaminated territories.

In the Autumn of 1986, despite high exposure levels, breeding of rodents was observed at practically all sites, although reproduction was ceased by mid-October. The mice reproduction was accompanied by a considerable embryonic mortality, only 67% of the potential numbers of animals were born in the affected areas as compared to 94% in the controls. In the Spring of 1987, the birth rate varied within the range of 62-91% in the experimental plots and 83-92% in the controls. The numbers of live embryos were lower in the plots with higher levels of radioactive contamination.

The studies of mice populations revealed some ecological differences between mice species. Survival preferences were associated with some species, which either feed on less contaminated food items (root voles), and/or live in sheltered places (e.g. house mice). These species (root vole, house mice) demonstrated considerable increases in numbers after the

Chernobyl accident (record T80), due to evacuation of people from the area, and abandonment of agricultural plants in fields.

The mouse-type rodents from the experimental plots, in the vicinity of the Chernobyl NPP, had morphological abnormalities in blood and liver, which resembled radiation sickness by a number of symptoms. Some of the animals had indications of liver cirrhosis and disorders in compensation-regeneration processes (Materij, 1990). Biochemical changes in metabolism were also detected, e.g. increased peroxide oxidation of lipids in tissues of wild rodents (Shishkina et al., 1990). The reported effects suggested that the health status of animals in the area exposed to the radioactive contamination was rather unstable.

In the first period after the Chernobyl accident, the peculiarities of radiation effects were probably associated with some specific radionuclides, e.g. heavy damage to liver found in many animals was characteristic for ^{144}Ce, damage to thyroid – characteristic for ^{131}I, etc.

In subsequent years, the radiation effects on wild mice populations were typical for animals living in contaminated areas: negative changes in blood, infestation with parasites, cytogenetic effects (records T39, T48, T49, T53, T54). Nevertheless, mice populations practically recovered within 2-3 years after the Chernobyl accident.

6.3.2.Effects in other terrestrial animals

Studies of radiation effects in other animals in the Chernobyl zone were not conducted in a systematic manner. In 1986, analyses of pathological changes in organs of animals hunted or that had died were carried out. In dogs, pigs, cows pathological changes in liver, kidney lungs and spleen were found (records T94, T95). All these animals had close contact with contaminated land, and picked up food from the land. Birds such as geese, ducks, pigeons, crows also had pathological effects associated with liver (T96-3). Analyses of such animals as red squirrel, coypu, and different species of forest birds did not reveal pathology in organs, probably because these animals had access to less contaminated food (records T92, T93, T96-1, T96-2).

The evacuation of human population from the 30-km zone of Chernobyl was in general favorable for wildlife. Despite the elevated levels of radiation contamination, populations of many species increased in numbers in the Chernobyl "reserve". The relatively large feeding areas used by large animals and birds probably reduced the actual exposure of animals in the non-uniformly contaminated Chernobyl zone.

By the Autumn of 1986, cows maintained in the most contaminated area during 2-4 months (doses to thyroid of up to 800 Gy have been estimated) showed signs of depression, impaired challenge-response, vascular disorders, and some of these animals died. Other groups of animals, which received lower doses (30-200 Gy to thyroid) showed a decline in thyroid function, and low levels of thyroid hormones. A similar decline in thyroid hormones was observed in sheep and horses in the Chernobyl Zone, and also in the Gomel and Bryansk regions (Kryshev, Ed., 1992).

Some radiobiological investigations were made with insects. In vinegar flies, which are a favourite subject for cytogenetic studies, increased levels of lethal mutations were observed in 1986-1987. In subsequent years, the differences with the control were insignificant (records T108-T109 with sub-records). In 1986, in the early period after the accident, within the 5-km zone of the NPP, the numbers of aphids decreased considerably, and some common species even vanished (record T98). For Colorado beetles, leaf beetles, and dragonflies, an increase in fluctuating asymmetry in morphometric structures was detected (records T100, T101). Cessation of agricultural activity caused some ecological changes in the insect populations: in the fields an increase of bush crickets and grasshoppers was reported, indicative of processes of pertaining to flouristic succession from agrocenosis to meadow.

6.4. Dose-effects relationships for terrestrial animals

Analyzing the information in the EPIC sub-database "Radiation effects on terrestrial animals", the selection of records was performed using the umbrella endpoints at different ranges of dose rates. The results of categorization based on the umbrella endpoints are given in Table 6.1. More detailed analysis of effects observed at different levels of chronic or acute radiation exposure made it possible to construct a preliminary scheme of dose –effects relationships for terrestrial animals of northern climatic zone (Sazykina, Kryshev, 2003). These dose-effects relationships are summarized in Table 6.2.

Table 6.1. Categorisation of records in the EPIC database “ Radiation effects on terrestrial animals” by the umbrella endpoints at different ranges of dose rates

RADIATION EFFECTS ON TERRESTRIAL ANIMALS (EPIC DATABASE)	
Range of dose rates : 10^{-5}-10^{-4} Gy d^{-1}	
Effects on morbidity	?55, ?56, ?64-3, ?64-4, ?64-5, ?65, ? 66, ?70-1
Cytogenetic effects	? -57, ? -58, ?70-2, ?108-3, ? 109-3, ?122-4, ? 122-5, ?122-6, ?123-4, ? 123-6, ?124-4, ? 124-5, ?124-6, ?125-3, ?126-3, ?131-6, ?131-7, ? 131-8
No effects on exposure	? 81-1, ? 81-2, ? 81-3, ? 81-4, ? 81-5, ? 82-6, ? 83-1, ? 83-2, ? 84-1, ? 84-2, ? 84-3, ? 84-4, ? 84-5, ? 84-6, ? 85-1, ? 85-2, ? 85-3, ? 85-4, ? 87-11, ? 88-12, ? 89-15, ? 90-13, ? 108-10, ? 108-11, ? 108-12, ? 108-13, ? 123-5
Other effects	? 41(stim), ? 82-1(ecol),? 82-2(ecol), ? 82-3(ecol),? 82-4(ecol), ? 82-5(ecol)
Range of dose rates : 10^{-4}-10^{-3} Gy d^{-1}	
Morbidity	? 42-1, ? 42-2, ? 46, ? 48, ? 49, ? 59-1, ? 59-2, ? 59-3, ? 60-1, ? 60-2, ? 61-2, ? 61-4
Reproduction	? 45
Cytogenetic effects	? 53, ? 122-3, ? 123-1, ? 123-2, ? 123-3, ? 124-2, ? 124-3, ? 131-1, ? 131-2, ? 131-3, ? 131-4, ? 131-5
Mortality	? 1, ? 59-4, ? 60-3
No effects on exposure	? 61-1, ? 61-3, ? 79-1, ? 79-4, ? 79-5, ? 80-5NE, ? 113-2, ? 113-6, ? 114-5, ? 114-5
Other effects	? 15(adapt), ? 59-4(ecol), ? 60-3(ecol), ? 79-2(ecol), ? 79-3, ? 80-1(ecol), ? 80-2(ecol), ? 80-3(ecol), ? 80-4(ecol), ? 80-5(ecol)
Range of dose rates : 10^{-3}-10^{-2} Gy d^{-1}	
Effects on morbidity	? 18, ? 19, ? 21, ? 22, ? 39-3, ? 39-4, ? 43, ? 51, ? 62-4, ? 94, ? -100, ? 101
Reproduction	? 2, ? 3, ? 17, ? 20, ? 28, ? 44, ? 47-1, ? 47-2, ? 62-1, ? 62-2, ? 62-3, ? 62-4, ? 77-5, ? 78-5, ? 86-1, ? 86-2, ? 86-3, ? 86-4, ? 87-10, ? 88-1, ? 88-5, ? 88-8, ? 88-11, ? 89-3, ? 89-4, ? 89-5, ? 89-6, ? 89-9, ? 90-9, ? 91-1, ? 91-2, ? 93-1
Cytogenetic effects	? 52, ? 69-1, ? 69-2, ? 69-3, ? 98, ? 108-2, ? 108-4, ? 108-5, ? 109-2, ? 113-5, ? 114-4, ? 122-1, ? 122-2, ? 124-1, ? 124-2, ? 125-2, ? 126-2, ? 126-4, ? 128-1, ? 129-1
Mortality	? 63, ? 78-3, ? 78-4, ? 130-1, ? 130-2, ? 130-3
No effects on exposure	? 74-1, ? 74-2, ? 74-4, ? 75-1, ? 75-3, ? 75-4, ? 77-1, ? 77-2, ? 77-3, ? 77-4, ? 78-1, ? 78-2, ? 87-9, ? 88-4, ? 88-6, ? 88-7, ? 88-9, ? 89-1, ? 89-2, ? 89-7, ? 89-13, ? 89-14, ? 90-2, ? 90-3, ? 90-6, ? 90-7, ? 90-11, ? 90-12, ? 91-4, ? 92-1, ? 92-2, ? 93, ? 96-1, ? 104-2, ? 108-8, ? 109-7, ? -109-8, ? 109-9, ? 110-6, ? 110-7, ? 113-1, ? 114-2, ? 116-2, ? 119-6, ? 119-7, ? 119-8, ? 120-7, ? 120-8, ? 120-9, ? 121-2, ? 125-1, ? 126-1, ? 127-1
Other effects	? 12(adapt), ? 13(adapt), ? 14(adapt), ? 62-3(ecol), ? 74-3(ecol), ? 74-5(ecol), ? 75-2(ecol),? 86-5(ecol), ? 102(ecol), ? 103-1, ? 103-2, ? 105-2(ecol), ? 105-3(ecol)
Range of dose rates : 10^{-2}-10^{-1} Gy d^{-1}	
Effects on morbidity	? 4, ? 5, ? 6, ? 8, ? 16-1, ? 16-2,? 16-3, ? 16-4, ? 29, ? 35, ? 39-1, ? 39-2, ? 64-1,? 64-2, ? 95-1, ? 95-2, ? 96-3, ? 106-3, ? 107-3

Reproduction	? 26, ? 27, ? 30, ? 31, ? 40, ? 68-3, ? 72-5, ? 76-3, ? 87-2, ? 87-4, ? 87-5, ? 89-8, ? 89-10, ? 90-1, ? 90-4, ? 90-5, ? 90-8, ? 90-10, ? 115, ? 120-14, ? 120-13, ? 120-15
Cytogenetic effects	? 67, ? 68-1, ? 68-2, ? 108-1, ? 108-6, ? 110-4, ? 111-1, ? 112, ? 113-3, ? 114-3, ? 115, ? 116-1, ? 116-3, ? 116-5, ? 118, ? 119-1, ? 119-2, ? 119-4, ? 119-9, ? 119-10, ? 120-1, ? 120-2, ? 120-3, ? 120-4, ? 120-5, ? 120-10, ? 120-11, ? 121-3, ? 121-4, ? 121-10, ? 121-11, ? 121-12, ? 121-13, ? 126-5, ? 126-6, ? 128-2, ? 128-3, ? 129-2, ? 129-3
Mortality	? 9, ? 10, ? 11, ? 23, ? 24, ? 25, ? 32, ? 34, ? 50 (+EC) ? 72-6, ? 76-1, ? 76-2, ? 76-4
No effects on exposure	? 7, ? 72-3, ? 72-7, ? 72-8, ? 76-5, ? 87-1, ? 87-3, ? 87-6, ? 87-7, ? 87-8, ? 88-2, ? 88-3, ? 88-10, ? 89-11, ? 89-12, ? 96-2, ? 108-7, ? 108-9, ? 109-4, ? 109-5, ? 109-6, ? 110-5, ? 11-2, ? 113-4, ? 116-4, ? 116-6, ? 116-7, ? 117-1, ? 117-2, ? 117-3, ? 117-4, ? 117-5, ? 117-6, ? 117-7, ? 119-3, ? 119-5, ? 119-11, ? 119-12, ? 119-13, ? 119-14, ? 119-15, ? 119-16, ? 119-17, ? 119-18, ? 119-19, ? 119-20, ? 120-6, ? 120-12, ? 120-16, ? 120-17, ? 120-18, ? 120-19, ? 120-20, ? 120-21, ? 121-1, ? 121-5, ? 121-6, ? 121-7, ? 121-8, ? 121-9, ? 127-2, ? 127-3
Range of dose rates : >0.1 Gy d^{-1}	
Effects on morbidity	T54
Cytogenetic effects	T110-1, T110-2, T114-1, T125-4
Mortality	T33, T36, T37, T38, T71-1, T71-2, T71-3, T73-1, T73-4, T73-5, T106-2, T107-2
No effects on exposure	T71-4, T71-5, T73-2, T73-3, T73-6, T110-3

Table 6.2. The relationships between the dose rates of chronic radiation exposure and effects of radiation on terrestrial animals (based on the EPIC sub-database "Radiation effects on terrestrial animals", Annex A)

Dose rates of chronic radiation exposure	Radiation effects on terrestrial animals	Examples of effects in the database, see Annex A
$10^{-5} – 10^{-4}$ Gy d^{-1}	Recovery of populations after acute accidental exposure After-effects on progeny born from exposed parents Some negative changes in blood (α exposure) Some increase in chromosome aberrations in cells	T80; T83-1;T64-(4-5); T65; T66; T55;T56;T57, T58; T122-4
$10^{-4} – 10^{-3}$ Gy d^{-1}	Some negative changes in blood (α,β exposure) After-effects on progeny born from exposed parents (doses to parents >1Gy) Increase in chromosome aberrations in cells	T55; T56;T1; T64-(3-5); T65; T66; T53; T122-4; T123; T125-(2-3); T126-(2-3)
$10^{-3} – 10^{-2}$ Gy d^{-1}	Pathology in liver, kidney (radionuclide specific) Considerable decrease of reproduction potential (α+γ exposure), shortening of reproduction period Some mice species show compensatory increase of reproduction (physiological response to the decrease in population density) Some life shortening, also higher risk to be captured by predators Weakening of immune system, increase of infestation with parasites, increase of various infections (α,β,γ exposure) Negative changes in blood, chronic radiation disease (α,β,γ exposure) Cytogenetic effects, increase of embryonic losses	T94;T17;T3; T2; T74-4; T59-1; T63; T130; T22; T21;T48; T49; T18; T19;T20;T55; T56; T57; T58; T69-1; T88-11; T89-(2-6); T89-9;T89-13; T110-2; T113-7; T114-4; T122-1;T123-1;T126-4
$10^{-2} – 10^{-1}$ Gy d^{-1}	Sterility, decrease of gonad's mass Strong infestation with parasites Osteosarcomes (^{90}Sr), anomalous teeth Pathology in liver, kidney (radionuclide specific) Life shortening Negative changes in blood, chronic radiation sickness (α,β,γ exposure) After-effects in progeny born from exposed parents Decrease in some populations, replacement of some populations by those species, which received lower doses, or by more	T115; T118; T120; T4;T35; T6; T95; T23,T24;T25;T34;T29; T39; T106-3; T4;T64;T65; T8; 72; T73-1; T76-1;T86;T86-5; T27; T67; T68-1; T88; T89; T90-1; T110; T111-1; T112; T113-3;T114; T116; T119;T121; T125-4;T126-(5-6); T128

	radioresistant species Cytogenetic effects, increase of embryonic losses	
10^{-1} – 1 Gy d^{-1}	Acute radiation sickness Death of many organisms, decrease of populations	T16-1; T16-2; T106-1; T106-2; T107; T71; T73; T105
> 1 Gy d^{-1}	Acute radiation sickness Lethal dose received within several days	

7. EFFECTS OF RADIATION ON AQUATIC ORGANISMS

The EPIC sub-database "Radiation effects on aquatic organisms" is given in the ANNEX B (available in the accompanying CD).

7.1. Effects of ionizing radiation on fish

Fish are known to be the most radiosensitive among poikilothermic aquatic animals. In general, radiation effects in fish are similar to the effects reported for warm-blooded vertebrate animals. At the individual organism' level, the following groups of effects are important for the survival of populations: weakening of immunity, decrease of reproduction, increased number of abnormalities, and life shortening.

The information collated in the EPIC database on radiation effects in fish falls into two major categories: 1) results of laboratory experiments under controlled conditions; and 2) observations of effects in fish populations, inhabiting natural water bodies contaminated with radionuclides.

Laboratory radiobiological experiments with fish

The most extensive laboratory studies of the various effects of chronic radiation exposure on fish were conducted by Prof. I. Shekhanova and her colleagues at the Institute of Fishery and Oceanography (VNIRO, Russia). In these experiments fish were kept in aquariums, containing dissolved radionuclide (^{90}Sr). The effects of chronic irradiation were studied on various parameters of metabolism, immunity, development, and reproduction. In some experiments the radiobiological effects were observed during the whole lifespan of aquarium fish (more than two years). The dose rates of radiation exposure to fish were measured with special thermoluminescent dosimeters, also calculations of absorbed dose rates were performed with detailed consideration of radionuclide distribution within organism, as well as exposure of organs from neighboring tissues. The EPIC database contains an extraction of these results; the detailed description of experiments and results is given in the book by Shekhanova (1983).

Observations of radiation effects in fish from contaminated water bodies

For many years, radioecological studies of fish from natural water bodies contaminated with radionuclides were carried out in the Southern Urals, Russia (Muntyan, 1977; Peshkov et al., 1978; Voronina et al., 1974, 1977, 1978; Fetisov, 1995; Smagin, 1996). Some water bodies in this area were contaminated by radioactive waste releases from the "Mayak" nuclear materials production complex in the early period of its operation (1949 - late 1950s); these are the Techa River, Lake Metlino, Lake Karachai, water reservoir N.10 and some others (Kryshev et al., 1997, 1998). As a result of a radiation accident at "Mayak" complex in 1957 (Kyshtym accident), about 30 lakes in the Southern Urals were contaminated (Kryshev et al., 1997). The most contaminated lakes, such as Berdenish, Uruskul and some others were removed from all economic use. The EPIC database provides a collection of results of radioecological surveys of these lakes, which have been carried out in different periods after the initial impact.

