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RADIOBIOLOGY & RADIOECOLOGY

Textbook for students
of higher educational institutions

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Радіобіологія та радіоекологія (англійською мовою): Навчальний посібник для студентів вищих навчальних закладів. Вид. 2-е, переробл. та допов. – К.: НУБіП України, Житомирська політехніка, 2019. – 384 с. Табл. 51. Іл. 98. Бібліограф.: 17 назв.

Викладено основні положення сучасної радіобіології та окремого її розділу радіоекології. Наведено відомості про природу і джерела іонізуючих випромінювань, радіочутливість організмів різних таксономічних груп, реакції організмів на дію випромінювань, шляхи протирадіаційного захисту та післярадіаційного відновлення. Розглянуто міграцію радіоактивних речовин в об'єктах навколишнього середовища та їх захист від радіонуклідного забруднення, деякі особливості господарювання на забруднених територіях, шляхи використання випромінювань у сільському господарстві, медицині, харчовій промисловості. Висвітлено основні принципи радіаційної безпеки та радіаційної гігієни.

Для студентів спеціалізованих груп з викладанням дисциплін англійською мовою вищих навчальних закладів, магістрантів, аспірантів, викладачів.

Радиобиология и радиоэкология (на английском языке): Учебное пособие для высших учебных заведений.

Изложены основные положения современной радиобиологии и отдельного ее раздела радиоэкологии. Приведены сведения о природе и источниках ионизирующих излучений, радиочувствительность организмов различных таксономических групп, реакции организмов на действие излучений, пути противорадиационной защиты и пострадиационного восстановления. Рассмотрена миграция радиоактивных веществ в объектах окружающей среды и их защита от радионуклидного загрязнения, некоторые особенности хозяйствования на загрязненных территориях, пути использования излучений в сельском хозяйстве, медицине, пищевой промышленности. Освещены основные принципы радиационной безопасности и радиационной гигиены.

Для студентов специализированных групп с преподаванием дисциплин на английском языке высших учебных заведений, магистрантов, аспирантов, преподавателей.

Radiobiology and Radioecology (in English): Textbook for students of higher educational institutions.

This book presents principal propositions of modern radiobiology and radioecology. An overview of the field of science about the nature and sources of ionizing radiation, radiosensitivity of organisms of various taxonomic groups, reactions of organisms on the ionizing radiation, the ways of radiation protection and postradiation repair is provided. The migration of radioactive substances in the objects of an environment and their protection against radiation as well as management on radio-contaminated territories and the use of ionizing radiation in agriculture, medicine, and food-processing industry is discussed. The main principles of radiation safety and hygiene are provided.

The present book is designed to help in the education of groups of students with English training of special courses as well as for masters, post-graduate students, and teachers.

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The chapters 1, 10 and 13 were writing together.

PREFACE

The beginning of the 21st century is marked by deteriorating environment that is a global issue. The number and complexity of environmental concerns are growing all time, and sometimes it seems overwhelming. To face the immense challenge of tackling the problems the knowledge of radiobiology and radioecology, as the separate branch of biology, is required.

Although radiobiological and radioecological studies were carried out for many decades and the knowledge of environmental radioactive contamination is superior to other environmental pollutants, the knowledge and information of radioactivity among population have not improved significantly over the last many years. Hence there is a need to inform about the behavior and impact of radionuclides on a man and the environment.

The science of radiobiology exists since 1895. Although until 1986 relatively limited number of scientists has been working in the field of radiobiology and main efforts were focused on the use of radioactive substances for solving concrete fundamental and applied problems. In April 1986 the Chernobyl accident in Ukraine occurred and turned the attention back towards radiobiology and radioecology.

After the Chernobyl accident the situation has changed drastically. It is absolutely clear that there is the necessity of radiobiological and radioecological knowledge for specialists working in different fields of economy and other branches. But, first of all, such knowledge is necessary for those working in the field of medicine and for radiologists, ecologists, geologists, food industry workers, foresters and many others. Radiobiological knowledge is especially important for agricultural workers (farmers) and specialists, working in this field – agronomist, soil scientists and veterinaries.

But it must be stressed that the course of radiobiology was read for some specialties, e.g. agrochemistry and pedology, veterinary medicine in institutes and universities of Ukraine from the end of 1950th. At that time the trend of this subject differed slightly by a character (medical radiology, practical X-ray diagnostics, method of radioactive indicators, radiobiological technologies, etc.). But the role of agriculturists, who were among that group of specialists, who struggled against consequences of the Chernobyl accident and who were aware of radiobiology is hardly possible to overestimate. Thus, these specialists made the main body of future teams, i.e. agronomists-radioecologists, veterinarians and medical doctors-radiologists, who actively participated in the liquidation of the consequences of Chernobyl catastrophe in the agricultural sector.

During almost two decades since the accident, the radiation background in many regions of the country has stabilized and approached to the natural level. Therefore, danger of so-called external irradiation is reduced substantially in comparison with the situation of the first post-Chernobyl years. However, radionuclides that are still present in the arable soil layers are taken up by plants and followed by food chains provides up to 95% of the total dose for a man.

The reduction of radionuclide absorption by a man and of radiation doses that would be received through the consumption of contaminated food is achievable through the production of clean plant and animal products. This is the only way to protect people from harmful ionizing radiation. It is obvious that the role of agronomists, soil scientists, veterinaries and other workers of agricultural sector for mitigating of adverse effects of the contamination is hardly possible to overestimate. Thus, only those specialists are able to provide dose reduction to the population in the contaminated food-producing areas as much as reasonably achievable. Contamination levels of food products in the contaminated areas must be kept under threshold values recommended for use, distribution or trade, so that the sale of these products was not restricted due to radioecological reason.

The present textbook is designed to help in the education of agronomists, soil scientists, veterinaries, ecologists, biologists, etc. The target reader is considered to be a student, thus the book provides a broad radiobiological and radioecological background rather than the description of the latest research findings and its interpretations. Emphasis in the book is put on the trends and problems of radiobiology and radioecology, its perspectives, sources of ionizing radiations in the environment, biological effects of radiation, transfer of radionuclides in the environment and, particularly, in contaminated food-producing areas. Short description of some of the methods that are considered to be potentially applicable for reduction of radiation doses that would be received through the consumption of contaminated food is provided.

The book provides the information to the future specialists who are in charge of radiation protection. The book also puts into perspective the appropriateness of the countermeasures, therefore, it is for agronomists, soil scientists, veterinaries, phytotechnicians and others concerned by the reduction of the radioactive contamination of the food chain and, hence, the reduction of human irradiation.

1. INTRODUCTION TO RADIOBIOLOGY: THE SUBJECT AND TASKS, THE HISTORY AND PERSPECTIVES

1.1. Definition of radiobiology and its place among adjoining sciences. 1.2. Trends and problems of radiobiology 1.3. History of radiobiology: stages of development. 1.4. Problems of radiobiology at modern stage. 1.5. Necessity of acquisition of radiobiological knowledge.