A number of radiobiological studies of fish have been carried out on the water bodies impacted by the Chernobyl radiation accident in 1986. The cooling pond of the Chernobyl NPP, located in close proximity to the destroyed reactor, was heavily contaminated as a result of the Chernobyl accident. Long-term studies had been carried out with fish, which survived in the cooling pond after the radiation accident, as well as fish born in the subsequent years (see the EPIC database bibliography: Belova et al., 1993; Makeeva et al., 1994; BIOMOVS II, 1996). These results are summarized in the EPIC sub-database "Radiation effects on aquatic organisms.

7.1.1.Radiation effects on fish morbidity

Effects of chronic radiation on morbidity of aquatic animals include the deterioration of various physiological and metabolic characteristics, which lead to a decline in health and well-being of the organisms. They represent early signs of the reduced fitness of organisms. The following specific effects can be identified as effects on the morbidity of fish (effect code – "MB"):

- negative changes in blood composition;
- weakening and delay in immune response to bacterial/viral infection;
- weakening of the resistance to parasite infestation;
- negative changes in functioning of organs and tissues, etc.

Records A1, A2, A3, A4, A7, A8, A9, A10, A62, A65, A66 (including sub-records) represent the experiments, demonstrating radiation effects on fish immunity.

Radiobiological experiments were performed to test the changes in various parameters of fish immunity: the blood composition (records A65-1; A65-2; A66-1; A66-2), dynamics of phagocytic activity of leucocytes (records A1-1; A1-2; A1-3; A1-4, A2-1; A2-2; A2-3; A2-4), immune response on experimental infection of fish with bacteria (records A3, A4). Experiments were performed with carp, *Cyprinus carpio,* grown in aquariums with dissolved ^{90}Sr at concentrations $5\text{x}10^{-8}$ Ci L^{-1} ($1.85\text{x}10^{3}$ Bq L^{-1}) and 10^{-6} Ci L^{-1}($3.7\text{x}10^{4}$ Bq L^{-1}). The doses to the kidney of carp in the experiments were within the range from $2\text{x}10^{-4}$ Gy to 2.8 Gy. Results of experiments with increased radiation exposure demonstrated a gradual weakening of the immune system associated with the lymph: leucocyte concentrations and their phagocytic activity decreased with dose; immune response delayed and weakened (Shleifer & Shekhanova 1977, 1980; Shekhanova et al., 1978; Shekhanova, 1983). Early signs of such effects were detected at chronic dose rates of about 1 mGy d^{-1} and accumulated doses above 0.05-0.2 Gy. It is interesting that at lower levels of exposure, the effects in lymph had a phase character. For instance, in the experiments with carp (see record A1-4) the phagocytic activity of leucocytes in fish blood was found to recover in 180 days of exposure in ^{90}Sr solution containing $5\text{x}10^{-8}$ Ci L^{-1} (accumulated dose to kidney 0.2 Gy). At dose rates of 7-12 mGy d^{-1} and accumulated doses of 2.5-3 Gy the effects on fish immunity were clearly distinct (Shekhanova, 1983).

In the natural conditions, the effects of radiation on fish immunity manifest themselves by an increased percentage of organisms in the population infested with parasites, and subjected to various infections. Usually these effects are not linked with the radiation exposure. The development of morbid effects can result in more serious consequences, such as loss of competitive capacity, early mortality, etc.

7.1.2. Negative biochemical changes in organs and tissues

Records A7, A8, A9 present some results of biochemical studies of radiation effects in gonads, liver, and muscles of fish at low doses of exposure. The experiment with carp specimens (record A9), which were kept during one year in (1-2)$\text{x}10^{3}$ Bq L^{-1} ^{90}Sr solution (with resulting doses to liver and muscles of about 1 and 0.5 Gy, respectively) revealed elevated concentrations of lipidoperoxides in liver and muscles of exposed fish (Storozhuk & Shekhanova, 1977; Shekhanova, 1983). Lipidoperoxides are toxic chemical agents (radiotoxins) caused by ionization in living matter. Increased concentrations of lipidoperoxides lead to violation of cell membranes, and inhibit some metabolic processes in liver and muscles. The generation of radiotoxins in biological tissues as a result of radiation exposure is a well-known phenomenon in radiobiology, and effects in fish did not differ from those in other animals (Bacq & Alexander, 1966; Kuzin, 1986).

Records A7, A8 shows the early signs of weakening in gonad' function in loach males, which were kept in aquariums with enhanced concentrations of ^{90}Sr (Shekhanova et al.,1969; Shekhanova, 1983). At doses of 0.5 Gy received over 90 days, glycogen concentrations in the gonads became close to zero, and normal gonadal tissues began to be displaced by fat. The fattening of gonads as a result of low functional activity has been observed in radiobiological experiments with animals (Turner, 1975; Moskalev, 1991).

Records A10, A62 describe a dysfunction of eyes in exposed fish. Pathological deterioration of eyesight in small fish was observed at doses to eyes above 1.5-2 Gy from ^{90}Sr accumulated in head bones (Nilov et al.,1976; Shekhanova, 1983).

7.1.3. Radiation effects on fish fertility/fecundity

This endpoint includes effects on the fertility and fecundity of organisms. The effects on reproduction manifest the damage to the vital system of organisms; these effects can be observed at some higher levels of radiation exposure than initial morbidity effects.

The following specific effects can be identified as effects on the reproductive success of aquatic organisms (effect code – "REPR"):

- increased number of abnormalities and mortality in developing embryos of fish;
- morphological and functional abnormalities in gonads;
- sterility;
- teratogenic effects; and,
- decrease in the production of healthy progeny by irradiated organisms.

Records A11, A12, A13, A14, A15, A16, A22-A28, A60, A61 (including sub-records) represent the experiments and observations, demonstrating radiation effects on reproduction of fish. These records refer to lifetime experimental studies or long-term observations of fish in natural water bodies highly contaminated with radionuclides.

Records A60-1, A60-2, A60-3, A61-1, A61-2, A61-3 show the results of lifetime reproduction of fish Tilapia (*Tilapia mossambica*), which lived their entire life in aquariums with ^{90}Sr solutions that ranged from 3.7 up to 3.7×10^{4} Bq L^{-1}. These experiments demonstrate considerable changes in the reproduction of fish with the increase of radiation exposure: at dose rates below $(4\text{-}5)\times10^{-6}$ Gy day^{-1} reproduction was normal; at $(4\text{-}5)\times10^{-4}$ Gy day^{-1} the overall production of normal larvae was 80% of the control despite some increase in the number of eggs produced; at 3×10^{-2} Gy day^{-1} the reproduction was completely suppressed – all males were sterile, 80% of females had abnormalities in ovaries, and on experimental impregnation with normal males the produced larvae died within 5 months (Voronina, 1973,1974; Shekhanova, 1983).

Records A11, A12, A13, A14, A15, A16, A17, A18 refer to studies of natural fish populations (goldfish, roach) dwelling in highly contaminated water bodies of the Southern Urals, Russia (studies of 1970s, 15-20 years from the period of acute contamination. See the EPIC database bibliography: Ermokhin, Muntian, 1977; Peshkov et al., 1978; Voronina et al., 1977; Muntian, 1977). In the experimental catches, the percentages of adult fish specimens with morphological abnormalities were higher than in the control. Abnormalities in gonads (including unpaired gonads and sterility) were heavier and more common than those in the control. In the water reservoir with the highest radiation exposure of fish (record A11), the estimated fertility of roach was about 2 times lower than that in the control, with delays in spawning of approximately 2 weeks compared with the control. Dose rates to fish in the contaminated water bodies in 1970s were within the range 2-8 mGy d^{-1}. Despite the increased number of abnormalities in gonads, the growth and nutritional state of fish are normal in each of the contaminated lakes.

Radiation-induced damage was studied in the gonads of silver carp *Hypophthalmichthys molitrix,* which survived in the Chernobyl NPPs' cooling pond after the accident of 1986, and in the subsequent generations of silver carp (records A22, A23, A24, a25, A26, A27, A28). The silver carp were grown in fishing cribs in warm waters of the cooling pond for commercial purposes. At the time of the radiation accident the fish specimens were 1-2 years old. Estimated accumulated doses to fish by 1989 were about 4.5 Gy; whole-body dose rates decreased from about 8-9 mGy d^{-1} in the early period after the accident (1986) to about 0.4 mGy d^{-1} in 1989-1992 (Belova et al., 1993; Kryshev et al., 1996; Kryshev, 1998; Kryshev et al., 1999).

Over the period 1989-1992, 7.1% of specimens were sterile from 70 silver carp examined, 35% of females and 48% of males showed gonad abnormalities (Belova et al., 1993; Makeeva et al., 1994; quoted in the UNSCEAR report, 1996). In the control, populations of silver carp very rarely exhibited sterility (less than 0.25%).

Some of the best specimens of exposed silver carp from the cooling pond were used in 1989-1990 for producing offspring; the young fish were kept also in the contaminated cooling pond (Makeeva et al., 1994). Abnormalities in the fish born from exposed parents were examined in 1992 (records A27, A28). From the offspring born in 1989 (3 years old in 1992), about 14% specimens had significant gonad deformities, including 2.8% sterile bisexual specimens. In addition, about 15% of the specimens had other morphological abnormalities (abnormal body shape, etc.). In total, the offspring from exposed parents had a considerable number of abnormalities in their reproductive systems.

In summarizing the information on the effects of chronic radiation on the reproductive organs of fish, a conclusion can be made that obvious morphological and functional effects in reproductive systems were observed at dose rates above 2-5 mGy d^{-1} of chronic exposure. Furthermore, minor biochemical changes can be revealed, already, at dose rates around 0.5 mGy d^{-1}. However, even in highly contaminated water bodies, exposed fish are able to produce sufficient numbers of offspring to maintain natural fish populations.

7.1.4. Radiation effects on mortality/life shortening of fish

Effects of chronic radiation on fish mortality and life shortening are presented in the records A13, A63, A64, A67 (including sub-records).

At low doses, an increase in mortality cannot be observed directly, but mortality usually manifests itself in the form of a reduction in age-dependent survival. The effect of life shortening may be a cumulative result of effects on morbidity, as well as abnormalities in reproduction, and cytogenetic damages. Thus, a slight life shortening may occur at relatively low dose rates of chronic exposure, and may have a greater effect on long-lived than on short-lived organisms.

In laboratory experiments, life shortening can be revealed from a comparison between the average lifetime of the control and exposed fish. Records A63-1, A63-2, A63-3 show the results of unique whole-life experiments with aquarium fish *Tilapia mossambica.* Specimens of *Tilapia* were kept in solutions of ^{90}Sr during the whole life cycle from birth up to natural death. Observations were made for up to 800 days. Survivals at the end of experiment were: 71% of control fish, 54% of fish from aquariums with ^{90}Sr activity 3.7×10^2 Bq L^{-1} (dose rate 0.4 mGy d^{-1}), and only 33% of fish from aquariums with ^{90}Sr concentration 3.7×10^4 Bq L^{-1}(dose rate 30 mGy d^{-1}). These experiments demonstrate that the average lifetime of exposed fish was noticeably shorter, than that of the control specimens (Orlov, 1973,1974; Shekhanova, 1983).

Records A64-1, A64-2 demonstrate the mortality of exposed fish specimens following an experimental infection with parasites (pre-exposure before infection for 180 days). At dose rates of about 0.4 mGy d^{-1} only a slight increase in mortality was observed; at dose rate of 30 mGy d^{-1} the mortality of exposed fish from infection was 2-4 times higher than that in the control (Orlov, 1973,1974). This experiment is supplementary to the studies on the immune response of exposed fish (see records A1, A2, A3, A4 with sub-records), and shows the final result of weakening of the immune system, i.e. increased mortality from infections.

Under natural conditions, the changes in the age structure of exposed population can be observed, in terms of a decrease in the number of some age groups of organisms (see record A13). Experimental catches (1973-1975) of goldfish *Carassius auratus gibelio* from two contaminated Ural lakes Uruskul and Berdenish, revealed that there were no specimens older than 8 years, specimens of 4-6 years of age dominated in the spawning shoals. The absence of older age groups is not typical for goldfish, especially taking into account that there was no fishery in these lakes since 1957 (Voronina E.A. et al., 1977). Estimated highest dose rates to goldfish in the year of the Kyshtym accident (1957) were approximately 30-40 mGy d^{-1}. During the periods of experimental catches (1972-1975), dose rates to goldfish were 3-5 mGy d^{-1} in Lake Uruskul, and about 0.5 mGy d^{-1} in Lake Berdenish (NCRP, 1991; Kryshev et al., 1997; Kryshev, 2002).

Radiation exposure of parent fish leads to increased mortality of offspring: the example of such effect is described in the records A67-1, A67-2. A population of pike was dwelling for many years in a water reservoir impacted by the releases of liquid radioactive solutions from the radiochemical plant at PA “Mayak” in the Southern Urals, Russia. Offsprings of pike were obtained by artificial incubation of roe, and samples of 1000 forelarvae were analyzed. Dose rates to the gonads of parent pike were estimated to be about 7 mGy d^{-1} (Smagin, 1996). The percentage of common abnormalities (spinal curvature) was about 20% both in the control and experiment; however, for the control most of these abnormalities were caused by transportation of roe from the distant lake to the fish-farming plant. The number of specific abnormalities was 1.1% in control (absence of yolk sac), and 8.3% in experimental forelarvae (absence of eyes, absence of yolk sac, body depigmentation, combinations of various deformities). Forelarvae with abnormalities of development died within the first month of life, i.e. were cut off by natural selection.

The early death of weak fore-larvae decreases the competition amongst the remaining specimens, which, in turn, is favorable for their growth and survival (compensatory effect on population level); as a result, the pike population in the highly contaminated water body is maintained for many years, and nutritional state of fish is normal, see record A67-3 (Smagin, 1996).

7.2. Dose-effect relationships for fish in the EPIC database

The results of chronic experiments and observations, compiled in the EPIC database and discussed in the previous sections, provide a possibility to develop a preliminary scale of dose-effects relationships for fish from northern and temperate climatic zones. The approximate threshold levels of chronic exposure above which specific types of effects can be detected are the following:

- dose rates of 0.5-1 mGy d^{-1} with accumulated doses above 0.05-0.2 Gy are threshold levels for the appearance of the first negative changes in fish blood, and early signs of decrease in immune system. At lower dose rates (less than 0.5 mGy d^{-1}), the organisms seemingly are able to adapt provisionally to radiation with gradual restoration of normal health parameters;
- dose rates of 2-5 mGy d^{-1} with accumulated doses above 1.5 Gy are threshold levels for appearance of negative effects on the reproductive system;
- chronic dose rates of 5-10 mGy d^{-1} and higher over the lifetime of the organism lead to life shortening of adult fish.

With an increase of radiation exposure, several types of effects can be found in one organism.

7.3. Effects of ionizing radiation on fish eggs

The EPIC database includes 262 records describing the effects of ionizing radiation on the survival and development of fish eggs. In the radiobiological studies of aquatic organisms, fish eggs are a favorite subject for experimental work because of easy availability of embryos and the possibility of observing the development of embryos within eggs. Radiobiological experiments with fish eggs can be divided into two main categories: a) incubation of roe in water containing radionuclide or mixtures of radionuclides at different concentrations; b) external exposure of roe (mainly acute exposure), using gamma-sources.

Investigations of radiation effects on fish embryos developed in radioactive solutions were performed mainly with radionuclides of ^{90}Sr and ^{137}Cs (Pitkyanen, 1971,1978; Neustroev, 1966; Fedorov, 1962; Kulikov, 1968,1975; Kasatkina, 1973; Timofeeva, 1964, 1970, 1971; Pitkyanen, Shvedov, 1971; Pechkurenkov, 1978; Shekhanova, 1983). Some of these experiments were made with the roe from parent fish dwelling in the water bodies contaminated with these radionuclides. Few experiments were performed with other radionuclides, such as ^{60}Co, ^{54}Mn, ^{144}Ce, ^{14}C, mixture of fission products, etc. (Lyapin et al., 1971; Mashneva, Sukalskaya 1973; Kasatkina, 1973; Fedorova, 1974). The ranges of radionuclide activities in incubation solutions varied in different experiments within very wide ranges from a few Bq L^{-1} up to about 10^7 Bq L^{-1}.

In the experiments with external exposure, fish eggs were subjected to acute gamma-exposure at particular stages of the embryo's development (see the EPICdatabase bibliography:

Gorodilov, 1974; Kulikov, 1970, 1975; Alshitz, 1970). In different experiments, the moment of acute exposure varied from the first minutes of embryo's development till the last days before hatching. Doses of acute gamma-exposure of fish eggs were within the range 0.25 – 12 Gy.

Typically, the following parameters were observed and analyzed as effects of ionizing radiation: increased death of embryos; amount of abnormalities in embryos and fore-larvae; survival of fore-larvae; time of hutching; chromosomal aberrations; development of blood cells; primary sex cells in embryos; changes in blood, organs and tissues of fore-larvae.
The radiobiological studies with fish eggs, despite the simplicity of experimental technique, provide some difficulties to researches due to a high variability and low reproducibility of results especially at low doses of radiation. Eggs of many fish species are not easily incubated under laboratory conditions, being sensitive to variations in temperature above optimal values, deficiency in oxygen, mechanical disturbances and other factors, which themselves may cause considerable increases in mortality/abnormalities of embryos. The summation of effects of incubation with effects of radiation exposure resulted in considerable variability between replications of one and the same experiment. Also, the natural qualities of eggs obtained from artificial impregnation of fish may vary considerably, providing additional variations in the survival of embryos (Shekhanova, 1983).