A life on our planet dates back to some three thousand million years ago. A number of millennia have elapsed since plants, animals and humans developed from a single-cell organism. There were and still are the numbers of factors that effect living organisms. Among them large variations of temperature, air precipitation in the form of drizzle, rain, sleet, showers and hail; the air movement from a weak wind to hurricanes and storms; variations in atmospheric pressure, duration of days and nights, etc. Radioactivity originates in natural sources (natural radioactivity) implies the consistent radiation exposure of the indigenous population of all organisms. Naturally-occurring background radiation is the main source of exposure for humans. During the 18th–20th century, the level of natural radiation background on the Earth is increased due to industrialization followed by extraction from the Earth, such valuable minerals or geological materials as building materials, raw materials for the production of mineral fertilizers and other minerals that contain natural radioactive elements. By burning of coal, oil, combustible oil-shale a large amount of natural radioactive isotopes enter the atmosphere.

In the middle of the 20th century, the artificial radioactive isotopes (artificial radioactivity) and sources of ionizing radiation have been created. The world's first nuclear weapons explosion took place in July, 1945, when the United States tested its first nuclear bomb. In following years, several nuclear weapons tests were conducted. After the Second World War was over, the use of nuclear power as an energy source began.

During nuclear weapons explosions, the nuclear fuel cycle, as well as nuclear accidents, a large number of naturally occurring and artificially produced radioactive isotopes, eventually, enter the environment, which in turn leads to the appearance of local areas and large territories with high levels of radioactivity.

How do radioactive materials move in and through the environment?, what are the pathways that radionuclides enter into plants, animals and humans?; how those organisms can be protected from radioactive substances? Those and other similar questions dealing with interactions of organisms and ecosystems with radionuclides and ionizing radiation are the subject of both radiobiology and radioecology, as the branch of biology.

1.1. Definition of radiobiology and its place among interdisciplinary sciences

The radiobiology, or radiation biology, is a science studying effects of ionizing radiation on living organisms and their associations. Radiobiology borders with sciences investigating biological effects of low-energy electromagnetic waves of infra-red, visible and ultra-violet rays and radio waves of millimetre and centimetre ranges – photobiology and biophysics. Radiobiology is a specific science dealing with extremely high energy of quanta and particles, which exceed energy of atoms ionization and are able to deep penetration into substance, affecting molecules and atoms.

The major objects of investigation in radiobiology are living organisms (human beings, animals, plants, microorganisms) and communities of commonly living organisms of different taxonomic groups representing ecological unity. Generally, radiobiology has no specific object of study; however, depending on a specific subject of researches, several trends of radiobiology can be distinguished: human radiobiology, radiobiology of animals, plant radiobiology, radiobiology of microorganisms and others. However, a subject of studying of radiobiology is also the macromolecules, subcellular substances, cells and their populations, cultures of tissues and organs, some metabolic processes, and metabolites are also objects of study in radiobiology. During last decades several trends of radiobiology, as molecular radiobiology, radiation biochemistry and radiocytology are appeared. Modern definition *of radiobiology is a science studying effects of ionizing radiations on living systems of all levels of organization.* Last definition of radiobiology is not alternative to the first and does not contradict it, but supplements it. Both definitions are correct.

The radiobiology should not be mixed with radiology – a science about action of ionizing radiation on the matter. Radiobiology, together with radiophysics and radiochemistry can be considered as a part of radiology.

On a joint of radiobiology and ecology there is a separate section that sometimes is related to ecology or is considered as an original science – radiation ecology, or radioecology. In the radiobiological nomenclature *the* *radioecology is the area of radiobiology studying concentration and migration of radioactive substances in the environment and their action on living organisms.*

1.2. Trends and problems of radiobiology

The modern radiobiology is a complex interdisciplinary area of the biological sciences, which has clearly distinguished separate trends. The major trends are: radiation medicine and medical radiobiology including radiation protection and therapy, radiation hygiene, radiation immunology and radiobiology of tumors; radiation ecology; radiation genetics; agricultural radiobiology that is an independent discipline, which includes veterinary radiobiology; radiation cytology; radiation biochemistry; radiation biophysics; space radiobiology etc.

Some of those trends have specific object of study others have not. However, each of them deals with specific problems.

The main task of the radiobiology determining a subject of its researches is to study laws of the biological effects of ionizing radiation on living organism to control and manage radiation-induced reactions.

Proceeding from this general problem the specific targets of each trend of radiobiology are formulated also according to the specific objects of researches and other features.

So, the *radiation medicine* studies the effects of ionizing radiations on a human organism, principles of prophylaxis and treatment of radiation damages, possible consequences of an irradiation of the population.

The *radiation ecology* investigates ways of migration of radioactive substances within biogeocenosis components and estimation of their quantities and biological effects of incorporated radionuclides.

Agricultural radiobiology investigates the radiosensitivity of agricultural plants and animals, opportunities of its modification, development of possibilities to minimize accumulation of radioactive substances in agricultural products.

Veterinary radiobiology is an independent trend of agricultural radiobiology that studies features of pathological processes, proceeding from the effects of ionizing radiation on an organism of domestic animals. It deals with the development of radioprotective measures in management of animal husbandry in areas contaminated by radionuclides, prophylaxis and treatment of such animals carrying out of the radiometric sanitary control of animal products.

Many of these tasks are derivatives of the main task of radiobiology and are closely related to problems of other trends. The problem of the largest trend of so-called *applied radiobiology* that has the aim of the practical implementation of tasks of all trends of radiobiology has an independent value.

Trends of radiobiology and basic communications, illustrating their interaction and subordination are shown in Fig. 1.

1.3. History of radiobiology: stages of development

Radiobiology is considered as a young science. It is fair, compared to such biological sciences as botany, zoology, anatomy, physiology, which history goes deep into centuries and even millennia.

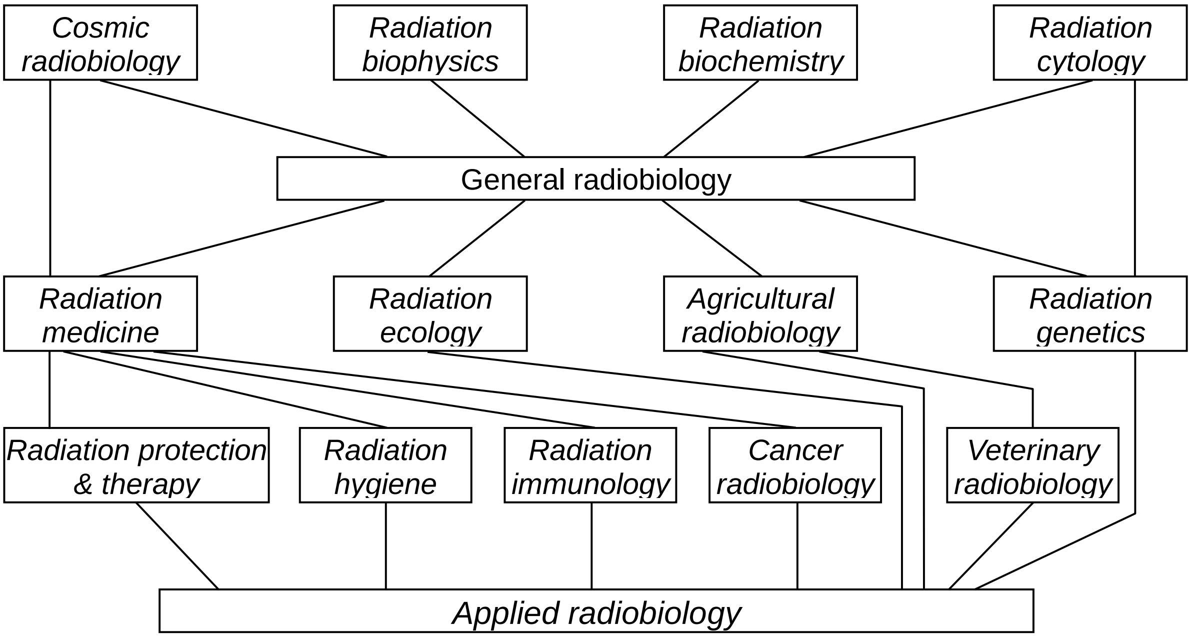
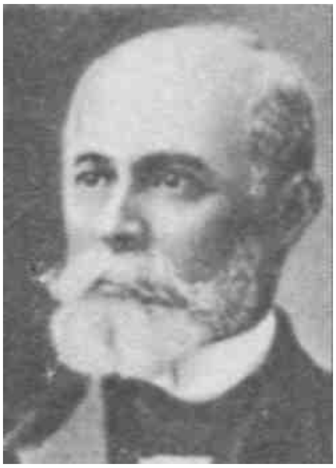


Fig. 1. The main trends of radiobiology.

At the same time radiobiology is older such biological sciences as molecular biology, molecular genetics, cellular biology, genetic engineering, which appeared in the second half of 20th century. In 2020 radiobiology has note centenary and quarter.

The birth of radiobiology as the independent science, is obliged to three great discoveries in the field of physics, made in the end of 19th century: the discovery of X-rays by German physicist W.K. Röntgen (1895) named subsequently after his name; the discovery of natural radioactivity of uranium by French physicist A. Becquerel (1896) followed by the discovery of radium and polonium by French physicists M. Sklodowska-Curie and P. Curie the new radioactive elements (1898). These discoveries were so great that W. Röntgen was awarded the first Nobel Prize on physics in 1901. Two years later in 1903 the same premium A. Becquerel and spouse Curie were awarded. It should be mentioned that in 1911 M. Sklodowska-Curie was again awarded the Nobel Prize for obtaining of radium in a metal state.

W.C. Röentgen
(1845–1923)



A.A. Becquerel
(1852–1908)

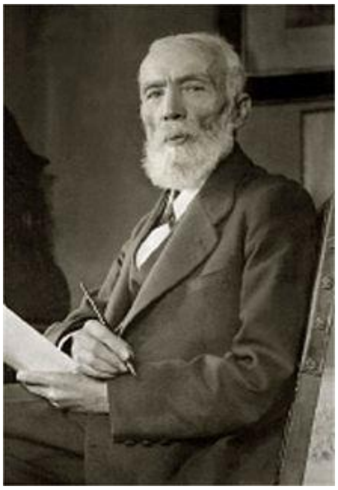
P. Curie
(1859–1906)

M. Sklodowska-Curie
(1867–1934)

Later on other radioactive elements were discovered. It was found out that all heaviest elements placed in the end of D. Mendeleyev periodic system starting with atomic number 84 to 92nd, including polonium, radium, uranium as well as astatium, radon, francium, actinium, thorium, plutonium and some others being radioactive. In 1906 radioactivity of ^{40}K – a potassium isotope was discovered. Potassium is an important biogenic element, which can be found in great amounts in cells of living organisms.

Long before the discovery of X-rays by W. Röentgen, many physicists experimented with cathode rays. Moreover, they observed a similar fluorescering glow when they hit certain substances. However, the W. Röentgen was the first one, who has "seen" the invisible X-rays that make up the component of a Crookes tube.

One of those who experimented with cathode rays was the professor of physics at the University of Vienna Ivan Pavlovich Pul'uj. He was born in the city of Grimailov in the Ternopil region. In 1864 he graduated from the Ternopil Gymnasium and entered the Theological Department of the Vienna University. At that time the Ternopil region was the part of Austria-Hungary, and Vienna was considered as the capital. After graduation he became a student of Philosophy Department and after having finished his studying Ivan Pul'uj began to investigate physical processes and phenomena. There is documentary evidence that in the middle of 1895, six months before the X-rays were discovered by W. Röentgen (there are evidences that this was even earlier), he received the first photographic images of various objects with the invisible component of cathode rays and readily shared these evidences with his colleagues. I. Pul'uj was personally acquainted with W. Röentgen, since they both were trained in the laboratory under the guidance of August Kundt at the University of Strasbourg in the early 1980s. However, W. Röentgen was the first who published the research results and in such a way reported these results to the scientific community, which is legally declared his discovery.


I. Pul'uj
(1845–1918)

Following investigations of radioactive emanation by radioactive elements showed that there are three kinds of emissions: positively charged nucleus of helium atoms named an alpha (α)-rays;

negatively charged electrons received the name beta (β)-rays and electromagnetic waves of very high frequency and high energy – gamma (γ)-rays (Fig. 2). All these rays (more correct – radiation) alike X-rays ionize, i.e. able to transform electrically neutral atoms and molecules of substance in positive and negatively charged ions.

Investigations of ionizing radiation effects on living organisms were carried out practically at once after discovering of X-rays and the phenomena of radioactivity.

Well-known Russian physiologist I. Tarhanov, the pupil of I. Sechenov, was the first among other scientists worked in this field. Being a private-assistant professor in Petersburg University, I. Tarhanov investigated the effect of X-rays on frogs and insects and published a paper dealing with the influence of radiation on "a course of vital functions" (1896). In this paper he showed damaging ability of X-rays and assumed the possibility of practical application of radiation in medicine, which soon was proved to be a true. Similar investigations were carried out in Kiev University by Ukrainian professor G. Demets.

Apparently, the first researchers, who used X-rays for cancer therapy, were American doctor G. Dzhillman and physicist D. Grubbe. They used X-rays for an irradiation of the patient with an inoperable breast cancer in 23 days later after official announcement of W. Röentgen discovery of X-rays, on January, 29, 1896. Grubbe continued a practice of tumors roentgen therapy as the effect of treatment appeared positive.

In the beginning of 20th century fundamental researches of the effect of X-rays and radium rays on animals and plants were carried out by well-known Russian pathophysiologist and biochemist E. London, working at that time in the Institute of experimental medicine in Petersburg. He was the first who showed damaging effects of ionizing radiation on many vital systems of an organism and especially on blood-forming haemopoesis. He also described the growth inhibition in irradiated plants and found out that radiation may cause death in mice. London is the founder of native radiobiology. His book "Radium in Biology and Medicine" published in 1911 was the first monograph in radiobiology.

In 1904 German researcher G. Peters found out failure of cell division under the effects of ionizing radiation. The connection between inhibition of the growth of numerous and divers living objects with the following suppression of cell division was shown precisely. But at that time it was a discovery. The pupil of Peters M. Kernike who was working with plants found out in 1905 that the most damaged part of cell was a nucleus. He was the first who described various types of distortions of nuclei division and chromosomes and he was deservedly considered as the founder of radiation cytology.

The French scientist G. Bone who worked with spawn and spermatozoon of a sea-urchin and the German zoologist O. Getrvig who investigated the effects of X-radiation on sexual cells and developing germs of various amphibious came to the same conclusion of an extraordinary high radiosensitivity of a cell nucleus.