Techniques associated with radiobiological experiments on fish eggs have improved considerably since the time of early studies. Thus, more recent results are more reliable than those obtained in late 1950s-early 1960s. The early views (Polikarpov, 1966; Fedorov, 1964), that the fish eggs are extremely sensitive to radiation exposure were not, in general, supported by later experiments (Blaylock & Trabalka, 1978; Shekhanova, 1983; Woodhead, 1984).

Roe of several fish species typical in Russian water bodies (northern/temperate climatic zones) was used in radiobiological experiments. Among fish species, the roe of pike *Exos lucius* has been a favourite test subject for radiobiological studies (116 records in the EPIC database). Pike are very wide-spread in water bodies of the northern/temperate climatic zones, so its roe is easily available. The development of pike roe takes only 8-10 days. The roe is easily incubated under laboratory conditions.

In the EPIC database, special attention was given to radiobiological studies of roe of cold-water fish species: salmon *Salmo salar*, rainbow trout *Salmo irideus*, peled *Coregonus peled* (40 records in the EPIC database). The eggs of northern/Arctic fish develop very slowly (several months) at very low temperatures. The experiments with cold-water fish roe are much more time-consuming comparing with those with short-developed eggs of fish from temperate/warm climatic zones.

Among other fish species, experiments were conducted with roe of tench *Tinca tinca* (75 records in the EPIC database), loach *Misgurnus fossilis* (21 records), also with roe of roach *Rutilus* rutilus, perch *Perca fluviatilis*, bream *Blicca bjorkna*, bleak *Alburnus alburnus*, goldfish *Carassius carassius*, and silver carp *Hypophtlmichthys molitrix*.

7.4. Dose-effects relationships for fish eggs in the EPIC database

The threshold concentrations of radionuclides, at which negative effects on development and survival of fish eggs were revealed, are the following:
^{60}Co, ^{54}Mn – (1-10)x10^{4} Bq L^{-1} (records A37-2; A37-3; A38-2);
^{14}C – (7.4-74)x10^{4} Bq L^{-1} (records A43; A44);

^{144}Ce - 5.2×10^{3} Bq L^{-1} (records A41-2; A41-6; A41-8);
^{137}Cs - 1.9×10^{4} Bq L^{-1} (records A42-2; A42-4; A42-6; A42-8);
^{90}Sr – $(3.7\text{-}370)\times10^{4}$ Bq L^{-1} (records A118-3).

In many publications dealing with the incubation of fish eggs in radioactive solutions, doses to eggs were not estimated, so the authors of the EPIC database made preliminary dose estimations using appropriate dosimetric methodologies (IAEA, 1976, 1979; Kryshev, Sazykina 1990; Kryshev et al., 2002).

7.4.1. Dose-effects relationships for roe of cold-water fish (Salmonidae, Coregonus spp.)

Records A36, A37, A39, A40, A41, A42, A56, A57, A58 represent the results of radiobiological experiments with roe of cold-water fish (see the EPIC database bibliography: Lyapin et al., 1971; Neustroev, 1966; Fedorov, 1964; Gorodilov, 1971; Mashneva, Sukalskaya, 1973; Kasatkina, 1973, Shekhanova, 1983).

Roe of cold-water fish, such as Salmonidae, Coregonus species are potentially vulnerable to the presence of radioactive substances in aquatic media. Development of roe of these species takes several months, whereas warm-water fish eggs are developed within a few days. So, at the same level of environmental contamination, doses accumulated by fish eggs in the Arctic are considerably higher than those for fish with short-time development.

Salmon and other cold-water fish species are known to be among the most radiosensitive species dwelling within water bodies in temperate/northern climatic zones.

The preliminary scale of radiation effects in developing eggs of cold-water fish based on the EPIC database collection is given in Table 7.1.

Table 7.1. Dose-effects relationships for developing roe of cold-water fish

Exposure	Effects
Chronic exposure from radionuclide in aquatic media during the whole period of fish eggs development	
Chronic 5×10^{-8} Gy d^{-1}	Slight stimulation of salmon's eggs development (record A36)
Chronic < 10^{-4} Gy d^{-1}	Effects are insignificant (records A38-3;A38-6)
Chronic $(1\text{-}2)\times10^{-4}$ Gy d^{-1}	First effects appeared: some cytogenetic changes in blood of fore-larvae (records A38-2; A41-2; A41-4; A41-6; A41-8; A41-10); some slight decrease in survival of embryos (records A42-2; A42-4; A42-6; A42-8)
Chronic $(1\text{-}5)\times10^{-3}$ Gy d^{-1}	Decrease in survival of eggs, appearance of dead and abnormal embryos, in some cases damaged were 30-50% of eggs (records A38-1; A38-4; A41-1; A41-3; A41-5; A41-9; A42-1; A42-3)
Chronic 3×10^{-2} Gy d^{-1} Chronic 0.13-0.33 Gy d^{-1}	Considerable decrease in survival of roe, mortality about 50% (record A37-2) Practically total death of roe (records A37-1, A37-4)
Acute external gamma exposure during fish eggs development	
Acute exposure 3Gy	LD_{50} for salmon eggs exposed at the initial period of development (record A56-1)
Acute exposure 5Gy	Practically 100% mortality of salmon eggs exposed at the initial period of development (record A57-1; A58-1)

7.4.2. Dose-effects relationships for roe of pike

Records A34, A35, A49, A51, A67, A80, A89, A90, A91, A105, A106, A107, A108, A115, A116, A118, A119, A120 (with sub-records) represent the results of radiobiological experiments with roe of pike.

Pike eggs are rather radioresistant among other fish species – pike is known to survive even in highly contaminated water bodies. Pike eggs are developed within 8-10 days.

The scale of dose-effects relationships for pike eggs, based on the EPIC database, is presented in Table 7.2.

Table 7.2. Dose-effects relationships for developing roe of pike

Exposure	Effects
Chronic exposure from radionuclide in aquatic media during the whole period of fish eggs development	
Chronic >3x10^{-4} Gy d^{-1}	Increase in cytogenetic effects appeared (records A118-3; A49-2; A119-3; A119-4; A119-5; A120-4; A120-5)
Chronic 5x10^{-3} Gy d^{-1}	Some decrease in the time of embryo's development – hutching occurred earlier comparing with the control (eggs from non-exposed fish (record A34). Eggs obtained from exposed parent fish had increased number of abnormalities (A67-1; A67-2)
Chronic 3x10^{-2} Gy d^{-1}	Increase of chromosomal aberrations – bridges and fragments (records A118-4; A119-4; A120-4)
Chronic 0.3-0.47 Gy d^{-1}	Decrease of survival of pike eggs and fore-larvae (records A35-2; A51-2; A116-5; A118-5; A119-5; A120-5)
Chronic 0.94 Gy d^{-1}	Total death of pike roe (records A35-3; A51-3)
Acute external gamma exposure during fish eggs development	
Acute exposure 2Gy	Survival decreased by 30%; considerable amount of embryos had abnormalities (records A107-4; A108-4)
Acute exposure 4Gy	Practically 100% mortality of pike eggs exposed at the initial period of development (record A107-5)

Data on dose–effects relationships for salmon and pike roe define the differences in radiosensitivity between sensitive and relatively radioresistant fish species. Available information from the EPIC collection shows that the radiosensitivities of roe from other fish species lie somewhere between the sensitivities of salmon and pike.

7.5. Radiation effects in molluscs

Records A20, A50, A55, A72, A73, A83, A84, A96, A97, A98, A99, A100, A101, A102, A103, A104, A111, A112 (with sub-records) represent the results of radiobiological experiments on molluscs.

In the EPIC collection, the radiation effects in molluscs are represented mainly by experiments with the mollusc pond snail, *Limnea stagnalis*. This mollusc is very common in freshwater ecosystems on northern/temperate climatic zone. Field studies of the effects of chronic irradiation of pond snails were carried out in the Ural area in experimental ponds, and lakes contaminated with ^{90}Sr, ^{137}Cs and other radionuclides (see the EPIC database bibliography: Famelis, 1973; Kulikov, 1970, 1975; Marey, 1976; Fetisov, 1993).

Considerable numbers of records refer to the effects of acute exposure on molluscs or mollusc's eggs (Kulikov, Famelis, 1970; Kulikov, 1975).

The summary of dose-effects relationships for mollusc *Limnea stagnalis* is given in Table 7.3.

Table 7.3. Dose-effects relationships for mollusc *Limnea stagnalis*

Exposure	Effects
Chronic exposure from radionuclide in aquatic media	
Chronic whole-life exposure for several generations $1.7x10^{-2}$ Gy d^{-1}	Decrease in mollusc's size (record A84); Increase in radioresistance to probing acute exposure (record A83-1, A83-2; A83-3; A83-4)
About 10^{-2} Gy d^{-1} from a mixture of fission products	In the experimental pond molluscs died during few months
Exposure of mollusc's eggs 2.1 Gy d^{-1}	Decrease of mollusc's eggs survival, increase of abnormalities (record A111-6)
Acute external gamma exposure during mollusc's eggs development	
Acute exposure 3Gy	Some decrease in survival, large variations depending on the time of exposure (record A96-1)
Acute exposure 6Gy	About 50% embryos died (record A72-1)
Acute exposure 12-15 Gy	Total death of mollusc's eggs (record A101-6)

7.6. Effects of ionizing radiation on zooplankton

Records A53, A54, A59, A71, A75, A76 (with sub-records) represent the results of radiobiological experiments with zooplankton (see the EPIC database bibliography: Onanko, 1973; Raziulute, 1973; Telitchenko, 1958; Stroganov, 1959).

Zooplankton is known to be rather sensitive to chemical toxicants, and biological tests with zooplankton are often used in the aquatic toxicology. In radiobiology, however, zooplankton is shown to be more radioresistant than, for example, fish.

Radiation effects in zooplankton were studied either under conditions of acute external exposure of zooplankton in experimental flasks, or by keeping zooplankton in solutions of radionuclides (^{90}Sr, ^{106}Ru, ^{238}U, ^{232}Th, and others).

The following characteristics of zooplankton were observed in radiobiological experiments: mortality of animals, fertility rate, pubescence and molting intervals. The most common species of zooplankton used in experiments is Daphnia. It should be noted however, that zooplankton species have considerable variability in radiosensitivities.

The threshold concentrations of radionuclides in aquatic media, at which radiation effects can be revealed, are the following:

^{90}Sr – $3x10^{4}$ Bq L^{-1};
^{106}Ru – $1.9x10^{8}$ Bq L^{-1};
^{238}U 0.05 mg L^{-1} or 0.6 Bq L^{-1};
^{232}Th 0.005 mg L^{-1} or 0.02 Bq L^{-1}.

The summary of dose-effects relationships for zooplankton is given in Table 7.4.

Table 7.4. Dose-effects relationships for zooplankton

Exposure	Effects
Chronic exposure from radionuclide in aquatic media	
5.5×10^{-6} Gy d^{-1} (^{232}Th solution, 0.005 mg L^{-1})	Slight decrease of litter per one female Daphnia (A75-24)
3.7×10^{-5} Gy d^{-1} (^{238}U solution, 0.6 mg L^{-1}) 5.5×10^{-4} Gy d^{-1} (^{232}Th solution, 0.5 mg L^{-1})	Some decrease of litter per one female Daphnia (record A75-12) Decrease of fertility rate and litter per one female Daphnia, longer periods between moltings, increase of pubescence intervals (records A75-13; A75-14; A75-15; A75-16)
7.4×10^{-4} Gy d^{-1} (^{238}U solution, 1 mg L^{-1}) 2×10^{-3} Gy d^{-1} (^{90}Sr solution)	Decrease of fertility rate and litter per one female Daphnia, longer periods between moltings, increase of pubescence intervals (records A75-1; A75-2; A75-3; A75-4) Weak compensatory stimulation of reproduction (record A76-12)
2×10^{-2} Gy d^{-1}(^{90}Sr solution)	Some decrease in fertility, increase of pubescence interval (records A76-5; A76-7; A76-8)
3.3 Gy d^{-1}(^{106}Ru solution)	Decrease in Daphnia survival (record A59-2)
Acute external gamma exposure of zooplankton	
Acute exposure 2Gy	Some decrease in survival of Daphnia (record A53)
Acute exposure 20Gy	In a community of 6 Cladocera species compensatory increase of fecundity was observed (record A54)
Acute exposure 200 Gy	Number of species in zooplankton community decreased from 9 to 3 (record A71-3)

7.7. Radiation effects in phytoplankton and bacterioplankton

Records A68, A69, A70 (with sub-records) represent the results of radiobiological experiments with phyto-, and bacterio-plankton (Raziulute, 1973). Also, data on microorganisms are collected in the sub-database on microorganisms.

In general, unicellular microorganisms are among relatively radioresistant species, however, the variations in radiosensitivity between different species are very large. External exposure of the phytoplankton community with doses within the range 100-40000 Gy revealed that some species may be depressed at doses of approximately 100-400 Gy, whereas other species can survive even at very high doses (records A69, A70). Exposures of bacterioplankton at doses 400-40000 Gy resulted in stimulation of bacterioplankton (record A68).

It can be concluded that in aquatic ecosystems, unicellular microorganisms are not vulnerable compared with phylogenetically more complex organisms. Even in case of 90% mortality of microorganisms, the remaining 10% of cells can recover the whole population within a few hours or days. The sensitivity of microorganisms is associated mainly with concentrations of toxic chemicals (products of water radiolysis, radiotoxins) in the media. In aquatic ecosystems, the concentrations of radiotoxins are not high because of dilution and reactions with dissolved organic matter.

7.8. Summary of dose-effects relationships for aquatic organisms.

Table 7.5 provides an overwiew of radiation effects on aquatic organisms, from the EPIC database, categorized by umbrella effect endpoint and dose rates/doses of radiation exposure. Furthermore, Table 7.6 relates dose rates/doses to radiation effects.

Table 7.5. Selection of records in the EPIC sub-database " Radiation effects on aquatic animals" by the umbrella endpoints at different ranges of dose rates

RADIATION EFFECTS ON AQUATIC ANIMALS (EPIC DATABASE)	
Range of dose rates : 10^{-6}-10^{-5} Gy d^{-1} (chronic)	
Reproduction	A61-1, A78-1, A79-6
Cytogenetic effects	A77
Mortality	A39-1, A39-2
No effects on exposure	A38-3, A38-6, A43-2, A60-1, A79-1, A79-2, A79-11, A79-16, A111-1, A112-1, A113-1, A113-2, A114-1, A114-2, A115-1, A116-1, A118-1, A119-1, A120-1
Other effects	A32 (STIM), A36 (STIM)
Range of dose rates : 10^{-5}-10^{-4} Gy d^{-1}(chronic)	
Effects on morbidity	A1-2, A66-1,
Reproduction	A75-12, A75-20, A75-24, A78-1
Cytogenetic effects	A77
No effects on exposure	A1-1, A65-1, A75-18, A75-22, A76-17, A76-19, A76-20, A113-3, A114-3, A115-2, A116-2, A118-2,
Other effects	A5-1(STIM), A75-9(STIM), A75-10(STIM), A75-11(STIM), A75-17(STIM), A75-19(STIM), A75-21(STIM), A75-23(STIM), A76-18(STIM)
Range of dose rates : 10^{-4}-10^{-3} Gy d^{-1}(chronic)	
Morbidity	A1-3, A5-3, A41-4, A86-3, A87-6,
Reproduction	A12, A16, A22, A23, A24, A25, A26, A27, A28, A52, A60-2, A61-2, A75-1, A75-2, A75-3, A75-4, A75-8, A75-13, A75-14, A75-15, A75-16, A78-2, A79-7
Cytogenetic effects	A41-6, A41-8, A41-10, A87-4, A87-5, A118-3, A119-2
Mortality	A38-2, A41-2, A44, A63-1, A64-2
No effects on exposure	A5-2, A17, A18, A19, A37-3, A38-5, A45, A46, A76-13, A76-14, A76-16, A79-12, A79-17, A82, A86-1, A86-2, A87-1, A87-2, A87-3, A111-2, A112-2, A113-3, A115-3, A116-3, A120-2,
Other effects	A1-4(ADAP), A75-5(STIM), A75-6(STIM), A75-5(STIM), A75-7, A76-15 (STIM)
Range of dose rates : 10^{-3}-10^{-2} Gy d^{-1}(chronic)	
Effects on morbidity	A2-1, A2-2, A3, A9, A41-3, A42-2, A65-2, A66-2, A84
Reproduction	A7, A14, A33, A67-1, A78-3
Cytogenetic effects	A41-5, A41-7, A41-9, A42-4, A42-6, A42-8, A80, A119-3
Mortality	A13, A20, A21, A38-1, A41-1, A43-1
No effects on exposure	A67-2, A67-3, A76-9, A76-10, A76-11, A79-3, A79-13, A81, A85-1, A85-2, A88, A111-3, A112-3, A120-3
Other effects	A6-1 (STIM), A34 (STIM), A76-12 (STIM), A83-1(ADAPT), A83-2(AD), A83-3(ADAPT), A83-4(ADAPT), A115-4(STIM)