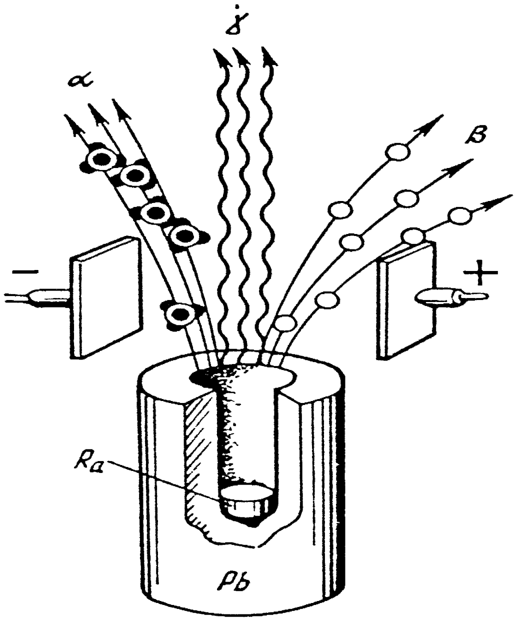


Fig. 2. Deviation of ^{226}Ra radiation in electromagnetic field.

The French scientists J. Bergonie and L. Tribondeau moved even further in their research and found that semen cells differed in their sensitivity to ionizing radiation. It was shown that spermatogoniums are the most radiosensitive while spermatozoon is radioresistant. In 1906 based on the experiment results Bergonie and Tribondeau suggested that *the radiosensitivity of a tissue is directly proportional to its mitotic activity and inversely proportional to its state of differentiation*. It is the process of mitosis that is radiosensitive and it was the fact that confers sensitivity on rapidly dividing cell population. This dependence that nowadays is known as a rule, or Bergonje and Tribondo law, is one of the fundamental laws in radiobiology.

At the very beginning of the radiobiology development in 1898 French physiologists M. Maldiney and K. Thouvenin made one more important discovery – the phenomenon of *radiation stimulation.* They found out that the radiation induced speeding up of germination of the seeds irradiated with low doses of X-rays. Universality of this phenomenon of growth speeding up and the development of organisms when any kind of plants, animals and microorganisms is being irradiated was proved during the following years. However, reasons for stimulation under low doses radiation are not well understood and intrigue radiobiologists during more than hundred years

Last years of the 19th and the first two decades of the 20th centuries can be accounted as the first stage of radiobiology development. During this period the great number of facts about effects of X-rays and radiation of radioactive elements on various biological objects were collected. These studies were conducted out by physiologists, zoologists, botanists, doctors, microbiologists, mycologists within the field of their own sciences. Thus, the results of these studies had a fundamental value and contributed considerably to the development of radiobiology although such studies were descriptive by nature.


G.A. Nadson
(1867–1940)

Mentioned above period was summarized up by the Russian microbiologist and botanist G. Nadson who was working in the State Radiological Institute in Petrograd in 1920. Nadson generalized the results of his own researches and more than one hundred of other scientific sources dealt with the effects of ionizing radiation on plants, animals, bacteria and fungi. He analyzed in details what was common and different in reactions of cells of various organisms in response to irradiation. Nadson also described the phenomenon of the cell death after several divisions, which is known now as an interphase death, or apoptosis, the phenomenon of “recuperation” of the irradiated cells and “recovery” of an organism as a whole.

However, radiobiology as an independent science did not exist yet. There was no satisfactory theory that could be able to explain the mechanism of ionizing radiation effects on the organism. The necessity of such theory was obvious. An explanation of so-called *“the radiobiological paradox”*, consisting in enormous discrepancy between insignificant quantity of ionizing radiation energy absorbed by a biological object and a degree of reactions revealed by this object, quite often resulting in organism death urgently demanded. This energy, expressed in the form of heat was immeasurably small.

Remarkable discoveries and new ideas that appeared during 1920–1930th were the starting points of radiobiology. Namely, the “*oxygen effect”* stating that in the presence of oxygen (O_2) almost all biological systems so far tested were more sensitive to X- and γ rays than when they were irradiated at very low levels of oxygen (hypoxia) or in the absence of oxygen (anoxia) was formulated.

German plant physiologist E. Petri was one of the first researchers who introduced the idea of oxygen effect. In 1923 E. Petri reported that radiation induced damage of wheat seeds and seedlings in an atmosphere with carbon dioxide decreased in comparison with that in ambient air. Later studies carried out with various biological objects allowed formulating unequivocally proposition about general biological nature of this phenomenon. It is difficult to overestimate the value of oxygen effect discovery for the development of theoretical basis of radiobiology. Moreover, it was firstly quantitatively shown that modifications of ionizing radiation effects on an organism are possible.

In 1920 G. Nadson came to the conclusion that the observable final radiobiological effect results in two opposite development processes: radiation-induced damage, on the one hand, and recovery processes that proceed side by side and simultaneously, on the other hand. Later, in 1925 French researchers P. Antsel and P. Vintemberger came to the same conclusion. Thus, so far an assumption about the possibilities of post radiation recovery of damaged cells and an organism as a whole for the present was only intuitively stated. Such assumption was rather courageous and even revolutionary, since long three decades most of the biologists kept firm opinion that any recovery processes during the postradiation period were impossible.

These years were marked by the important discovery – *mutagen action* of ionizing radiation and its abilities to affect the hereditary of living organism. The first time this phenomenon was shown by G. Nadson and G. Filippov with the lowest fungi in 1925. In 1927 American geneticist G. Meller, one of the authors of the chromosomal theory of heredity using *Drosophila* fruit flies, was the first who noted that chromosomes were very susceptible to radiation. This was quickly confirmed in the studies of many species of plants and animals. Thus, in 1928 American scientist L. Stedler showed a mutagen effect on high plants. The first Ukrainian geneticists A. Sapegin and L. Delone (1930) applied ionizing radiation to obtain artificial mutations in cereals. Such mutations resulted in the rise of new highly productive strains of wheat and barley.

Researches in the field of radiation mutagenesis of plants got a wide spreading in the world. Over three thousands strains of agricultural, decorative and other plants were raised by using radiation mutagenesis.

The phenomenon of radiation mutagenesis led to appearance of a new trend of radiobiology – radiation genetics. G. Meller who was awarded in 1946 the Nobel Prize, so far unique in radiobiology, and that divided with genetics is considered to be an ancestor of radiation genetics.

These discoveries made a basis for some general conclusions and theories that explained the essence of radiobiological paradox. In the beginning of 1920th German physicist F. Dessauer began to investigate this phenomenon. In fact, even at a lethal radiation dose only small amount of molecules can be damaged. According to some calculations 1 cm^3 of a biological tissue contains up to 10 billion (10^9) cells each of which, in turn, contains about 10 billion of biologically important molecules, having molecular mass over 5000. At a lethal dose of X-irradiation of mammal organisms up to 5×10^{12} molecules are destroyed (the greatest possible number of ionizations). It is the small part of molecules due to relation to the total number (about one molecule per 200 thousand unaffected molecules $(1 \times 10^{18}):(5 \times 10^{12})$. The question was how to explain radiobiological effect?

F. Dessauer thought that the electrons ejected from an atom do not move far a way but undergo recombination, resulting in neutral atoms and molecules. As a result of energy absorption a heat is emitted causing temperature increase in the particular place. If such event occurs in a specific place of a cell, for example, in chromosomes, such local damage can result in cell damage and even its death.

So, there was the first theory that explained the effects of ionizing radiation on an organism named dot heat theory that was precursor of direct action theory.

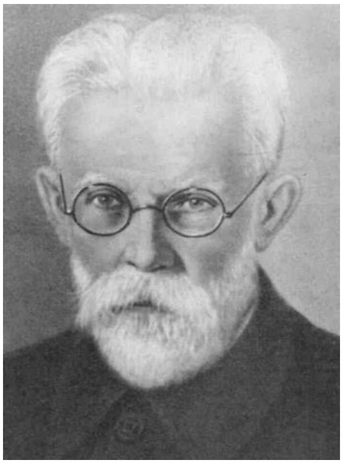
Later, D. Krouter in the Great Britain (1924–1927), F. Holvek in France (1928–1938) and others scientists developed ideas about step-type behavior (intermittence of ionizing radiation effects) and about processes of energy absorption as a sum of single acts interaction of a photon or a particle with molecules or structures of a cell. These ideas received the further development as so-called “a principle of hit” and the target theory formulated in 1935 by our compatriot – the outstanding radiobiologist and geneticist N. Timofeeff-Ressovsky and German physicists K. Zimmer and M. Delbruck. They laid basis of the theory of direct action of radiation on living cells.

In 1930th a theory of indirect action of radiation appeared. It was based on the radiochemical studies of O. Risse and H. Fricke who found that X-rays irradiation of water and water solutions causes radiolysis with following formation of short-lived chemically active radicals, as well as hydrogen peroxide and organic peroxides. Interaction of these products with biologically important substances results in their inactivation that can become a reason of cells death.

In 1930th a new trend in radiobiology – *radioecology* appeared. V.I. Vernadsky – the outstanding biogeochemist and radiogeologist was the first who revealed the basic laws of radium accumulation in fresh-water and aboveground plants. Under the guidance of Vernadsky in Biogeochemical laboratory of Academy of Sciences of the USSR and State Radium Institute the accumulation of natural radioactive elements in plants and animals and basic regularities of their migration in the environment was studied. The first studies on biological effect of radiation of incorporated radioactive substances on living organisms were carried out under his guidance. In the view of the discoveries of those years the special attention was given to genetic change.

The second stage of radiobiology development came to the end at the beginning of the Second World War. By that time the experimental material was collected and general conclusions were made. Some theories, certain principal ideas of which were thought to be hypothetical, but nevertheless were able to explain some facts and phenomena proposed. However, radiobiology as an independent science was not built. Even the term "radiobiology" existed only among narrow circle of scientists. Mainly enthusiasts – biologists, physics, and physicians-radiologists, made the investigations of the effects of ionizing radiation on living organisms. The potential opportunity to use an atomic energy was not known. There was no atomic energy, the nuclear weapon, and, hence, the threat of mass radiation danger was not known. However, Curie couple and great English physicist E. Rutherford created basic concepts about radioactivity, as well as other scientists assumed great power opportunities of atom and how danger it could be. V.I. Vernadsky unequivocally warned about the global radiation danger and called physicists-nuclear engineers for care and responsibility.

N.W. Timofeeff-Ressovsky
(1900–1981)



V.I. Vernadsky
(1863–1945)

The Second World War gave strong rise to the development of nuclear physics and atomic engineering. In 1945–1950th atomic bombs were created and used as a weapon by the American army in Japan. A number of nuclear weapon tests were conducted in an atmosphere in some countries and as consequence there was a real danger of mass irradiation of people and biosphere as a whole. It was a period when interest to consequences of biological effects of ionizing radiation increased remarkably, and this period determined the beginning of the third stage of radiobiology development.

In these years the radiobiology was finally formed as an independent area of science. The new problems arose: comprehensive investigation of radiation damage of multicellular organisms and, first of all, mammals under their total irradiation; the reasons of different radiosensitivity of organisms; the reasons and laws of appearance of the late effects of irradiation (decrease of immunity, occurrence of tumors, lifespan shortening, genetic effects of ionizing radiation). The investigation of possible pharmacological agents for radiation protection of organism became the most urgent practical problem in radiobiology.

At that time in the USA, Europe and Asia many radiobiological laboratories and research institutes appeared at the largest nuclear centers. It is necessary to mention Brookhaven, Oakridge, Argonne National Laboratories (USA), Laboratory of Radiobiology of the Nuclear Center in Harwell (Great Britain), Biological Department of the Nuclear Center in the Sakle (France), Institute of Biophysics in Frankfurt am Main (Germany), Radiobiological Department of the Nuclear Center in Thrombi (India), Radiobiological Institute in Sibe (Japan) and many others.

In 1950–1960th large radiobiological centers in Moscow in Institute of Biophysics, Institute of Chemical Physics, Cancer Center, Moscow State University, Institute of Biophysics in Pushchino, Institute of Medical Radiology in Obninsk, Leningrad Institute of Nuclear Physics, Institute of Biology in Syktyvkar, Institute of Biology of the Southern Seas in Sevastopol, Institute of Physiology and Institute of Plant Physiology in Kiev and others were established. During this period in radiobiology the powerful group of highly qualified specialists was generated.

Results didn’t keep them waiting. In 1949 radioprotective properties of aminoacid cysteine and sodium cyanide were discovered. In 1951 Z. Bacq showed the high protective efficiency of synthesized by him cysteamine which till now remains one of the most effective among protective compounds. The doctrine about radioprotectors (protective agents) arose.

In 1950th the phenomenon of postradiation reparation of a cell was experimentally proved. Russian radiobiologists V. Paribok, N. Luchnik and V. Korogodin are among those who contributed considerably to this field of science.

It was necessary to solve new problems in radiobiology in connection with nuclear weapon tests performed by many countries during 1950th – beginning of 1960th and global contamination of the Earth. The migration of artificial radioactive substances in biosphere, ways of penetrating into plants, animals and men organisms, the peculiarities of effects on an organism in connection with the specificity of distribution in tissues and bodies, various duration of removing and a chronic irradiation of cells was to be investigated. During this period radioecology was developing rapidly. Irradiation of an organism under low doses and following effects was a topical problem in radiobiology.

Achievements in radiobiology were widely used for solving practical problems *during those years. Ionizing radiation was intensively used in medicine for* diagnostics and treatment of diseases; in agricultural practice to raise the better strains of plants, increasing their productivity, for pests' control of agricultural plants and animals; disinfection and conservation of products in the food industry.

1970th are characterized by deepening penetration into radiobiological ideas of molecular biology, biophysical and biochemical methods of researches. Enriched by new experimental data theories of direct and indirect action of radiation were finally formulated and it was becoming evident that DNA molecule can be considered as a target for radiation.


A.M. Kuzin
(1906–1999)

The history and development of native theoretical ideas in radiobiology is connected first of all with the name of A. Kuzin. He was the author of the hypothesis explaining of stimulating effects of ionizing radiation and the structural-metabolic hypothesis that explain the mechanism of radiation damage of a cell with distortions of a metabolism and following formation of toxic substances.

The development and formation of modern radiobiology and radioecology in Ukraine is associated with the names of D.M. Grodzinsky and G.G.

Polikarpov – the founders of world famous scientific schools of plant radiobiology and marine radioecology.