Range of dose rates : 10^{-2}-10^{-1} Gy d^{-1}(chronic)	
Effects on morbidity	A2-3, A2-4, A4, A6-3, A10, A42-1, A62-1
Reproduction	A8, A11, A15, A60-3, A61-3, A76-5, A76-7, A76-8, A79-8
Cytogenetic effects	A42-3, A42-5, A42-7, A49-2, A118-4, A119-4, A120-4
Mortality	A37-2, A37-5, A38-4, A51-2, A63-2, A64-1
No effects on exposure	A6-2, A47, A48, A49-1, A51-1, A59-1, A76-6, A79-4, A79-19, A111-4, A112-4, A113-5, A116-4, A117
Other effects	A115-4 (STIM)
Range of dose rates : 0,1-0,5 Gy d^{-1}	
Reproduction	A31, A76-(1-1), A108-2, A116-5
Cytogenetic effects	A118-5, A119-5, A120-5
Mortality	A35-2, A51-2, A50-1
No effects on exposure	A99-1, 100-1, A101-1, A102-1, A103-1, A104-1, A106-1, A107-2, A108-1, A109-1, A109-2, A110-1, A111-5, A115-5
Others	A105-1 (STIM), A105-2 (STIM), A107-1(STIM)
Range of dose rates : 0,5-1 Gy d^{-1}	
Reproduction	A51-3, A108-3, A75-24, A78-1
Mortality	A35-3, A30
No effects on exposure	A105-3, A106-2, A107-3, A109-3, A110-3
Range of dose rates: 1-5 Gy d^{-1} (acute)	
Reproduction	A53, A89-(1-20), A90-(1-19), A91-(1-19), A92-(1-13), A93-(1-13), A94-(1-13), A95-(1-14), A96-(1-14), A97-(1-14), A98-(1-14), A99-3, A100-2, A100-3, A105-(4-5), A106-5, A107-(4-5), A108-4, A109-5, A110-4, A111-6, A111-7, A112-6, A112-7
Mortality	A40-2, A50-2, A56-1, A57-1, A58-(1-2), A74-2, A89-(1-20), A90, A92, A93, A94, A98, A100-(2-3), A50-2
No effects on exposure	A99-2, A101-2, A101-3, A102-(2-3), A103-(2-3), A104-(2-3), A106-(3-4), A109-4
Range of dose rates: 5-10 Gy (acute)	
Reproduction	A55-1, A73-1, A99-1, A100-4, A105-6, A107-6, A109-6
Mortality	A56-2, A57-1, A57-2, A58-(1-2), A72-(1-5), A74-1, A57, A58; A99-3
No effects on exposure	A101-4, A102-4, A103-4, A104-4
Range of dose rates: 10-20 Gy (acute)	
Mortality	A55-2, A54, A73-2, A99-5, A100-5, A101-5, A101-6, A102-5, A103-6, A104-6, A109-7
No effects on exposure	A103-5, A104-5
Range of dose rates: 20-50 Gy (acute)	
Reproduction	A99-6, A101-7, A103-7, A111-8
Range of dose rates: 100-200 Gy (acute)	
Mortality	A71-1, A71-3
Range of dose rates : 200-500 Gy (acute)	

Mortality	A70; A71-2
Other effects	A68-(1-3)

Table 7.6. The relationships between the dose rates and effects of radiation on aquatic organisms based the EPIC database (Sazykina, Kryshev, 2003a, 2003b)

Dose rates of chronic radiation exposure	Radiation effects on aquatic animals	Examples of effects in the sub-database “Radiation effects on aquatic animals “
$10^{-7} – 10^{-5}$ Gy d^{-1}	No effect or weak stimulation	A32; A36; A60-1; A60-2; A75-(21-24); A11-1; A112-1;A113-3
$10^{-5} – 10^{-4}$ Gy d^{-1}	No effects on morbidity, fertility or mortality (γ,β exposure). Suppression of bleak gonads (U) Some increase in fertility of Daphnia (U, Th) Slight changes in phagocytic response on infection, some changes in leucocytes (Sr-90, fish) Some increase in chromosome aberrations in cells (α,γ,β exposure).	A1-1; A43-2; A65-1; A76-17; A113-4; A115-2; A76-(17-20) A78-1; A78-2; A75-(9-12); A75-(17-20); A1-2; A77
$10^{-4} – 10^{-3}$ Gy d^{-1}	Decrease of immunity, lowering of phagocytic response on infection (Sr-90, fish). Tendency to the increased mortality from various infections (fish) Increase of mortality and abnormalities in embryos of trout (long-developed eggs), no effects on short-developed fish eggs (pike) Some negative changes in male gonads, no noticeable decrease in reproduction (Sr-90, small fish) Suppression of bleak gonads (U) Some increase in fertility of Daphnia (U) Decrease in fertility of Daphnia (Th) After-effects on fish progeny born from exposed parents (increased level of abnormalities) Increased levels of chromosome aberrations in cells	A1-3; A5-3; A64-1; A38-2; A67-2; A115-3; A60-2; A61-2; A78-2; A75-(4-8); A75-(13-16) A12; A16; A26-A28; A87-(4-5), A118-3
$10^{-3} – 10^{-2}$ Gy d^{-1}	Negative changes in blood, imbalance between different forms of leucocytes (α,β,γ exposure) Decrease of immunity, lowering of phagocytic response on infection. Increase of lipidoperoxides content (radiotoxines) in fish liver Decrease of functional activity and	A65-2; A66-2; A2-1; A2-2;A3; A9; A7; A14; A80; A76-1; A38-1; A38-4; A78-3; A76-(9-12); A84; A33;A14; A76-1; A83 (1-4); A80; A33

	morphological abnormalities in fish gonads (β,γ exposure) Increase of abnormalities in embryos of fish Degeneration of fish gonads (U) Weak stimulation effect on fertility of Daphnia (Sr-90) Decrease in size of shells of pond snail After-effects on progeny born from exposed parents (increased levels of abnormalities) Chronically exposed animals showed higher radioresistance to acute exposure Cytogenetic effects	
10^{-2} – 10^{-1} Gy d^{-1}	Negative changes in blood, decrease of bacteriostatic capacity of blood Considerable decrease of immunity, lowering of phagocytic response on infection. Deterioration of fish eyesight (Sr-90, doses>1,5Gy) Underdevelopment of male gonads; decrease of gonad’s mass; total sterility (fish, frogs) Morphological abnormalities and underdevelopment of fish ovaries Increased levels of abnormalities in embryos of fish, increased mortality of fish eggs of some species (peled) Decrease in fertility of Daphnia (Sr-90) Increase of fish mortality from various infections Life shortening (fish) Cytogenetic effects	A6-3; A2-3; A2-4;A4; A10; A62-1; A15; A29; A60-3; A61-3; A60-3; A61-3; A40-1; A118-4; A119-4; A120-4; A76-(5-8); A64-1; A63-2; A63-2; A49-2; A118-4; A119-4; A120-4
10^{-1} – 0,5 Gy d^{-1}	Considerable decrease in fertility of Daphnia Considerable increase of mortality and abnormalities in embryos of pike Increased mortality of eggs of pond snail	A31; A76-(1-4); A35-2; A51-2; A50-1
0,5 - 1 Gy d^{-1}	All pike embryos had abnormalities, high lethality Decrease of lifetime of Daphnia	A35-3; A51-3; A30
1 – 5 Gy d^{-1}	Lethal dose is received within several days (fish) Considerable (up to100%) mortality of fish eggs; pond snail’s eggs	A40-2; A50-2; A56-1; A57-1; A58-(1-2); A89-(1-20). A90; A92; A93; A94; A98; A100-(2-3); A50-2
5-10 Gy (acute	Lethal doses for fish	A55-1; A73-1; A73-1; A57,

exposure)	Increased fecundity of Ostracoda (benthos) Sterility of scallop High mortality of fish eggs and eggs of pond snail	A58; A72-(1-5); A99-3
100-200 Gy (acute exposure)	Mortality of some zooplankton species, decrease of biodiversity in zooplankton association.	A71-1; A71-3
200-500 Gy (acute exposure)	Total mortality of zooplankton Mortality of some phytoplankton species Stimulation of bacterioplankton	A71-2; A70; A68-(1-3)

8. RADIATION EFFECTS ON TERRESTRIAL PLANTS

The EPIC sub-database "Radiation effects on terrestrial plants" is given in ANNEX C (available in the accompanying CD).

Considerable amounts of information on the radiation effects on plants and herbaceous vegetation were obtained from observations in the territories impacted by the Kyshtym and Chernobyl radiation accidents. The radiation consequences of large accidental releases of radionuclides in the environment include as a rule two phases – acute period immediately after the accident, and long-term after-effects.

8.1. Kyshtym radiation accident of 1957: Radiation effects in plants and herbaceous vegetation

Effects of radiation on plants and herbaceous vegetation in the territory contaminated in 1957 as a result of the Kyshtym accident are described in the records P8, P19, P22, P31, P32, P33.

8.1.1. Acute period after the Kyshtym accident

At the time of the Kyshtym accident (29 September, 1957), most plants had stopped their vegetation and had formed seeds. The metabolic activity of aerial components of herbaceous and woody plants had entered the phase of physiological dormancy.

The absorbed doses from accidental fallout arosed mainly due to beta radiation (Tikhomirov, 1993). The contribution of gamma radiation to the exposure dose to most species of plants was insignificant.

In forests, from 80 to 100% of the deposited radioactive mixture was retained by the crowns of trees.

In the "acute" period, the half-loss period of radionuclides in the aerial part of pine trees was about 120 days, and the effective half-loss period (with allowance made for radioactive decay) was about 80 days. The absorbed dose rate of beta radiation in the needles of pine trees immediately after the accident amounted to 30-50 nGy d^{-1}, normalized to Bq m^{-2} of ^{90}Sr fallout. At the beginning of the vegetation period of 1958 it decreased to 5-10 nGy d^{-1}, normalized to Bq m^{-2} of ^{90}Sr fallout. At the beginning of the vegetation period of 1958, the accumulated doses to the needles of pine trees were as great as 5×10^{-6} Gy normalized to Bq m^{-2} of ^{90}Sr fallout.

A different relationship between the dose loads and contamination density was observed for deciduous species of trees represented primarily by common birch. The initial self-purification of the crowns in the period of autumn leaf-fall resulted in a rapid decrease in the absorbed dose rates in the cambium of birch buds. By the beginning of the vegetation period of 1958, the accumulated doses to the birch buds were as great as (0.5-2)x10^{-6} Gy (normalized to Bq m^{-2} of ^{90}Sr fallout), i.e. to the values half as great as those observed in pine buds.

The formation of dose loads on herbaceous plants and seedlings of woody species in the forest was determined by the type of forest and the density of the crowns. The dose loads varied within an order of magnitude, with a maximum in meadow phytocenoses and deciduous forests after the leaf fall, and a minimum in dense coniferous forest stands.

Upon the resumption of new vegetative growth in the spring of 1958, a major part of terminal and lateral buds of common pine growing in the territory of the Kyshtym radioactive trace did not begin to grow, and those buds that did emerge developed into shortened clusters of shoots (record P42-1). Subsequently, the crowns of pine trees turned yellow and dried up, i.e. suffered severe chlorosis. The area of ruined pine trees extended gradually and by the Autumn of 1959 was as great as 100 km^2, with a contamination densities over 7.4 MBq^{90}Sr m^{-2}. In an area covering approximately 200 km^2, with a contamination density of 1.5-1.8 MBq^{90}Sr m^{-2}, a partial damage to the crowns of pine trees was observed (record P42-2). The damage was characterized by effects inclusing dessication and loss of needles, primarily in the lower part of the crown, and retarded growth of shoots and wood.

Lethal effects in birch trees showed themselves at contamination densities over 50 MBq^{90}Sr m^{-2} (record P42-3). The total destruction of birch stands was observed at contamination densities over 150 MBq ^{90}Sr m^{-2}, i.e. at levels that were two orders of magnitude higher than the lethal contamination densities for pine trees (record P42-4).

Partial damages to birch forests, characterized by a 50% loss and 10% loss of leaves, and covered areas of 3 km^2 and approximately 12 km^2, respectively.
A substantial difference in the damage to pine forest compared to birch forest stands is determined by the higher intrinsic radiosensitivity of pine species, as well as by the formation of increased dose loads to their crowns.

According to the results of investigations reported by R.T. Karaban et al. (1968,1977), a lethal absorbed dose in the needles (a critical organ of pine under conditions of radioactive contamination of the crown), that results in a complete drying of pine trees amounts to 30-50 Gy. Lethal doses to the bud meristem were 15-25 Gy.For birch trees a lethal absorbed dose in the apical meristem of buds resulting in a general drying of birch stands was 4-6 times higher than that for pine trees and exceeded 200 Gy.

The difference in radiosensitivity of pine and birch trees can be explained, apart from interspecific distinctions, by the difference in the rate of their crown decontamination of the deposited radioactive mixture under the action of wind and rainfall.

The specificity of the manifestation of radiation damage in forests was studied in some detail. In the case of radioactive fallout from the Kyshtym accident, drying of needles, leaves, and tissues of the apical meristem began, as a rule, in the lower part of the crown and then in the middle section. The drying of forest was most pronounced on the windward side with respect to the motion of the radioactive cloud. Top shoots retained their viability, even if up to 95% of the crown died. In the trees exposed to sub-lethal doses, damage of their needles and leaves, also some cytogenetic, physiological and morphological disorders were observed (Kalchenko *et al.*, 1993), see record P8-1. For example, at a dose of 0.1 LD the deterioration of pollen was recorded for a few years following the accident. An increase in the frequency of chromosome disorders in divisible cells of the leaf and apical meristems was observed.

Phenological disorders, such as a shift in time of seasonal phenomena, were persistently retained in common birch during four years after the accident and showed themselves in a two-week delay in leaf opening and blossoming.

A full manifestation of radiation effects in pine has been completed by the Autumn of 1959, with an area of ruined pine forests being as great as 100 km^2 (10% of the area of the Kyshtym radioactive trace).

In the period 1957-1958, primary radiobiological effects on herbaceous plants, soil mesofauna, mammals, birds and fish were not investigated directly. Because of this,the estimates are based on observations carried out during the ensuing years, and on specially performed experiments and theoretical analysis.

8.1.2. Long-term after-effects of radiation exposure

From the results of geobotanic investigations carried out following the "acute" period, it was found that among herbaceous plants, the most profound radiation effects were revealed in perennial plants with regeneration buds located on the soil surface (hemicryptophytes) or just above the ground (hameophytes) for which the highest absorbed dose rates were apparent. Disappearance of some species from the community was observed during the "acute" period at exposures with doses to regeneration buds over 200 Gy, or at contamination densitity over 55 MBq^{90}Sr m^{-2}. The loss of seed germination of annual and perennial herbaceous plants during the first 2-3 years after the formation of the radioactive contamination trace, was recorded at contamination densities over 37 MBq^{90}Sr m^{-2}. Radiation damage of herbaceous plants was observed in an area of less than 15-20 km^2.

Within 4-6 years after the accident, communities of meadow and forest herbaceous plants began to return to their original species composition. This was primarily due to the fact that the dose loads had decreased by at least an order of magnitude, as compared to the initial level after the accident. However, it took no less than 20 years to restore completely the original herbaceous community. An important factor for the functioning of radioactively-contaminated herbaceous communities is the phenomenon of radioadaptation, i.e. increasing radioresistance of a population under conditions of prolonged exposure to radiation doses exceeding the natural background (Kalchenko, 1995), see records P19-4, P19-5, P19-6. Radioadaptation was revealed in experiments with additional irradiation of seeds of herbaceous plants, which were growing for 7-10 years prior to the experimental exposure in a plot with a contamination density of 11 MBq^{90}Sr m^{-2} (300 Ci ^{90}Sr km^{-2}). The frequency of chromosome disorders in divisible cells of the plants grown from these seeds was 1.3-1.5 times higher than that for irradiated seeds from non-contaminated plots (Shevchenko, 1998), see records P22-1, P22-2. This gives grounds to expect that in plant populations subjected to prolonged exposure, selection of radioresistant forms occurs, which in turn leads to increased radioresistance of the plants..

8.2.Chernobyl accident of 1986: Radiation effects in plants and herbaceous vegetation

Effects of radiation on plants and herbaceous vegetation in the territories contaminated in 1986 as a result of the Chernobyl accident are described in the records from P1 to P18; P20, P21, P24, P25, P26, P30, P38, P39.

8.2.1. Radiation effects on coniferous forests

The radioactive releases resulting from the Chernobyl accident, were largely trapped by the forests surrounding the nuclear power plant (NPP), which acted as a buffer partly preventing the wider dispersal of radionuclides from the affected area. On more negative note, the retention of radioactive material by the forest ecosystems resulted in their significant damage, and coniferous stands suffered particularly (see the EPIC database bibliography: Kozubov et al., 1987, 1988, 1990, 1994; Tikhomirov & Sidorov, 1990; Tikhomirov & Shcheglov, 1994; Abaturov et al., 1996; Sokolov et al., 1994; Ilyin & Gubanov, 2001). In the Spring, the radioresistance of trees were lower, as compared to the Autumn dormancy period, due to extensive growth processes. The timing of the Chernobyl accident, i.e. in the end of April, accounted for the significant injuries experienced by the coniferous forests in the area close to the Chernobyl NPP.

The forests cover about 40% of the 30-km zone around the Chernobyl plant. The predominant tree species is pine, although pine forests (over 80% of the area under forests) also include some birch, oak, aspen, alder and other deciduous trees. At the time of the Chernobyl accident (1986), the trees were, on average, 30-40 years old, though older forests were also encountered.

After the passage of the radioactive plume over the forests, exposure of trees was primarily due to external irradiation from radionuclides deposited on the soil and irradiation from radionuclides retained by above-ground parts of trees. The estimated doses of external irradiation from the soil are given in Table 8.1 (Kozubov et al., 1990, 1994). The larger part of the external irradiation dose was received in 1986. The highest irradiation levels were recorded at a distance of about 1,5-2,0 km to the west from the nuclear power plant near the village of Yanov. This area was covered with 40-50 year-old pine stands. By autumn of 1986, all the pines perished here (the so-called "red forest"), the external irradiation dose was about 100 Gy.

Table 8.1. The dynamics of external irradiation dose on experimental plots with coniferous trees close to the Chernobyl NPP (Kozubov et al., 1990, 1994).

Number of plot	Azimuth with respect to the Chernobyl NPP, degrees	Distance from the Chernobyl NPP (km)	Absorbed dose (Gy) / Exposure dose rate (10^{-5} Gy h^{-1})		
			By 01.10.86	By 01.10.87	By 01.05.88
9	260	2.0	100/1000	126/250	130/220
1	260	5.0	10/100	12/25	12.5/24
2	245	4.0	4/40	5.1/12	5.5/12
4	255	6.0	2/20	2.6/6	2.8/5
3	165	3.5	1/10	1.2/3	1.3/2
6	205	16.0	0.012/0.12	0.014/0.04	0.015/0.03
5	130	30.0	0.01/0.10	0.012/0.04	0.013/0.03

Note. Absorbed external irradiation doses and exposure dose rates are given with respect to gamma radiation at 1 m height from the soil surface.