In the first half of 1980th in many countries completely unjustified tendencies to reduction of radiobiological studies were observed. So, in the USSR the number of radiobiological laboratories had decreased in comparison with 1960th almost in three times by that period. To some extent it can be connected with some self-calmness caused by prohibition of nuclear weapon tests in an atmosphere, a space and under water (the Moscow treaty of 1963), with the decrease of radiation background with short-sightedness of some leaders of the science bewitched by propagation about ostensibly safe enterprises of nuclear power.

D.M. Grodzinsky
(1929–2016)

G.G. Polikarpov
(1929–2013)

Dramatic events on the Chernobyl nuclear power plant showed harm of such irresponsibility. They highlighted many shortages not only in nuclear physics and nuclear power, a civil defense and authorities, but also showed that in the country there were not enough highly skilled specialists-radiobiologists and the collectives who were able to decide medical problems operatively, and also problems of many spheres of managing in conditions of similar disasters.

On April, 26, 1986 the third stage came to the end and the fourth stage of the development of radiobiology began.

It was quite natural that not only radiobiologists, working in Russia, Ukraine and Belarus, countries, who were affected to the greatest degree by Chernobyl accident, but also scientists in other countries had to change the priorities in their researches and to put efforts in studying radiation effects of the accident, migration of ejected from collapsed reactor radioactive substances in various components of the environment and their effects on the biota to minimize consequences of the accident.

Large research establishments were organized, because new problems could not be solved by available forces. The main task for the nearest period was to study radiobiological effects caused by Chernobyl accident. The Scientific Center of Radiation Medicine and Ukrainian Scientific Research Institute of Agricultural Radiology (Kiev), Institute of Radiobiology (Minsk), the Byelorussian Scientific Research Institute of Agricultural Radiology (Gomel) and others scientific centers were founded. In many higher educational institutions there were radiobiological, radioecological, radiological departments, sectors, laboratories, faculties. The great army of scientists came to radiobiology from adjacent sciences.

Many lessons have been learned from the accident in Goiania (Brazil) and accident at the *Fukushima* Daiichi Nuclear Power Plant in Japan. According to IAEA Report (1988) on September 13, 1987, a shielded, highly radioactive source of ^{137}Cs (50.9 TBq, or 1375 Ci, at that time) was removed from its protective housing on a teletherapy machine at an abandoned clinic in Goiania, Brazil, and subsequently ruptured. As a result, many people have received large doses of radiation, due to both external and internal radiation.

Following an earthquake, a tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing a nuclear accident on 11 March 2011. About 30,000 km^2 of the land was contaminated by long-lived ^{137}Cs. The earthquake and tsunami caused great loss of life and considerable damage to buildings and infrastructure. It was the worst emergency at a nuclear power plant since the Chernobyl disaster in 1986.

1.4. Problems of radiobiology at modern stage

The major problems arisen in the field of radiobiology in 1945–1960th in connection with the possible use of the nuclear weapon and peaceful use of atomic energy were only partly solved and they are still topical. However, Chernobyl accident, which is considered as a global catastrophe forced to revise these problems and placed new accents concerning their priority.

At the modern forth stage the main problems of radiobiology are:

1. Features of effects on living organisms under low doses of ionizing radiation;
2. Specificity of chronic irradiation effects on living organisms;
3. Prophylaxis and therapy of acute and chronic radiation damages;
4. Radiation induced distortion of immunity;
5. Consequences of an irradiation;
6. Combined effects of ionizing radiation and other factors on an organism;
7. Migration of artificial radioactive isotopes in components of biogeocenosis;
8. Radiation induced damage of living organisms due to action of incorporated (included in cells) radioactive substances;
9. Minimization of accumulation of radioactive substances in plants, animal organisms and men;
10. Removal of radioactive substances from human organism.

The problem of effects of so-called low doses of ionizing radiation on living organisms (exceeding a level of a natural radiation background) is one of the central problems of radiobiology now. During all three stages of the history radiobiologists basically were engaged in studying of high doses effects on an organism that causes radiation diseases and organism death. After the accident at Chernobyl nuclear power plant millions of people were irradiated and continue to be irradiated under low doses. The data about radiation-induced reactions of immune system of an organism and its genetic status are very limited. Practically no information on radiation stimulation of human cells is available; there are no data on possible transformation of cells at low doses that can result in cancerogenesis.

The problem of low doses effects borders directly with the problem of chronic irradiation. All living organisms on the huge territories turned out to live under conditions of the chronic effect of radiation. What are the effects on plants and animals, their specific diversity and quantitative structures and how will it affect millions people living in similar conditions?

Such traditional problems for radiobiology as prophylaxis and therapy of radiation damages are still topical. More than half-century has passed since the time when first radioprotectors, including most effective and mentioned above cysteamine were discovered. However, till now suitable radioprophylactic agents which could promote organism to stand at least two times higher dose are not found. Practically there are no means by which could be possible to protect an organism at a chronic irradiation. The therapy of irradiation consequences is even more difficult.

One of the most serious outcomes of irradiation for men is radiation-induced damage of immune system. Low doses radiation induces suffering of nonspecific protective reactions and factors of specific immunity, change of allergic reactions, the development of autoallergy, which in its turn, causes appearance of endogenic and exogenic infections that can become a reason for many diseases and even death of an organism.

Later effects of radiation damage that can be observed after many years and even in the next generations (appearance of leucosis and malignant neoplasm, aging speeding up and lifespan shortening, mutagen effects and some others) and their prevention are the least investigated. The importance of such studies is obvious. The lack of knowledge in this area is mainly due to limited experimental data. As a rule, later effects on men are manifested after many years of an irradiation that requires long-term investigations.

Living organisms besides of various naturally occurring environmental factors are also affected by number of artificial substances. Apart of additional irradiation by artificial radioactive isotopes, there is a great number of other factors, including chemical substances that affects living organisms. Those are emissions and waste products of the industrial enterprises, exhausts of internal-combustion engines, mineral fertilizers, pesticides, acid rains etc. Theoretically, in some cases, such substances may mitigate effects of ionizing radiation; however, they usually strengthen radiation-induced damage. Joint effects of radiation and listed above factors can enhance considerably their total effect. For this reason the analysis of the combined effects of ionizing radiation and other factors on an organism including non-ionizing radiation, is one of the most important problems of radiobiology.

Studies on migration of radioactive substances and artificial ones in particular is the most important and topical problem of radiobiology, especial in the last years. It is necessary to investigate their uptake from various soil types by plants and further food chains of an organism of agricultural animals and men, the sites of their accumulation and concentration in various organs depending on chemical properties of radioactive compounds and features of a metabolism in various species of organisms. Estimates of radiation effects caused by incorporated radioactive substances on the organism are closely related to the problem mentioned above. During a metabolism stable essential elements may be replaced by radioactive substances, which also can be accumulated in some organs in great amounts and cause their local irradiation in high doses. Dosimetry of radiation in such situations is rather problematic.