The levels of radioactive contamination and internal irradiation doses, based on observations in October of 1987, are given in Table 8.2 (Kozubov et al., 1990; Kryshev (Ed.), 1992). It should be recognized that the assessment of internal irradiation doses for different parts of a pine is a difficult task, because measuring the radioactive composition of tree contamination was labour-consuming. Furthermore, coniferous forests were unevenly contaminated even over a relatively small area. Nevertheless, it was important to conduct such an assessment, because the internal irradiation doses, as shown in Table 8.2, were substantial as compared to external irradiation doses from the soil.

Table. 8.2. Radionuclide content and internal irradiation dose rate to pine needles in the near zone around the Chernobyl NPP, measurements in October of 1987; kBg/kg wet weight (Kozubov et al., 1990; Kryshev (Ed.), 1992).

Number of plot	^{144}Ce	^{106}Ru	^{95}Zr	^{95}Nb	^{134}Cs	^{137}Cs	Internal irradiation doze rate, cGy/day
9	13400	4100	800	1500	1500	4100	34
1	190	100	10	20	20	70	0.56
2	150	60	8	15	17	72	0.40
3	2	20	3	5	5	21	0.05
6	1.5	0.6	0.1	0.17	0.18	0.55	0.004

Note: For plot 9 the data are for dry dead needles.

The data from Tables 8.1 and 8.2 show that the levels of external radiation of pine needles varied greatly within the near zone of the Chernobyl accident. Radioactive contamination of soils varied by four orders of magnitude, reflecting the non-uniform pattern of radioactive contamination in the 30-km zone.

During the first three months following the accident, doses absorbed by flora and fauna in the near zone of the Chernobyl NPP, ranged from 0.1 to 300 Gy, with ^{137}Cs contamination density in soil and vegetation varying from 0.2 to 15 MBq m^{-2} (Spirin *et al.*, 1990).

With regards to the radiobiological effects arising from the accident, it should be remembered that some parts and tissues of tree species were exposed to microscopic “hot particles”. The activity of these particles was chiefly determined by ^{95}Zr, ^{106}Ru, ^{137}Cs, ^{144}Ce, and occasionally reached hundreds of kBq. The light-microscopic analysis of necrotized shoots revealed tiny particles sticking to wax and resinous matter. Further analyses using a scanning electron microscope showed that these particles were of irregular shape, and their size varied from 2-10 to 30-40 μm. Given exposure to hot particles, the local absorbed doses could be orders of magnitude higher than the external irradiation doses. When screening the needles from the edge pines killed in 1986, indentations in the form of “hollows” were observed with hot particles lying in the bottom. The “hollows” were “burnt out”, as it were, by the hot particles of high activity (Kozubov et al., 1990).

Four zones were defined according to severity of radiation damage of forests (Table 8.3) (Kozubov *et al.*, 1990; Kryshev, 1992; Sokolov *et al.*, 1994):

- zone of complete pine death and partial damage of deciduous trees (“red forest”),
- zone of severe (sublethal) damage of coniferous plants; partial for decidous trees, injuries of needles and buds, morphological changes in deciduous trees,

- zone of medium damage of coniferous trees: growth suppression, partial needle loss, suppression of reproductive ability and genetic disturbances,
- zone of minor damage: occasional abnormalities in growth and reproductive processes, morhological disturbances.

The pine stands in the close-in area of the Chernobyl NPP were acutely irradiated at a time when active growth of shoots started. As a result, pines were killed within several days in this lethal dose zone ("red forest").

In the zone of sublethal doses, young shoots died off in 90 – 95% of the trees under study, though some branches had replaced lateral buds. On some trees apical shoots survived, but became reduced in length or twisted, and others had the top necrotized.

The zone of medium exposure was characterized by the death of most young shoots, but many second-year shoots were being replaced by buds. Apical buds of the trees were frequently defective. In the autumn of 1986, pine shoots in the zone of minor exposure did not show observable abnormalities.

In 1986, at absorbed doses to pines below 0.7-1.0 Gy compensatory growth of needles was observed. The mass of needles per one shoot increased by 54% when compared with that in 1985 (record P12-1). At doses of 1.5-2.0 Gy, the mass of needles in 1986 did not differ from the control (record P12-2). At doses to pines of 3-4 Gy, the mass of needles decreased by 2 times (record P12-3). In zone of sublethal damage of pines (8-10 Gy), needles developed only on some shortened shoots as dense wisps with a characteristic greenish color. At absorbed doses of 8-12 Gy, mass extinction of pine needles occurred.

Table 8.3. Spatial distribution of forest radiation damage in the area around the Chernobyl NPP (Kozubov et al., 1990; Kryshev, 1992; Sokolov et al., 1994)

Degree of radiation damage	Absorbed dose from external γ-radiation (Gy)	Exposure dose rate (10^{-5} Gy h^{-1}) by 01.10.86	Estimates of absorbed dose in needles (Gy)
1. Complete death of pines within 4 km^2 area. Partial damage of deciduous trees.	over 80 - 100	over 500	over 100
2. Sublethal zone: death of most growth points, partial death of coniferous trees, morphological changes in deciduous trees. Area of pine forests – 38 km^2.	10 - 20	200 - 500	50 – 100
3. Zone of medium damage: suppressed reproductive ability, dried needles, radiomorphosis. Area under pine forests – 120 km^2.	4 - 5	50 - 200	20 – 50
4. Zone of minor damage: disturbances in growth and reproduction, morphological disturbances in coniferous trees.	0.5 – 1.2	less than 20	less than 10

Based on the spatial pattern of damage inflicted on pine forests, A.V. Abaturov (Abaturov, 1990, 1996) supposed that a 3-D high-intensity radiation cloud existed in the early stage of the accident, which was moving westward close to the ground and penetrated far into the forest. The so-called “red forest”, in which pines up to 25 m height were destroyed, is situated exactly along this plume, within a distance of 2 km from the Chernobyl plant. At a distance of up to 5.5 km, where young deciduous and pine trees grew, all pines perished along the plume axis. Within 200 – 300 m from the plume axis, active growing points of trees were completely or partially injured up to crown heights of approximately 15 m above the ground. Farther along the plume axis, dead trees were not observed. The height to which the canopy was damaged decreased with distance from the NPP, and became about 3 m in height at a distance of 8 km from the plant. The radioactivity decreased sharply laterally from the plume axis. The pattern presented above is of a qualitative nature and needs to be supplemented by by quantitative estimates of pine exposure dose, given varying scenarios of the plume location.

As mentioned above, the acute exposure of trees and corresponding absorbed dose of 100 Gy led to the death of above-ground parts of pines in a short time. However, in the autumn of 1986 and the spring of 1987, green shoots emerged on some trees which on first scrutiny looked seemingly dead, although these new growths subsequently withered. This suggests, that some growing points of pines remained viable even at substantial doses of acute and chronic irradiation. The reason for this was that the deposited radionuclides largely occurred in a thin topsoil layer in 1986-1987, and the roots were not exposed to highly elevated levels of radiation. In the spring of 1987, within the zone of sublethal exposure the surviving growing points gave rise to robust young shoots with a light-green bark and widely-spaced elongated needles. Stemwood remained viable, with the exception of “red” forest. Due to this fact, the growth of pinewood decreased in 1986 only by 10-25% when compared with 1985. By 1988, the growth of pine stemwood recovered to pre-accidental levels.

The radiosensitivity of spruce was found to be higher than that of pine. Spruce demonstrated disturbances in needle morphogenesis, bud germination, and inhibited growth of shoots at absorbed doses as low as 0.7 – 1.0 Gy. In 1986, the radiation-induced injuries of spruce consisted in inhibited growth of shoots, shortened and elongated needles, death of most growing points, and the presence of multiple buds. In spruce trees that received doses of 2.5-4.0 Gy, spruce needles were flat in form with sharp and very hard tips. The color of these needles was dark-brown in 1986, and it became reddish-brown in 1987, a colour associated with the decay of chlorophyll. At absorbed doses higher than 3.5-4.0 Gy, mass extinction of spruce needles was observed. In 1987, most of spruce trees developed big apical shoots with needles 35-40 mm length. These were twisted, curved top or straight.

In 1986, in spruce trees which received doses of 0.7-1.0 Gy and above, a significant inhibition of growth processes occurred. In 1987-1988, recovery processes were under way in all spruce trees. However, in 1989, quantitative parameters for vegetative shoots of young spruce trees appeared to be lower than in 1988, which was probably due to an imbalance in the growth of above-ground and underground parts of irradiated trees (Kozubov et al., 1990). The growth of spruce stemwood in 1986 was 2-2.5 times lower than that in 1985. By 1988, parameters of stemwood growth in spruce recovered to pre-accidental levels.

Reproductive parts of coniferous trees appeared to be the sensitive to ionizing radiation. For equal exposure doses, the reproductive parts were damaged to a greater extent than vegetative parts. In 1987, the frequency of chromosomal aberrations of meiosis in microsporocytes increased three-fold in comparison with the control at external irradiation doses as low as 0.7-1.1 Gy, and five-fold at doses of 1.7-2.3 Gy (Table 8.4) (Kozubov et al., 1990). At absorbed doses greater than 5 Gy, the level of chromosomal aberrations was 7 times higher than that in the control (record P5-9). In 1988, the occurrence of chromosomal abnormalities in pine decreased. However, in trees that had received doses higher then 5 Gy, levels of cytogenetic effects in 1988 were 2-3 times higher than those in the control (record P5-10).

Table 8.4. Chromosomal aberrations in pine microsporocytes in the near-zone area of the Chernobyl accident (Kozubov et al., 1990).

Estimated absorbed dose, Gy	Year of study	Numbers of cells analysed	Numbers of chromosomal aberrations, %
0.7 – 1.1	1987	4200	22.0
	1988	1800	14.4
1.7 – 2.3	1987	6300	30.2
	1988	2200	9.6
Control	1987	3000	5.7
	1988	1000	5.8

In pine trees, which received doses of 3.5-4.7 Gy, pollen viability reduced to 48% in 1987 (control values in 1987 – about 76%). Given absorbed doses of 1.8-2.6 Gy, about 50% of seed buds were necrotized, and at 3.8-5.1 Gy – about 75% (Kozubov et al., 1990). At absorbed doses of 5-8 Gy, high sterility of pollen grains was observed (record P9-3). In the boundary of the "red" forest (absorbed doses of 20-25 Gy), practically all pollen grains were sterile (record P9-4). By 1989, pollen viability in all surviving trees did not differ greatly from the control (record P9-2).

The second-year cones of pine retained their viability even in the zone of sublethal radiation levels, and some of them produced germinating seeds. Male and one-year female cones of pine were found to be more radiosensitive; the one-year cones remained viable only in the zones of low radiation levels. In 1986, pine seed germination decreased considerably in the zone of sub-lethal damage, and, in some cases, did not exceed 3%. In the subsequent years, pine seed germination returned to pre-accidental level (record P11-4; P11-5; P11-6).

When the concentrations of radionuclides were determined in the necrotized microstrobiles and mature cones collected from pine grown in the sublethal exposure zone, the radionuclides accumulation in microstrobiles was found to be 20 times that in cones (Table 8.5) (Kozubov et al., 1987).

Table 8.5. Concentrarion of radionuclides in pine necrotized microstrobiles and in two-year old cones. Zone of sublethal exposure, October of 1986. Aabsorbed dose of external irradiation from soil 8-10 Gy. (Kozubov et al., 1987).

Radionuclide	Microstrobiles (Bq g^{-1})	Cones (Bq g^{-1})
^{141}Ce	62.2	2.8
^{144}Ce	977.0	35.8
^{103}Ru	96.9	5.4
^{106}Ru	279.0	32.3
^{95}Zr	422.0	18.6
^{95}Nb	729.0	35.8
^{134}Cs ^{137}Cs	83.3 167.0	6.6 12.0
^{140}Ba	40.7	4.0
Dose rate of internal irradiation (cGy d^{-1})	2.6	0.15

In October of 1986, the dose rate of internal irradiation of microstrobiles was still as high as 26 mGy d^{-1}; immediately after the accident it was much higher. Increased irradiation of microstrobiles and their enhanced radiosensitivity resulted in severe damage to male shoots of pine (Kozubov et al., 1987).

In the "red" forest (absorbed doses of 80-100 Gy) shortly after the accident, stems of pine trees were infested by stem vermin (*Ips sexdentatus Boern., Buprestis mariana L., Rhagium inguisitor L.* and others). As a result of infestation, rapid extinction of all living growth points occurred. In 1987, within the zone of sublethal damage of pines (absorbed doses of 10-20 Gy), parts of trees without living buds and needles but with living bast were infested by *Tomicus (Blastophagus) piniperda L.* and *Monochamus galloprovincialis Ol.* As a result of this infestation, the reserve of living vegetative growth on the trees decreased by 24%, i.e. this damage was considerable (record P15-1). By the spring of 1991, all pines with dead buds in the sublethal zone dried up.

The phenomenon of increased infestation of irradiated trees with insects was studied in earlier experiments in pine-birch forest subject to acute irradiation with doses from 1 to 230 Gy (Spirin et.al.,1985), where the intensive infestation of trees with xylophagous insects was observed. At absorbed doses of 100-230 Gy, numbers of damaged trees were up to 100% (record P40-3). At absorbed doses of 30-100 Gy, numbers of pines damaged by xylophagous were 60-78% (record P40-2). In the plot with doses to pines of 10-30 Gy, numbers of damaged pines were 10-18% (record P40-1). In the control, numbers of pines damaged by xylophagous insects was 5%.

8.2.2. Radiation effects in deciduous plants

Deciduous trees, represented in the Chernobyl zone predominantly by birch (*Betula pendula* Roth.), aspen (*Populus tumula* L.), alder (*Alnus glutinosa* Gaerth.) and oak (*Quercus robur* L.), proved to be much more resistant to radioactive contamination than the coniferous species (Sokolov et al., 1994). Radiation damage to deciduous tree crowns was found only in the immediate vicinity of the damaged reactor, at levels of radioactive contamination one order of magnitude higher than that associated with similar damage to coniferous species. For birch trees, which had received absorbed doses of few hundreds Gy, young apical shoots partially died out, and in the middle of August 1986, most of the leaves became yellow and fell off. By the Autumn of 1986, necrosis of some large branches of birch trees was observed. In the Spring of 1987, many birches were blooming abundantly, although some generative parts had anomalous structures. In 1988, birch foliage returned to normal.

Survival of birch seeds after irradiation was studied in experiments with acute irradiation at doses from 175 Gy to 300 Gy (Pozolotina, Kulikov,1988). Seeds of *Betula pendula Roth.* were irradiated before sowing. At doses to birch of 250 Gy and 300 Gy, germinating plants died completely at the stage of leaf formation (record P29-1). At doses of 175 Gy and 200 Gy, survival of germinating plants was 80 and 67%, respectively (record P29-2, P29-3). One year after the irradiation at doses of 175 and 200 Gy, the heights of shoots were 3-4 times lower than that in the control (record P29-4); 2-3 years after irradiation, heights of shoots were 1.5-2 times lower than in the control (record P29-6, P29-7).

On the whole, studies in the 30 km zone around the Chernobyl plant have shown that most forest stands (with the exception of the "red forest") retained their viability. Forests ecosystems acted as an efficient bio-geochemical barrier capable of significantly reducing migration fluxes of radionuclides (Kozubov et al., 1987).

8.2.3. Radiation effects on herbaceous vegetation after the Chernobyl accident

Herbaceous communities have an enhanced radioresistance as compared to other biocenoses with respect to changes of species composition, ecological and physiological characteristics induced by radiation. At the same time, effects of ionizing radiation in herbaceous vegetation may show themselves at the genetic level. That is why some of the most radiosensitive genetic test systems of plants can be used as "biological dosimeters" (Taskaev et al., 1988).

Radiation effects on herbaceous vegetation in the 30 km zone around the Chernobyl NPP and outside were studied for 30 frequently-occurring herbaceous species. Particular emphasis was placed on seed studies, since the acquired changes might be present implicitly in dormant seed and become evident during germination only. Germinating seeds were key objects in ecological-genetic studies of natural vegetative populations in the 30-km zone.

In 1986-1991, the seed quality and chlorophyll mutation frequency of *Dactylis glomerata L.*, growing within 30-km zone of the Chernobyl NPP were studied (Shershunova, Zainullin, 1995). In the initial post-accidental period (1986-1987) the parameters seed quality and chlorophyll mutation frequency depended on the external gamma radiation at the sampling plots. In the plot with dose rate of about 2-2.5 mGy h^{-1} in 1986, none of the 300 seeds sprouted up (record P17-2). At dose rate about 0.80 mGy h^{-1} in 1986, seed germination was 3.7% (record P17-1). The effects of radiation on the investigated parameters had an uncertain character in 1987. In 1988-1989, the seed quality deteriorated in all plots; the seed germination varied from 0% (0.07-0.12 mGy h^{-1}) to 20,7% (1-2 μGyh^{-1}) in 1988 (record P17-3; P17-4). In1989, in seed germination of *Dactylis glomerata L* varied from 0.7% (6-8 mR/h) to 13% (0.02-0.03 mR/h) (record P17-5). Pollen sterility of *Dactylis glomerata L.* was (8.4 – 46.7)% in 1991 (in the control 2-4%). In 1987, chlorophyll mutation frequency depended on the dose rate; a sharp increase of this parameter was revealed in the plots with dose rates of 0.4-1.1 mGy h^{-1} (record P17-6).