In connection with the mentioned above the prevention of radioactive substances absorption, their accumulation in an organism of men and following elimination is very important. The prevention of radioactive substances uptake is a complex problem that can be solved on different stages of food chain by experts in different fields of study. On the initial stages of the agricultural production the main role belongs to agricultural experts. By the application of ameliorants and fertilizers, depending on physical and chemical properties of soil as well as by changing a set of plants in a crop rotation and a mode of an irrigation of crops, by the manner of keeping and feeding of animals it is possible to reduce considerably the amount of radioactive substances in agricultural products. Essential reduction of radioactive substances concentration in food products can be reached by technological processing. This problem can be solved by the food-processing industry workers. At last, correctly made by doctors-hygienists, experts in the field of radiation medicine the diet enriched with proteins, vitamins, macro- and microelements, special biologically active compounds can promote blocking of absorption of radioactive substances by an organism.

Some radioactive substances, which were incorporated in an organism with foodstuffs, water and air, are rather quickly eliminated from it by natural ways. However, some of them can be strongly bound to some tissues and organs, for example, in a skeleton, subjecting the last and nearby cells to a prolonged irradiation. Therefore, the problem of elimination of radioactive substances in complex therapy of the damages caused by an internal irradiation takes especially important place.

It is quite obvious that listed above problems cannot be solved only by biologists and physicians, but also by many researchers, working in other fields. At the present stage radiobiology has already accumulated the facts about reactions to an irradiation of different systems of an organism, various biological species. Now it requires their deep, all-round analysis and generalization. Extensive and close connections of radiobiology with other sciences, versatile, and sometimes unconventional approaches to the decision of many questions allow hoping for new discoveries in this area of biology in the nearest years.

1.5. Necessity of acquisition of radiobiological knowledge

In the middle of 1980th neither biologists nor doctors including experts who were not related to the field of biology were not enough represented than the science of radiobiology needed. Since the spring of 1986 the situation has changed. Many articles, brochures devoted to questions of effects of ionizing radiation on men and other living organisms, biosphere as a whole appeared in periodic, popular scientific editions. The large contingent of people worldwide, being before far from biology, medicine, preservation of environment, nuclear physics, atomic engineering and other areas of science and manufacture, to some extent revealed unusual interest to problems of radiobiology. It was due to the terrible full of dramatic nature events which had happened on the Chernobyl nuclear power plant.

If to turn back to the history of the development of radiobiology it is possible to see precise peaks and slumps of interest to it. And peaks always followed by tragic events in the world.

The first peak of relatively great interest to radiobiology fell at the middle of 1930th when in the press of different countries articles and the books about initial experiences of scientists working with X- and radium radiation were published. Soon, journalists' ominous terms "beams of death", "rays-murderers" appeared. But it was found out that it basically concerned a small circle of the "curious" scientists' voluntary going on contacts with such rays which did not represent dangers to the population. Therefore, public interest to such rays at the same time and to problems of radiobiology as well as all sciences connected with ionizing radiation fell.

Hundreds thousand peace inhabitants' lives were lost in the result of explosions of two nuclear bombs in Hiroshima and Nagasaki (Japan, August, 1945). It caused the second peak of general attention to radiobiology all over the world. But war was over and to the middle of 1950th the interest to it decreased again. In the beginning of 1960th it drastically changed again. The mass tests of nuclear bombs resulted in tragic events with human victims and increasing of radiation background all over the world. But the interdiction on nuclear bomb tests in the environments followed the probability of occurrence of nuclear war and, thus, the governments and public interest to radiobiology obviously decreased. It was completely unfair. Catastrophe on the Chernobyl Nuclear Power Plant stimulated interest to the science again.

However, nowadays even in the countries injured by the accident, negligible interest to its consequences encouraged by the authorities that hoped for autopurification of biosphere from radioactive substances and adaptation of the population to low doses of radiation is marked. Law interest to problems of radiobiology is obvious.

The main reason of it is the unilateral understanding of the problems associated only with nuclear threat, i.e. consequences of the possible nuclear conflict or accidents at the enterprises of atomic engineering. However, proceeding from mentioned above, radiobiology is a polyaspect and multiplane science. To some extent problems are really connected with the liquidation of the consequences of nuclear catastrophes. It would be incorrect to assert that these problems are of the second importance of radiobiology. But our epoch is also the epoch of submarines and ice breakers with nuclear engines, research nuclear reactors and nuclear power plants. The atom is often applied in daily use together with the most sensitive and exact technique of scientists, the most thin and irreplaceable tools of doctors, new progressive technologies, methods in agriculture. Inept or simply illiterate application of such methods, tools and technologies can result in sad consequences.

Thus, the knowledge of radiobiology basis is necessary not only for scientists-naturalists, but also for each man engaged in the sphere of material manufacturing and spiritual values. That is why radiobiology becomes stronger among both general educational sciences and the specialized disciplines such as biological sciences, mathematics, physics, and chemistry.

Control points to chapter 1:

1. Definition of radiobiology and radioecology as the sciences.
2. A place of radiobiology among adjacent sciences.
3. The basic trends of radiobiology.
4. The main problems of radiobiology and radioecology.
5. Discoveries in the field of physics that gave rise to the development of radiobiology.
6. Stages of radiobiology development.
7. The contribution of the scientists of our country to the development of radiobiology.
8. Modern problems of radiobiology.
9. Theoretical and practical value of radiobiology.
10. Necessity of wide propagation of radiobiological knowledge.
11. Prospects of the development of radiobiology.

2. TYPES OF IONIZING RADIATION, THEIR CHARACTERISTIC AND DOSIMETRY

2.1. Structure of atom. Isotopes. 2.2. Phenomenon of radioactivity. Law of radioactive decay. 2.3. Types of nuclear transformations. 2.4. Types of ionizing radiation. 2.4.1. Electromagnetic ionizing radiation. 2.4.2. Corpuscular ionizing radiation. 2.5. Interaction of ionizing radiation with matter. 2.5.1. Interaction of electromagnetic radiation. 2.5.2. Interaction of corpuscular radiation. 2.5.3. Linear energy transfer of ionizing radiation and their relative biological efficiency. 2.6. Radiometry and dosimetry of ionizing radiation. Units of radioactivity and doses. 2.7. Relations between radioactivity and dose of radiation. 2.8. Forms of irradiation.

Living organisms as well as non-living objects of the environment are affected by set of various factors of the physical nature including radiation (visible light, ultra-violet, infra-red, magnetic fields, radio-waves of various ranges). Ionizing radiation of natural radioactive elements and isotopes as well as space radiation also acts. However, if the majority of types of radiation is reflected from subjects or is absorbed by superficial layers, ionizing radiation penetrates into deep layers interacting with atoms and molecules of substance.

Radiobiology studies effects of ionizing radiation on living organisms. The term of ionizing radiation stands here to explain such high-energy radiation that interacts with matter and results in ionization of its atoms and molecules, their following transformation from electrically neutral particles in positively and negatively charged ions. The ionized state of atoms and molecules proceeds very short time (only 10^{-8} s.). Then ions again turn to neutral particles. And by itself it is not dramatic for a cell and its components. But the transfer to the ionized state is accompanied by the occurrence of great quantity of the secondary high-energy particles capable as an ionizing radiation, to penetrate deeply into substance of tissues and cause damages.

So, the average kinetic energy of gamma-quanta of the radioactive isotope of caesium ^{137}Cs that is one of the several most dangerous artificial long-lived radioactive contaminants injected in the environment due to explosion of the nuclear weapon and accidents on nuclear reactors. It makes 660 000 eV (ultra-violet light, for example, 12 eV, and visible light – only from 1 up to 3 eV).