As the radioactive fallout was non-uniform in space and time, the impact of ionizing radiation on the same species at different plots varied by radionuclide composition, external and internal irradiation rate, and duration in time. Radiation exposures were primarily assessed in terms of external gamma-radiation dose rate at the soil surface. To obtain total absorbed doses to vegetation, account must be taken of the acute exposure during the early period following the accident, and the chronic irradiation from incorporated radionuclides. These components of absorbed doses to plants are as important as the doses of external irradiation from soil.

The studies of cytogenetic effects of radiation on herbaceous plants undertaken in the Chernobyl zone included the following:

- morphological-physiological analyses aimed at detecting aberrations in reproductive processes in irradiated seeds and viability of a subsequent generation;
- cytogenetic analyses of radiation-induced injuries in vegetation using the test of "chromosome aberrations in root meristem of germinating seeds". The "embryonic lethality" test was also used for investigating mutation variability;
- detection of potential aberrations in hereditary material through the use of testing acute irradiation.

In 1986-1987, in order to obtain express-estimates of the biological effects arising from radiactive contamination, experiments were conducted with a highly radiosensitive test plant of spiderwort Clone 02 (Taskaev *et al.*, 1988a). Mutation alterations in spiderwort were recorded in stamen filament hair, with cells changing colour from blue to pink. In the experiments, the spiderwort plants were exposed to radiation at different dose rates (0.003-2.5 mGy h^{-1}). A linear relationship was established between frequency of mutations and increase of external irradiation up to a dose rate 2 mGy h^{-1} (Table 8.6). The frequency of mutations doubled at a dose rate of 0.04 mGy h^{-1} (0.1 cGy d^{-1}), suggesting a high radiosensitivity of the test.

Table 8.6. Frequency of mutation in stamen filament hair of spiderwort at different dose rates (Taskaev et al., 1988).

Year of observation	Dose rate of external gamma irradiation, 10^{-5} Gy h^{-1}	Frequency of mutations, %
1986	0.35	0.22 ± 0.02
	5.0	0.56 ± 0.05
	15.0	0.92 ± 0.04
1987	20	1.90 ± 0.08
	100	8.40 ± 0.26
	200	14.95 ± 0.32
	250	15.13 ± 0.55
Control	0.01	0.22 ± 0.03

Note: In total, 180,000 samples were analyzed in 1986 and 53,000 samples in 1987.

It should be noted, that in case of acute radiation exposures, a dose-effect curve normally shows a maximum mutation rate of 10-15% at doses of 1-2 Gy. In this experiment, at dose rates of 0.20-0.25 cGy h^{-1}, the levels of mutagenesis were occasionally as high as 30%, and 15% on average. The conclusion was made, that chronic exposure for spiderwort in the affected area, was no less damaging than acute exposure (Taskaev *et al.*, 1988).

In addition to these studies, mutation processes were investigated in natural populations of *Arabidopsis thaliana*, an annual plant frequently occurring in the Chernobyl region. The spontaneous level of lethal mutations in *Arabidopsis* was known to be 1-10%. The three years of observations of mutation processes in *Arabidopsis* populations have shown, that the levels of mutation burden in places with initial dose rates up to 0.1 mGy h^{-1} did not exceed the control (8.0%) in the first two years after the accident. The mutation burden increased to 13% in the subsequent generation indicating a tendency towards the accumulation of a genetic burden (Abramov et al., 1990). In *Arabidopsis* populations, at sites of high initial dose rates (2-2.4 mGy h^{-1}), the level of mutations was as high as 40-80 % in the first years after the Chernobyl accident, but later it decreased. However, at sites of sufficiently high exposure dose, however, the mutation burden level remained elevated (30-50%). A build-up of the genetic burden in plant populations, chronically exposed to radiation, may also be influenced by the radionuclides transferred via the roots (in case of long-lived radionuclides penetrating deeply into the soil and transformed into more mobile forms).

The genetic injuries observed in the herbaceous species growing on the most contaminated areas of the Chernobyl zone included those, which did not usually occur in experimental conditions after acute exposure to gamma-radiation. In particular, multiple chromosome injuries were detected in dandelion (*Taraxiacum*) plants. Such effects are known to occur when a sample is exposed to radiation in a heavy particles accelerator. The multiple chromosome injuries found in herbaceous plants within the affected area may be attributed to an aggravated severity of radiation damage due to the combined effect from γ-, β- and α-emitters. This seems to be also the reason behind the reduced activity of DNA reparation systems in samples from dandelion populations growing on a heavily contaminated area, as well as the increased mutation rate in spiderwort plants mentioned above (Taskaev *et al.*, 1988). Predictions of long-term eco-genetic consequences of the accident should allow for a possible input of densely ionizing radiation to genetic injuries, as well as synergetic effects from radiation and non-radiation factors (e.g. chemicals used for decontamination and dust suppression in mitigating the consequences of the accident).

The previous experiments (in 1979) with acute irradiation of the meadow plants provided the following dose-effects relationships for herbaceous vegetation (Smirnov *et al.*, 1983): at doses of 200-1400 Gy species diversity of meadow plants decreased considerably (from 59 species only 8 remained) (record P23-1); at doses of 25-200 Gy species diversity of meadow plants decreased by a factor of 2 (from 59 species 25 remained in the experimental plot) (record P23-2); at doses to meadow plants below 25 Gy species diversity did not changed (record P23-3).

The investigation of seeds, from a large number of plant species exposed to the contamination, provides the evidences that the radiation has not caused significant changes in key parameters of seed viability such as mass, germination rate, germination energy and growth strength of seeds in the large part of the Chernobyl area. The exceptions were small plots within the affected territory with extremely high radioactive contamination where the enhanced genetic variations in herbaceous plants were found.

8.3. Dose-effects relationships in terrestrial plants and herbaceous vegetation

Analyzing the information in the EPIC database “Radiation effects on terrestrial plants”, the selection of records was performed using the umbrella endpoints at different ranges of dose rates. More detailed analysis of effects observed at different levels of chronic or acute radiation exposure made it possible to construct a preliminary scheme of dose –effects relationships for plants from northern/temperate climatic zones. These dose-effects relationships for plants are summarized in Table 8.7.

Table 8.7. The relationships between dose rates/doses of radiation exposure and effects of radiation on terrestrial plants and vegetation (based on EPIC database "Radiation effects on terrestrial plants")

Dose rates/ dose of irradiation	Radiation effects on plants
5×10^{-4} – 5×10^{-3} Gy d^{-1}	Cytogenetic effects in chronically exposed populations of trees and herbaceous species growing in contaminated areas. Increased morphological variability in plants. Decreased viability of seeds. (Effects include some burden from acute exposure in the past)
5×10^{-3} – 5×10^{-2} Gy d^{-1}	Cytogenetic effects. Increased morphological variability in plants. Some decrease in wood growth in coniferous plants (about 10%)
5×10^{-2} – 0.1 Gy d^{-1}	Considerable decrease of wood growth in coniferous trees; sterility of pollen, decreased viability of seeds.
>0.1 Gy d^{-1}	Considerable damage and death of coniferous trees within few years
0.5-1 Gy (acute)	Compensatory increase of growth processes (pine), complete recovering of damage to coniferous plants. Partial damage in spruce trees.
1-5 Gy (acute)	Moderate damage to coniferous plants: decrease in wood growth, morphological changes in sprouts, needles, seeds. Cytogenetic effects.
5-10 Gy (acute)	Considerable damage of crowns in coniferous trees, decrease of wood growth. Decreased production of pollen, sterility. Decreased germination of seeds. Damage to generative organs and sleep-buds (coniferous)
10-20 Gy (acute)	Sublethal damage to coniferous trees (about 90% of trees died). Death of most growth points, death of seedlings of coniferous trees. Morphological changes in decidous plants. High level of chromosomal aberrations (coniferous). Infestation of irradiated trees with insects.
20-100 Gy (acute)	Mass death of coniferous plants. Death of seedlings grown from irradiated seeds (deciduous). High infestation of irradiated trees with insects. Morphological changes of in herbaceous vegetation
100-200 Gy (acute)	Hard damage to deciduous plants . Displacement of phenophases in herbaceous vegetation . Low survival of seedlings from irradiated seeds (deciduous)
200-400 Gy (acute)	Full death of seedlings in stage of leave formation (deciduous). Decrease of species diversity (herbaceous) . Decrease of seed germination and low survival of seedlings (deciduous plants)
>400 Gy (acute)	Considerable decrease of species diversity in herbaceous communities

9. RADIATION EFFECTS ON SOIL FAUNA AND MICROORGANISMS

The EPIC sub-databases " Radiation effects on soil fauna" and "Radiation effects on microorganisms" are given in the Annex D and Annex E (available on CD).

The EPIC sub-database " Radiation effects on soil fauna" includes field studies of the soil fauna in the areas with elevated levels of radioactivity, including experimental plots in Komi AR, Kyshtym radioactive trace, Chernobyl zone, and others (Krivolutsky, 1983, 1994; Krivolutsky, ed., 1985, 1999). Effects on soil fauna were also studied in radioecological experiments with local grounds purposely contaminated with different radionuclides, or subjected to exposure from external γ-source. Effects on microorganisms were studied in the soil samples from the contaminated areas, also numerous experiments were conducted with exposure of microorganisms from external sources, or exposure in solutions of radionuclides (Shevchenko, 1979; Shevchenko et al., 1993).

In terrestrial ecosystems, communities of invertebrate animals in forests and meadows amount to 90% of the zoomass and number of species populating the landscape. Soil invertebrates are the least capable of migration.

Comparing with vertebrate animals and most sensitive plants, soil fauna is less radiosensitive component of terrestrial ecosystems. Lethal doses of acute exposure for adult specimens of mezofauna (worms, insects) lay in the range 20-2000 Gy (Krivolutsky, 1983, UNSCEAR, 1996). Depression of reproduction may occur at doses about 2-50Gy. In the same time, soil invertebrates are very sensitive to radiation at some critical stages of ontogenesis (eggs at early hours of development, early larva and pupa stages), lethal doses for these stages are rather low – 1.5-5 Gy for different species.

Soil fauna consist of numerous species of invertebrates, which differ in their sizes, duration of lifespan, metamorphoses during the life cycle, habitats within the soil profile, and feeding specializations. At the same level of soil contamination, both dose rates and accumulated doses to individual species of soil invertebrates may differ considerably. Many soil invertebrates are linked with ecological relationships; radiation injury in some species may result in violations of trophic relationships and decrease of biodiversity in soil zoocenoses.

In the conditions of chronic radiation exposure, the critical groups of soil invertebrates are the following: slow-moving organisms; invertebrates with long life cycle; invertebrates with long periods of egg/larva development; invertebrates with soft body, which is not protected by chitinous covers; and invertebrates, inhabiting the most contaminated soil layers. For example, soil worms, especially earthworms, are known to be most vulnerable to chronic radiation in contaminated soils. In the same time, soil worms are rather radioresistant to acute exposure (LD about 600 Gy); this example shows, that extrapolation of acute effects to the conditions of chronic exposure may lead to considerable mispredictions.

Detailed dose assessment for soil fauna is a rather complicated task, considering different exposure conditions of organisms in the natural soil zoocenoses. For most species of small soil organisms, considerable contribution in the external dose rate may be associated with beta/alpha radiation; internal exposure from incorporated radionuclides is of less importance, since soil invertebrates have no capacity to bioaccumulation of radionuclides. Many publications on radiation effects in soil fauna do not include dose estimates, and provide the data on radiation effects in form of radionuclide concentration- effects relationships. Additional work is needed to reconstruct dose loads to specific groups of soil fauna, inhabiting areas with enhanced levels of radionuclides in soil.

9.1. Effects of chronic irradiation on soil fauna

Soil fauna in the Kyshtym radioactive trace

A thorough investigation of soil fauna in the highly contaminated soils of the Kyshtym radioactive trace was conducted in 11-12 years after the Kyshtym accident, see records from S5-1 up to S5-19. Soil samples were taken from the forest area; activity concentrations of ^{90}Sr in this area were (6.7-12.6)x10^{7} Bq m^{-2}. Estimated dose rates to soil organisms were (10-17) mGy d^{-1}. In total, numbers of soil mezofauna found in contaminated soil samples were 2 times lower comparing with the control samples. The most damaged were larger saprophagous organisms, feeding on forest litter, such as earthworms, and millipedes, the total numbers of invertebrates in this group were about 10% of the control. The ecological function of litter utilization in the contaminated soil, most probably, moved to smaller and less damaged organisms, such as Enchitreides, springtails, and beetle mites.

In soil micro-invertebrates, no considerable changes were found, numbers and biomass of microfauna organisms in contaminated soil samples did not differ from the control. Invertebrates in soil microfauna are much smaller in size comparing with mezofauna, their typical lifetime is shorter; these factors are favorable for survival of microfauna in contaminated soils. However, a detailed analysis of biodiversity revealed the biodiversity decreased even in groups of soil organisms, which seemed non-damaged by radiation.

Numbers of mobile predators and necrophagous invertebrates were higher in the contaminated area. Biomass of necrophagous invertebrates, represented by few species, was about two times higher than that in the control; this increase was connected with the high infestation of irradiated forest with leaf miners; leaf miners, in turn, formed a feeding resource for necrophagous invertebrates.

The inspection of the soil fauna was repeated in 30 years (1987-1989) following the Kyshtym radiation accident; see record S20 with sub-records. In total, numbers and biomass of mezofauna found in soil samples from the Kyshtym plots were about 3 times lower comparing with the control soils. Numbers of earthworms were about 40% of the control, the share of adult specimens was abnormally low. Numbers of phytophagous invertebrates amounted to 16%, and predators – 61% of control values, respectively. Conclusion was made, that in the ^{90}Sr contaminated area, soil fauna is noticeably suppressed; recovering processes take many years and follow the natural decrease in soil radioactivity.

Soil fauna in the areas with enhanced levels of natural radioactivity

Inspections of soil fauna were carried out in different local areas in Komi AR of Russia, characterized with enhanced concentrations of natural radionuclides, namely, in thorium local area (highland tundra, Polar Urals), also in thorium and uranium-radium local areas in the middle taiga; see records S8, S9, S10, S11, S14, S17 (with sub-records).

In the thorium areas, decrease in numbers and biomass of soil mezofauna was revealed. The most damaged invertebrates were insect larvae, Enchitreides, spiders; numbers of earthworms were also lower than those in the control samples.

In uranium-radium areas, both numbers and biomass of invertebrates in soil mezofauna were lower than the control values. Decreased were populations of earthworms, Collembola, Diptera larvae, beetles larvae, mites, and many others. From histological analyses of coating mucosa and intestine epithelium in earthworms, violations in epithelium cells were revealed, combined with elevated numbers of mucous cells, and increased secretion of mucus. Some delay in reproduction activity of earthworms was observed.

Experimental grounds contaminated with different radionuclides

Radiation effects on soil fauna were studied on several experimental plots; each plot was contaminated with solution of individual radionuclide. Soil fauna were analyzed in two years following the contamination; see records S6, S7, S12, S13 (with sub-records). Preliminary estimated dose rates to soil invertebrates in the grounds contaminated with ^{137}Cs, ^{144}Ce, ^{106}Ru, ^{95}Zr, ^{90}Sr were within the range 10-30 mGy d^{-1}. In all experimental grounds, numbers of invertebrates in the groups of beetle mites, gamazid mites, springtails, were 2-4 times lower comparing with the control values.

In the experimental ground contaminated with ^{239}Pu, where estimated dose rates were about 40 mGy d^{-1}, total abundancy of mezofauna was 2.3 times lower than that in the control. Numbers of some small invertebrates decreased considerably, in particular, populations of microarthropods were seven times lower and populations of small mites – 18 times lower than the control numbers in non-irradiated soils. In contrast with low-LET radiation, irradiation from ^{239}Pu was damaging for both mezofauna and microfauna.

9.2. Effects of acute irradiation on soil fauna

Experimental exposure of forest and forest soil

In 1973, a large-scale experiment was conducted with exposure of natural forest area from mobile gamma-source, see records S1, S2, S3, S4.

Doses to soil surface in the most exposed area were estimated to vary from 10 to 250 Gy. Forest area was exposed in September of 1973, when many soil organisms were in the rest period. Inspections of soil fauna in the irradiated forest were carried out repeatedly starting soon after the exposure, in May of the next year, in 1 year, and 2 years following the exposure. Inspection of soil fauna soon after the exposure had revealed considerable decrease in earthworm population, also in the numbers of spiders. In contrast, some mobile species of invertebrates were attracted to the irradiated forest, since damaged trees was not able to resist infestation. Inspection in May of 1974 (9 months after the experiment) revealed decrease in earthworms, beetle mites, whereas numbers of Collembola and gamazid mites were higher than those in the control samples. Repeated inspection in September of 1974 (1 year after the exposure) revealed a twofold decrease in soil mezofauna abundancy; decreased were populations of beetle mites, gamazid mites, earthworms, and ants. Additional inspection in autumn of 1975 (2 years after the experiment) showed, that the earthworm population was not recovered even in two years following the experiment.

Impact of the Chernobyl radiation accident on soil fauna

After the radioactive fallout from the Chernobyl, the majority of radioactive products were concentrated in the upper soil layer, and the soil invertebrates in this layer of the biogeocoenosis were under the most intensive influence of ionizing irradiation.

Effects of accidental Chernobyl irradiation and subsequent recovering of soil fauna are described in the records S15, S16, S17, S18, S19 with sub-records.

Between July and September of 1986 and during the field season of 1987, estimates of abundance in the main groups of meso- and microfauna were carried out at distances 3, 30, and 70 km to the south of the Chernobyl NPP. In these regions, the sandy soil with significant litter and spots of green mosses was studied in pine forest, the humus horizon being 1-2cm. These studies have unambiguously shown that soil animals, dwellers of forest litter, were severely damaged. In the area located 3 km from the Chernobyl (place Izumrudnoye), the numbers of mass groups of soil mites and sexually immature invertebrates reduced by the middle of July 1986 approximately 30-fold. Radioactive contamination affected the normal reproduction of populations of many slow-moving soil invertebrates. The larvae and nymphae of many species were absent altogether in the soil fauna of the pine forest. Since the irradiation doses in the soil were estimated, it was concluded that doses of about 30 Gy induced catastrophic changes in the soil fauna, and doses of about 8Gy induced noticeable but insignificant changes in the soil invertebrates.

In order to evaluate the radiation effects on soil mesofauna of cultivated land, standard estimates of soil invertebrates in agrocoenoses were carried out at distances of 4 and 80 km from the Chernobyl NPP. The abundance of mesofauna in the thickness of cultivated soil was reduced markedly less than in forest soils (two- to threefold). In cultivated lands, no considerable mortality of adults was observed, but the abundance of young earthworms was lower by fourfold than in the control regions. In the cultivated soil even at a total dose of β- and γ-irradiation of 86 Gy on the soil surface (contribution of beta-radiation about 94%), the soil animals were relatively weakly damaged in the soil thickness. In cultivated soils, dwellers of lower horizons proved to be shielded from the effect of ionizing irradiation by the upper soil layers. No catastrophic mortality of soil fauna was recorded here for any group.

Since 1987, soil fauna was intensively restored even in the most damaged regions. Numbers of microarthropodes in the 30-km zone of the Chernobyl NPP recovered to pre-accidental level in 2-3 years due to species inhabiting lower soil layers; however, the biodiversity in this group was only 50% of the control within 5 years following the accident. In 1987, the abundance of earthworms in place Kopachi was about 15% of the control; the presence of worm's cocoons suggested they were reproducing even in the highly contaminated area. The total abundance of soil invertebrates in the contaminated forest area (place Kopachi, 1987) was 45% of the control. However, mesofauna was represented mainly by insect larvae, i.e. forms, which could repopulate the damaged soils from outside areas. The biodiversity in invertebrates, inhabiting forest litter and surface soil was reduced for several years; even in 1995, the biodiversity in surface soil fauna was about 50% of the pre-accidental level. By 1995, the total numbers of soil invertebrates integrated by the soil profile accounted to 70-80% of pre-accidental biodiversity (Krivolutsky, 1996).

9.3. Radiation effects on soil microorganisms

Microorganisms traditionally are considered as highly radioresistant organisms; the lethal doses (LD_{50}) for different species vary within a great range from about 50 Gy for Escherichia coli) up to 5000-10000 Gy for most resistant species. Also, microorganisms are able to restore population rapidly after an acute exposure, even if doses were high enough to cause mortality of 90% microorganisms (Krivolutsky, 1983; UNSCEAR, 1996). Obviously, from data on acute exposures, microorganisms cannot be considered as vulnerable component of natural ecosystems.

Since the exposures at extremely high doses are out of scope of the project, the EPIC sub-database on microorganisms is concentrated on the radiation effects observed in field conditions. These field observations demonstrated considerable differences between the responses to acute and chronic irradiation.

Characteristic example is given in the record M1 (with sub-records). Soil samples were collected in the Chernobyl area in 1993-1995; activity of ^{137}Cs in samples was about 1.1E+4 Bq kg^{-1}. The microbiological analyses shown that some species of microorganisms were not damaged, e.g. concentrations of *Bacillus sereus, Methylobacterium extorguens* did not differ from control values. In the same time, concentrations of specialized bacteria (nitrifying, cellulose-destroying, sulphate-reducing) were 10-100 times below the control values. The dose rates to microorganisms were obviously below the lethal levels. The hypothesis was proposed, that microorganisms were damaged not by irradiation itself, but by chemical products of water radiolysis created by irradiation. An experiment was conducted with keeping individual species of microorganisms in solutions of hydrogen peroxide (0.1-1 molar solutions), which represents the persistent product of water radiolysis. The results of this experiment confirmed proved the hypothesis of indirect radiation damage: microorganisms sensitive to the elevated concentrations of H_2O_2 were also declined in the Chernobyl soils; in contrast, microorganisms which were insensitive to the increased H_2O_2 levels, were not damaged in the Chernobyl soils. Most probably, water radiolysis occurs in thin films of water covering the contaminated soil particles, forming concentrations of H_2O_2 harmful for some microorganisms.

Microbiological studies of soils in the Kyshtym radioactive trace (7.4E+7 Bq m^{-2}) also revealed a decrease in populations of some microorganisms, namely in groups of Flagellata, Ameboida, Infuzoria, see records M4-M9.

Mutation processes in irradiated cultures of unicell algae Chlorella were studied by V. Shevchenko and his colleagues (Shevchenko, 1979; Shevchenko et al., 1993). Laboratory cultures of different Chrorella species were irradiated either from external source, or were grown in the solutions of different radionuclides. The numbers of mutant cells were counted during the exposure and in the post-exposure periods, see records M10-M15 with sub-records. The mutation processes and viability of irradiated cells were investigated in the irradiated Chlorella populations. The increased levels of mutant cells were formed in chronically irradiated Chlorella populations; correlations were obtained between the dose and share of mutant cells in the population. After an acute exposure, a dynamic mutation process was observed: at the initial post-exposure period, numbers of mutant cells increased till some maximum; after several cycles of reduplication the less-viable mutant cells were gradually removed from population.

In studies of wild Chlorella strains separated from the Kyshtym soils and cultivated in the laboratory, a phenomenon of the increased radioresistance was found. The testing exposure of wild Chlorella strains from the Kyshtym area revealed a higher survival capacity of wild strains when compared with the control cultures of the same Chlorella species, see records M14-M15 with sub-records. The increased radioresistance of Chlorella from the Kyshtym area was observed already in the 5th year following the accidental contamination, and maintained in the subsequent years.

The general conclusion can be made, that harmful effects of radiation can be observed in natural soil fauna at dose loads far below the reported values of LD_{50} to adults, which were obtained in the laboratory experiments. The increased radiosensitivity at some critical stages of ontogenesis is critical for reproduction of some soil invertebrates and, therefore, determines the overall radiosensitivity of their populations. The threshold for noticeable effects may be suggested at approximately 10 mGy d^{-1} for the northern areas, with dose to eggs/larvae accumulated during the winter period above 2-3 Gy.

10. CONCENTRATION EFFECTS OF NON-RADIOACTIVE SUBSTANCES FOR REFERENCE (OR RELATED) ARCTIC ORGANISMS

10.1. Non-radioactive contaminants in the Arctic and effects on biota

In addition to radioactivity, many harmful contaminants are present in the Arctic as a result of anthropogenic activity. Chemical contamination of the Arctic is non-uniform in space. High levels of contamination are characteristic for areas of technogenic activities: oil/gas fields along the coast of the Arctic seas; Ni-Cu mining industry on Kola Peninsula; lumber industry, large sea ports, etc. Beside local contamination, the Arctic is impacted by dispersed contamination caused by long-distance transfer of toxicants with air masses from industrial and agricultural areas of temperate/warm climate. In the cold Arctic climate, many toxicants (persistent organic pollutants (POPs), sulphate oxides, etc.) are condensed from the air to waters and to land. At low Arctic temperatures, many persistent organic pollutants are degraded very slowly, thus accumulating year-by-year from atmospheric depositions in the Arctic environment. Being fat-soluble, POPs are accumulated in the fat of the arctic organisms, and pass through food chains with biomagnification of POPs concentrations in top predators. In poor Arctic soils and oligotrophic lakes, many of heavy metals are more mobile/soluble than would be observed under warmer climatic conditions; the increased mobility of metals increase the impact of toxic metals on Arctic biota. A description of the concentration effects of important chemical contaminants in the Arctic is given in Table 10.1.

Table 10.1. Important non-radioactive contaminants in the Arctic and their toxicity to living organisms (based on AMAP, 1997,1998; Issaev, Ed., 1998)

Heavy metal / POP	General information	Reported effects	Threshold levels of effects	Degree of hazard to Arctic biota
Hexachlorocyclohexanes (HCH)	HCHs are rather water-soluble compared with other POPs and the compounds are volatile. Highest level of worlds oceans found in Arctic waters.	Effects of lindane include reproductive effects, immunosupression and tumor promotion.	Harmful at even low concentrations.	Reported values in caribou/reindeer are very low and are not expected to cause effects.
Toxaphene	Toxaphene is a complex mixture of several hundred boranes and camphenes, the pollutant is not well studied in the Arctic. However, Canadian data suggest that toxaphene is the most significant pollutant in freshwater fish.	This pesticide is highly toxic to fish.	Lethal water concentrations in the range of 5-100 10^{-6} g/l.	Predatory fish from Canada (Greenland halibut) were reported to have levels of toxaphene close to those known to affect bone development and reproduction
Polychlorinated biphenyls (PCB)	PCBs were widely used in electric equipment, buildings, oil platforms, etc. More than 200 congeners of PCBs exist and most of them are extremely persistent in the environment. The most toxic PCBs resemble dioxins in their chemical structure.	Effects on the immune system, and reproduction of birds, fish and mammals.	Tentative allowable concentrations in soil <0.06 mg kg^{-1} *	PCB levels in seabirds from the Norwegian Arctic approach or exceed levels affecting reproduction. In Arctic mammals the PCB levels exceed the threshold for immune toxicity.
DDT	DDT was used in the Arctic to control mosquitos and flies. This pesticide is concentrated in fatty tissue of fish, birds and mammals.	Effects on reproduction and development. For instance, DDT causes significant egg-shell thinning if birds were exposed to DDT.	Harmful at even low concentrations. Prohibited for use.	DDT and PCB levels in seabirds from the Norwegian Arctic approach or exceed levels affecting reproduction
Tributyltin (TBT) .	The most toxic substance deliberately introduced to natural waters	TBT is used as a poison against algae, fungi, insects and mites	Chronic effects of TBT on oysters, mussels and crustaceans concentrations above 10^{-6} g L^{-}	

			^{1}.	
Petroleum products	Oil industry offshore and on the coasts of the Arctic Seas: oil slicks, seeps of crude oil, dumping of drilling waters, and processed waters . Low arctic temperatures inhibit oil oxidation: at t = 5^{o}C the oil film is oxidized for 6 months, at t = 0^{0} C the oil oxidation is prolonged for several years.	Offshore contamination with oil products has a negative effect on sea birds and marine mammals because their ability for thermal regulation is impaired by oil contamination. Contaminations of terrestrial ecosystems have negative effects on vegetation, birds and other animals.	Disorders of the respiratory system and cardiac rhythm of marine fish (above 0.003 - 0.15 mg L^{-1} of petroleum products in water). Disturbances in zooplankton metabolism (above 0.1 mg L^{-1} . Damage to phytoplankton (above 1 mg L^{-1}). MAC: 0.05 mg L^{-1} *	In the Arctic areas of petroleum production, the levels of oil contamination of water and soils may occasionally exceed the MAC by hundreds of times
Mercury (Hg)	The most important anthropogenic sources to Hg in the arctic environments are fossil fuel combustion (esp. coal).	Hg is a nerve poison that may influence reproduction in mammals and birds.	Max. allowable level in seawater 10^{-4} mg L^{-1} , in soil 2.1 mg kg^{-1} *	Effects of mercury have also been observed for fish and plants.
Cadmium (Cd)	Cadmium is toxic for most organisms and can be taken up directly from water or via food. Particularly fungi may contain high levels. In higher animals Cd is accumulated in kidneys and liver. Biological half-life of the metal may be up to several decades. The most important source for Cd in arctic environments is non-ferrous metal production (especially Zn and Pb).	Reduced growth and larval survival in invertebrates. Ionic imbalance and disturbed calcium metabolism in fish. Damage to kidneys and disturbances in vitamin D - and calcium metabolism in birds and mammals	Damage to kidneys: Sea birds: >60 mg kg^{-1} w.w. Mammals : >100 mg kg^{-1} w.w.	Terrestrial: Even though some concentrations in the arctic exceed threshold values believed to cause kidney dysfunction, no such effects have been observed or reported. Concentrations of Cd in kidneys of some marine birds and mammals are high enough to cause concern.

Lead (Pb)	In global scale the most important Pb source is lead-containing petrol. Pb is easily adsorbed to soil particles and sediments	Effects of lead poisoning are anaemia, brain damage. For fish, lead poisoning may lead to skeletal damage, and reduced larval survival. Terrestrial plants: wilted leaves, shortened roots	Max allowable concentrations 0.01 mg L^{-1} in seawater, 6 mg kg^{-1} in soil*	
Arsenic (As)	Sources include oil/coal industries, metal industries, and insecticides.	Terrestrial plants: necrotic spots on leaves, inhibition of new sprouts In mammals: gastroenteritis, weight loss, death at higher concentrations	Max allowable concentrations 0.01 mg L^{-1} in seawater; 2 mg kg^{-1} soil	Concentrations of As in the vicinity of petroleum-refinery plants and coal –fired power plants were reported to be up to 6000 mg kg^{-1}(Kabata-Pendias et al., 1979)
Nickel (Ni)	Ni-Cu smelters on the Kola peninsula	Terrestrial plants: greyish colour of leaves, wilted roots	Max allowable concentrations (MAC) 0.01 mg L^{-1} in water; 40 mg kg^{-1} soil	In the vicinity of metal smelter plants in the Kola Peninsula the concentrations of Ni and Cu in soils were reported to exceed MAC by more than 10^2 times .
Note: * maximum allowable concentration (Russian regulations)				

10.2. Concentration-effects relationships for contaminants

The regulations of chemical toxicants in the environment usually deal with the establishment of maximum allowable (no-effect) levels for individual toxicants in the environment. With respect to environmental protection, however, it is important to have the concentration-effects relationships for a large range of toxicant concentrations, providing a scale of effects on different organism's fuctions and different types of biota. An example of concentration-effects relationships for PCBs (polychlorinated biphenyls) in mammals is shown in Table10.2.

The assessment of radiation impact on biota is usually based on estimation of doses to organisms. This approach is different from impact assessment for non-radioactive contaminants, which is based on analysis of toxicant's concentrations in the environment. For the purposes of environmental regulation it may be practically important to develop a unified approach for assessment, using concentration-effects relationships for both radioactive and non-radioactive contaminants. The examples of concentration-effects relationships for radioactive elements are given below.

Table 10.2. PCB's threshold levels corresponding to different biological effects in mammals. (From: Arctic Pollution Issues, AMAP. Oslo, 1997, p.88)

Concentration of PCB in tissue, ng g^{1} lipid weight	Effects in organisms
500	Short-term memory**, human offspring cord blood serum
1000	Visual memory, human offspring cord blood serum
7500 9000	Kit survival*, muscle, otter Kit survival*, muscle, mink
$2x10^4$ $2.5x10^4$	Immune effects**, rhesus monkey Poor reproduction, harbour seal
$(4-5)x10^4$	EC_{50} litter size, liver, mink
$8x10^4$	Poor reproduction, ringed seal
$(8-10)x10^4$	EC_{50} kit survival, liver, mink
* lowest-observed-adverse-effect level; ** no-observed-effect level or no-observed-adverse effect level; EC_{50}=concentration at which half of animals in the study were affected.	

10.2.1. Concentration-effects relationships for uranium-238

Uranium-238 belongs to the group of heavy metals; by its chemical properties, uranium is a highly toxic element (protoplasmic poison), which can be compared with toxic properties of mercuric chloride. With its very long decay period, uranium-238 displays a rather low specific activity. Thus, ^{238}U may be considered as a demonstrative example of a radioactive element, whose chemical toxicity predominates over its radiotoxicity. The concentration-effects relationships, demonstrating the toxicity of ^{238}U for aquatic ecosystems are given in Table 10.3; activities of ^{238}U in water are given for comparison.

Table 10.3. Concentration-effects and activity-effects relationships for radionuclide ^{238}U in aquatic organisms (based on Guskova, 1972)

Concentration of ^{238}U in water, mg L^{-1}	Activity of ^{238}U in water, Bq L^{-1}	Effect on aquatic organisms
< 0.05	0.6	No observable effects on aquatic biota
0.5	6.15	Some decrease in growth of microalgae (about 10%)
1	12.3	Decrease in growth of microalgae by 50-60%. Some decrease in Daphnia reproduction.
5	61.5	Signs of acute toxicity in Daphnia, decrease of reproduction. Degeneration (sex transformation) in gonads of fish (bleak)
10	123	Decrease of bacterial growth, decrease of phytoplankton biomass; Total cessation of Daphnia reproduction. Degeneration in gonads of fish
25	307.5	Rapid regeneration (sex transformation) in gonads of adult fish (bleak)
100	1230	Acute lethal concentration for Daphnia, fish, cessasion of phytoplankton growth, oppression of bacterial mineralization processes

10.2.2. Concentration-effects relationships for strontium-90

The radionuclide ^{90}Sr is one of the widely dispersed radionuclides of technogenic origin. Currently, ^{90}Sr is present in all terrestrial and aquatic ecosystems of the Arctic. The radiobiological effects of ^{90}Sr for terrestrial and aquatic organisms were studied for many years in laboratory and field conditions. In the previous chapters, the dose- effects relationships for ^{90}Sr were discussed. For the purposes of environmental regulations, it is possible to place the radiobiological effects of chronic exposure from ^{90}Sr along the concentrations/activities of this radionuclide in the abiotic environment. The concentration-effects relationships for ^{90}Sr in aquatic biota are presented in Table 10.4. In general, it is possible to develop concentration-effects relationships for some well-studied radionuclides. However, impact assessments for mixtures of different radionuclides can be more easily performed based on dose-effects relationships.

Table 10.4. Concentration-effects relationships for radionuclide ^{90}Sr in aquatic ecosystem (based on Shekhanova, 1983)

Activity in water, Bq L^{-1}	Radiation effect
3.7-37 Bq L^{-1} (or 10^{-10} – 10^{-9} Ci L^{-1})	No effects or weak stimulation in aquatic vertebrate animals
370-1110 Bq L^{-1} (or (1-3)x10^{-8} Ci L^{-1})	Minor changes in blood of fish, minor effects on morbidity, compensatory effects on fish reproduction
(3.7-11.1)x10^{4} Bq L^{-1} (or (1-3)x10^{-6} Ci L^{-1})	Considerable decrease of fish fertility, up to sterilisation, negative effects on immunity, life shortening of fish
>3.7x10^{5} Bq L^{-1} (or >10^{-5} Ci L^{-1})	Decrease in reproduction of Daphnia, life shortening of Daphnia
1.9x10^{6} Bq L^{-1} (or 5x10^{-4} Ci L^{-1})	Violations in the development of mollusc's embryos
3.7x10^{7} -3.7x10^{8} Bq L^{-1} (or 10^{-3} – 10^{-2} Ci L^{-1})	Considerable oppression of microbial communities, oppression of saprophytic flora
3.7x10^{8} Bq L^{-1} (or 10^{-2} Ci L^{-1})	100% mortality of molluscs

11. CONCLUSIONS AND RECOMMENDATIONS

Main tasks and objectives

The main task of this report within the frame of the EPIC Project has been the compilation of dose-effects relationships on radiation effects in reference (or related) Arctic biota available from Russian/FSU sources. The information should be arranged in the form suitable for the purposes of the development the safety criteria for radiation protection of the environment. The central aim of this work was providing a scientific basis for the regulations in the radiation protection of the environment; the desirable result was to define the preliminary scale of the severity of radiation effects at different levels of chronic exposure. For this purpose, the compilation of data was focused on the effects of chronic radiation exposure at dose rates well below those that are known to cause short-term mortality of organisms. From the wide variety of radiation effects, selected were those, which are important for the survival and reproduction of organisms in the conditions of wild nature. The compiled data are concentrated on the effects in radiosensitive species in terrestrial and aquatic ecosystems, such as mammals, fish, and sensitive groups of plants (e.g. pines), less attention was given to rasioresistent species.

The EPIC database on radiation effects

The EPIC database includes data on radiation effects in wild organisms, which were observed in the northern areas of Russia, including sub-Arctic. These areas include the Kyshtym radioactive trace, local areas with enhanced levels of natural radioactivity in Komi Autonomic Republic of Russia, and some others. Data on radiation effects in the Low Arctic refer mostly to cold-water fish. There is a lack of data on the radiation effects in the polar deserts of the High Arctic. The database includes also the data from laboratory experiments with northern organisms, and some other characteristic, or unique experiments. Considering the great importance of the radiobiological studies of wildlife in the Chernobyl contaminated areas, these data were also included in the EPIC database.

In total, the EPIC database "Radiation effects on biota" contains about 1600 records from 435 papers and books. The structure of the EPIC database includes the following datasets (sub-databases):

- Radiation effects on terrestrial animals;
- Radiation effects on aquatic animals;
- Effects on terrestrial plants and herbaceous vegetation;
- Effects on soil fauna;
- Effects on microorganisms;
- Table of lethal doses.

The EPIC database information cover a very wide range of radiation dose rates to wild flora and fauna: from below 10^{-5} Gy d^{-1} up to more than 1 Gy d^{-1}.

Preliminary relationships "dose rate – effects" for chronic low-LET radiation

From the information, compiled in the EPIC database, the preliminary dose-effects relationships were derived for terrestrial and aquatic animals, also for terrestrial plants. The dose-effects relationships provide the scale of severity of radiation effects at different levels of chronic radiation exposure.

The following pleliminary scale of dose-effects relationships can be suggested for northern organisms (low-LET radiation, chronic exposure) based on the EPIC database:

10^{-6} -10^{-5} Gy d^{-1}	Natural radiation background for Arctic/northern organisms
10^{-4} – $5x10^{-4}$ Gy d^{-1}	Minor cytogenetic effects. Stimulation of the most sensitive species.
$5x10^{-4}$ - 10^{-3} Gy d^{-1}	Threshold for minor effects on morbidity in sensitive vertebrate animals.
$(2\text{-}5)x10^{-3}$ Gy d^{-1}	Threshold for effects on reproductive organs of vertebrate animals, decrease of embryo's survival.
$5x10^{-3}$ -10^{-2} Gy d^{-1}	Threshold for life shortening of vertebrate animals. Threshold for effects in invertebrate animals. Threshold for effects on growth of coniferous plants.
10^{-2} –10^{-1}Gy d^{-1}	Life shortening of vertebrate animals; chronic radiation sickness. Considerable damage to coniferous trees.
10^{-1} –1 Gy d^{-1}	Acute radiation sickness of vertebrate animals. Death of coniferous plants. Considerable damage to eggs and larva of invertebrate animals.
> 1Gy d^{-1}	Acute radiation sickness of vertebrate animals; lethal dose received within several days. Increased mortality of eggs and larva of invertebrate animals. Death of coniferous plants, damage to decidous plants.

A general conclusion can be made, that the threshold for deterministic radiation effects in wildlife lay somewhere in the range 0.5-1 mGy d^{-1} of chronic low-LET radiation. In the same time, populations of highly productive vertebrate organisms (mice, some wide-spread fish species) were found to survive even at dose rates about 10 mGy d^{-1}, despite of radiation effects.

Effects of chronic high-LET radiation on wild organisms

The effects of high-LET radiation on wildlife, represented in the EPIC database, refer mainly to the areas of enhanced natural radioactivity (U, Th) in Komi AR of Russia. Also, the database includes the results of some experiments with exposure of aquatic organisms in solutions of ^{238}U or ^{232}Th. The negative effects on health, reproduction and survival of organisms contacted with enhanced levels of U and Th, were considerably heavier, than in the areas contaminated with low-LET radionuclides. The comparison of dose-effects and concentration effects relationships for these radionuclides leads to the conclusion, that high chemical toxicity of ^{238}U and ^{232}Th is dominating over their radiotoxicity. In this context, alpha-emitting radionuclides, characterized by low specific activity and high chemical toxicity, are not suitable for the purpose of evaluating the radiation weighting factors for high-LET radiation.

Peculiarities of radiation effects in the Arctic organisms

Although the direct experiments with the Arctic organisms are very scarce, some peculiarities in the manifestation of radiation effects in low temperature conditions can be defined based on general radiobiological laws and peculiarities of metabolic processes in Arctic organisms.

The development of radiation effects in the Arctic poikilotermic organisms is expected to occur more slowly, because of the low environmental temperatures. On the other hand, the repair of radiation damage in cells and tissues is not effective at very low temperatures.

Lesions in the cooled animals (e.g. poikilothermic or hibernating animals) and plants are latent. However, if the organisms become warm, lesions are rapidly revealed. Development of embryos and young poikilotermic organisms in the Arctic occurs slowly at low temperatures, therefore, at the same dose rate, the Arctic organisms receive much higher dose during the radiosensitive stages of ontogenesis when compared with similar species in the temperate climate. Low biodiversity of the Arctic ecosystems provide low chances for compensatory replacement of damaged species by any others. From the other side, long-distance migrations of many animals in the Arctic prevent them from permanent staying at local contaminated places.

Recommendations for future research

1. The EPIC database provides a large collection of radiation effects on wildlife under the conditions of chronic exposure. At present, the radiation impacts in the datasets are given mostly as they appeared in the source publications, i.e. activity concentrations in biota and environment, and/or author's dose estimates. A detailed dose assessment, using modern models for dose-to-biota calculations, is required to provide reliable estimations of dose rates for the EPIC datasets, and make dose reconstructions in cases there only "radionuclide concentration-effects" data were available from source publications.

2. The dose-effects relationships for low-LET radiation derived from the EPIC database, in coordination with recommendations and achievements from other international programmes/projects can be used for developing the internationally agreed safety guidance for protection of wildlife from ionizing radiation.

3. Effects of some natural alpha-emitting radionuclides (U, Th) on wildlife demonstrate the complex simultaneous action of chemical toxicity and high-LET radiation. Consideration of these radionuclides arises a problem of developing a unified methodology for combined assessment for chemical toxicity and radiation on biota.

4. The problem of evaluating the appropriate weighting factors for high-LET radiation in the context of wildlife protection is still unsolved. It became evident, however, that heavy alpha-emitting radionuclides with very low specific activity and chemical toxicity can not be used for the purpose of w_r estimations, because the bulk of observed effects on biota is associated with chemical toxicity of these elements. The safety regulations for these radionuclides (e.g. ^{238}U, ^{232}Th) are more appropriate to establish for each radionuclide separately.

5. There is a lack of experimental data on radiation effects in typical Arctic organisms. Conduction of radiobiological experiments in the Arctic conditions is of great importance for understanding the differences in radiosensitivity and radiation effects in the Arctic biota.

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SUPPLEMENT I.
Natural radionuclides in the Arctic/Northern aquatic ecosystems

The generalized data on the concentrations for radionuclides of natural origin in the Arctic/Northern fresh-water ecosystems are given in Table AI-1. The data refer to lakes situated in the tundra area, namely: Lakes Vyalozero and Ostrovkovoe in the Kola peninsula (Russia); Lake Levinson-Lessing in the Taimyr peninsula (Russia); lakes Paijanne, Inari, Iso Valkjarvi (Finland); Ovre Heimdalsvatn (Norway); Hillesjon (Sweden), and others (Kauranen & Miettinen, 1969; Ermolaeva-Makovskaya & Litver 1978; Iskra & Bahurov 1981; Marey et al., 1984; Matishov et al.,1994; STUK,1987-1992; Bakunov et al.,1999; NRCC,1983). All these lakes are characterized as oligotrophic, with low water mineralization.

Characteristic concentrations of natural radionuclides in seawater, and marine organisms are given in Table AI-2 (Woodhead, 1973).

Table AI-1. Concentrations of natural radionuclides in North freshwater ecosystems (generalized data), Bq kg^{-1}

Components	Radio-nuclide	Average, Bq kg^{-1}	Range, Bq kg^{-1}
Water	^{3}H	3.8	2.7-7.9
Water	^{40}K	0.05	0.01-0.1
Water	^{210}Pb	0.004	0.0009-0.017
Water	^{210}Po	0.002	0.0002-0.008
Water	^{232}Th	0.0003	0.00005-0.004
Water	^{238}U	0.003	0.0005-0.01
Bottom sediments	^{40}K	400	220-540
Bottom sediments	^{226}Ra	45	12-170
Bottom sediments	^{232}Th	40	14-94
Bottom sediments	^{238}U	50	10-100
Fish	^{40}K	110	90-190
Fish	^{210}Pb	0.006	0.0037-0.0074
Fish	^{210}Po	0.6	0.14-1.15
Fish	^{232}Th	0.02	
Fish	^{238}U	0.03	

Table AI-2. Typical concentrations of natural radionuclides in surface seawater, and marine organisms (Woodhead, 1973)

Radionuclide	Sea water, Bq m^{-3}	Crustaceans, Bq kg^{-1}	Molluscs, Bq kg^{-1}	Fish, Bq kg^{-1}
^{3}H	22-110	0.02-0.1	0.02-0.1	0.02-0.1
^{14}C	7.4	22	18.5	15
^{40}K	12000	93	107	93
^{87}Rb	107	1.5	1.9	1
^{210}Po	0.2-1.6	15-60	15-41	0.02-5 (muscles); 7.4-33 (liver); 0.7-8 (bone)
^{210}Pb	0.4-2.5	1.5-2.6	0.2-0.4	0.007-0.09 (muscles); 0.4-0.9 (liver); 0.3-4.8 (bone)
^{226}Ra	1.5-1.7			0.007-0.2 (flesh)
^{234}U	48			0.003-1.3
^{238}U	44			0.0025-1.1

SUPPLEMENT II.
Territories in Russia/FSU with high levels of radioactivity in the environment.

There are several territories in Russia/FSU, which are characterized with high levels of radioactivivity in soils and waters. Among these territories are: (i) territory, contaminated in 1957 as a result of the Kyshtym accident; (ii) Chernobyl zone, impacted by the Chernobyl accident in 1986 and also other contaminated areas in Ukraine, Belorus and Russia; (iii) numerous local areas of high natural radioactivity were revealed in Komi Autonomic Republic in Russia.

Numerous radiobiological investigations have been made in these areas; some studies are still carried out by teams of Russian/FSU specialists, also by international teams of specialists from many countries. These contaminated territories constitute the unique grounds for studies of radiation effects on wildlife, which is not separated from stresses and risks of natural habitats.

Because of great importance of the above-mentioned radiobiological grounds, the brief descriptions of these areas are given below.

Kyshtym radioactive trace (radiation accident of 1957)
In September of 1957, a heavy radiation accident occurred in the Southern Urals, Russia. This accident at the "Mayak" nuclear materials production complex, east of the town of Kyshtym in Chelyabinsk Region, resulted from a thermal explosion of a concrete tank containing liquid radioactive wastes. Approximately 7.4×10^{17} Bq of fission products were released, with about approximately 7.4×10^{16} Bq dispersed in the environment outside the production site (Burnazyan, 1990; Nikipelov et al., 1990). This resulted in long-term radioactive contamination of the territory and the formation of the Kyshtym radioactive trace (or East-Ural radioactive trace, EURT) with a total area of 23 000 km^2 contaminated with ^{90}Sr at a density greater than 3.7 kBq m^{-2}. The radionuclide composition of the release was characterized by a high production of relatively short-lived radionuclides: ^{144}Ce, ^{144}Pr, ^{95}Zr and ^{95}Nb. From a long-term aspect, however, the presence of long-lived ^{90}Sr in the release (2.7% of the total activity) is a major radiation hazard. The spatial distribution of the radioactive contamination is characterized by a relatively monotonic contamination decrease along a central axis and a rapid drop of the contamination density in the directions transverse to the axis. The maximum contamination density of the area in the vicinity of the explosion site amounted to 1.5×10^{8} Bq m^{-2} for ^{90}Sr. An area of 1000 km^2 contaminated with ^{90}Sr at a density greater than 74 kBq m^{-2} was assessed as being hazardous to humans, and the population was evacuated from it; this part of the contaminated zone is about 105 km long and 8-9 km wide. The radioecological reservation was organized within the evacuated zone, numerous radiobiological investigations of aquatic and terrestrial organisms were carried out in this reservation (see EPIC database bibliography: Ilyenko, 1971; 1974; Ilyenko, Krapivko, 1989; Burnazyan, 1990; Lebedeva, 1994; Piastolova, 1996; Sokolov, 1993; Kryshev, 1996; Ilyin, 2001).

Territories contaminated as a result of the Chernobyl radiation accident of 1986
Great radiation accident occurred on April 26,1986 at the Chernobyl nuclear power plant (Ukraine). Reactor operators lost control on one of the reactor units (N.4); as a result the reactor went from low power level into a power surge, exploded and caught fire. The explosion ejected large amounts of radioactive debris into the atmosphere, and fire melted the fuel elements in the core of the reactor, releasing volatile fission products and gases. The

Chernobyl catastrophe resulted in widespread radioactive contamination over large areas of Belarus, Ukraine, Russia, and other countries. The 30-km zone around the Chernobyl NPP is characterized with the highest levels of radioactive contamination (up to 3.7×10^6 Bq m^{-2}), since 1986 this zone is used as a ground for extensive radiobiological studies (see EPIC database bibliography: Taskaev, 1988; Zaynullin, 1988; Kozubov & Taskaev, 1990; Sokolov et al., 1990; Kryshev et al., 1991,1992; Atlas, 1994; Eliseeva et al., 1994; Kryshev & Sazykina, 1995, 1998; Kudyasheva, 1997; Ryabtsev & Lebedeva, 1999; Ilyin, 2001; Voitovich, 2002, and many others).

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Local areas of high natural radioactivity in Komi AR (Russia)

A number of small local areas, characterized by high levels of natural radiation is situated in the western side of the Northern Urals, Russia. This territory administratively belongs to Komi Autonomous Republic of the Russian Federation. Geographically this area belongs to the zones of the northern taiga and tundra on the European side of Urals (60-66°N, 48-60° E).

In 1957-1965, numerous local spots of radium, uranium and thorium anomalies were revealed in the Komi AR within the area of more then 2500 km^2 (Maslov, 1972; 1976; 1983; Rubtsov,1971; Kichigin, 2001). In 1963, the governmental resolution was issued about organization of a radioecological reservation in this territory. Several stationary research sites were organized by KOMI Institute of Biology within the areas with elevated natural radioactivity. In addition, supplementary control sites were selected, characterizing with the same ecological, but normal radiation conditions. The scientific studies of the radiation effects on natural biota on the above radioactive areas have been carried out since 1957. Presently, the Institute of Biology, Komi Branch of the Russian Academy of Science disposes natural polygons in different climatic zones (tundra, taiga, forest-steppe), which differ by gamma-background level (1-80 μGy h^{-1}), and by radionuclide compositions in soils The first review on the biological effects of natural radiation in the Komi area was published in the international literature in 1967 in the Proceedings of the Int. Symposium "Radioecological Concentration Processes (Maslov, Maslova, Verhovskaya "Characteristics of the Radioecological Groups of Mammals and Birds of Biogeocoenoses with High Natural Radiation", pp.561-571) without identifying the location of the investigated area. This publication was mentioned by F.Turner in his review of 1975. Numerous publications on this subject have been published since 1957, mostly in Russian (see EPIC database bibliography: Verhovskaya et al., 1965; Maslov et al., 1967; Maslov, Maslova, 1972; Maslov, 1972; Maslova, Verhovskaya, 1976; Maslova, 1980; Materij, Maslova, 1977, 1978, and others).

The main results of radioecological studies in the Komi area are included in the EPIC database of radiation effects on terrestrial organisms.

There are some other areas of interest in the territory of Russia/FSU (Novaya Zemlya, etc.), however the amounts of available radiobiological information are rather scarce.