When only one hit of photon into substance occurs, up to 11 000 ionizations (660 000:60; 60 eV – an average binding energy of electron in atom) can take place during realization (exchange) of such quantity of energy producing an avalanche of electrons. At a dose only 1 R (roentgen) in 1 cm^3 of air 2.08×10^9 pairs of ions are formed. Only fewer amounts of ionization occur in 1 cm^3 of a living tissue. At a lethal to mammal doses 4–18 Gy (Tabl. 21), that is approximately 400–1800 R, – up to 5×10^{12} pairs of ions are produced. Accordingly, such quantity of transformations (damages) can theoretically be carried out in substances of a cell that in its turn can result in its destruction.

The physical and chemical nature of these phenomena also will be considered in these and subsequent chapters.

2.1. Structure of atom. Isotopes

The atom is the least particle of a chemical element that keeps its properties. The atom consists of positively charged nucleus and negatively charged electrons, rotating on orbits around it. *Electron (e)* is the easiest elementary particle of substance bearing a negative electric charge of the least possible number equal 1.602×10^{-19} C (Coulomb, or an ampere second. It is such quantity of electricity which proceeds through a conductor for 1 second at force of a current in 1 ampere). The absolute mass of electron makes 9.31×10^{-28} kg. According to the principle of equivalence of A. Einstein ($E=mC^2$) the electron mass can be expressed through the energy. The energy equivalent of electron makes 0.511 MeV. The total charge of electrons is equal to a charge of a nucleus and consequently as a whole the atom is electrically neutral.

Electrons rotating around a nucleus have the energy determined for each orbit. When an electron passes from one orbit to another one the energy of an electron changes in steps. When an electron passes from an orbit with higher energy to another one with lower energy (more remote from a nucleus), it is accompanied by release of energy. When an electron passes from an orbit with lower energy to another one with higher energy (closer to a nucleus), it is accompanied by absorption of electromagnetic radiation as a photon does. The second process that is accompanied by an increase of energy refers to as *excitation of electron*. Therefore the classical concept about an orbit of an electron in atom, as certain circle loses the sense. It appears that electrons, in which wave properties are inherent, are as though smeared in space and one electron can stay on various distances from a nucleus. It is spoken about so-called “electronic cloud” in the atom (Fig. 3), meaning thus the location of electron.

The radius of atom makes about 10^{-8} cm, and nucleus – only 10^{-12}–10^{-13} cm. Nucleus of atom comprises about 99.8% of atom mass. Nucleus of atom consists of *nucleons* – protons and neutrons.

The proton (*p*) is the elementary particle that has identical with an electron electric charge, but it is positive. The mass of the proton is 1836 times more the electron mass that is equivalent to 1.67×10^{-24} kg. The proton is a nucleus of the most simple by a physical structure of an element – atom of hydrogen. Positive charge of a nucleus will be neutralized by a negative charge of the only one electron.

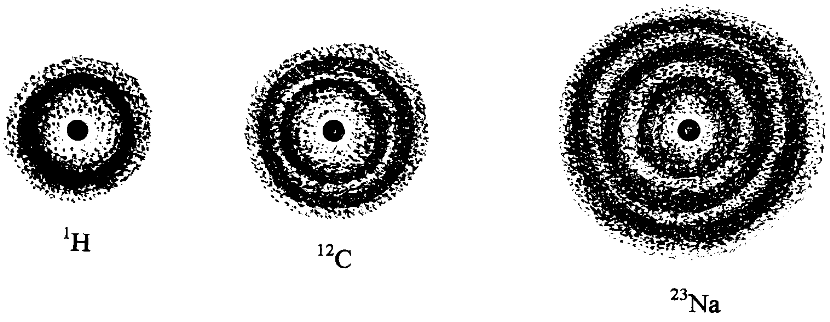


Fig. 3. Schematic picture of atomic electron shell of hydrogen, carbon and sodium.

The neutron (n) is the electrically neutral particle, the mass of which is equivalent to the mass of the proton. In connection with that the neutron has no charge, it neither interact with electrically charged particles nor deviates in a magnetic field.

The atomic nucleus includes also a set of other elementary particles: electrons, positrons, neutrinos, antineutrinos and mesons.

From the radiobiological point of view positrons are also of interest as possible type of ionizing radiation. The *positron* (e^+) is a particle identical with the physical properties of the electron, but having an equivalent positive charge.

The density of a nucleus is extremely great, reaching the values, which is hardly possible to imagine. It is 2^{14} g cm^3 or 200 million tone cm^3.

The number of protons defines an electric charge and a place of atom in the periodic system of elements of D. Mendeleev.

The atomic nuclei having the same number of protons but the different number of neutrons (and accordingly different mass) are called isotopes.

There are atoms with stable and unstable radioactive nuclei. Approximately 275 different nuclei among them that show no evidence of radioactive decay and, hence, are said to be stable with respect to radioactive decay. All atoms nuclei of isotopes of the elements placed after bismuth in the periodic system are radioactive.

What is the radioactivity caused by instability of nuclear nucleus?

2.2. The phenomenon of radioactivity. Law of radioactive decay

Nucleons are kept in a nucleus due to the nuclear forces. The nature of such forces is not well understood. Nuclear forces that operate on the very short distances not exceeding their diameter of a nucleus are thousand orders stronger in comparison with electromagnetic forces.

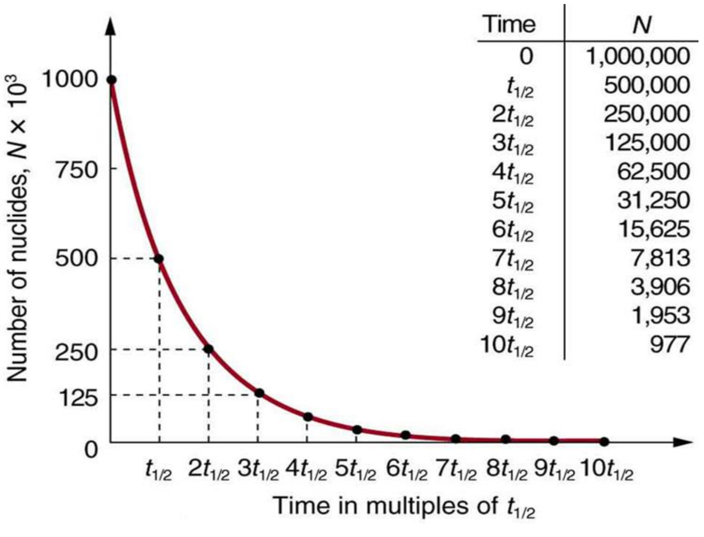
As we mentioned before there are approximately 275 different nuclei that show no evidence of radioactive decay and, hence, are said to be stable with respect to radioactive decay. When we compare constituent of nucleons of these nuclei, we find out that approximately 60% of them have both an even number of protons and an even number of neutrons (*even-even nuclei*). The remaining 40% are about equally divided between those that have an even number of protons and an odd number of neutrons (*even-odd nuclei*) and those with an odd number of protons and even number of neutrons (*odd-even nuclei*). Considering this pattern of the stable nuclei, we can conclude that nuclear stability is favoured by even numbers of protons and neutrons. The validity of this statement can be confirmed further by decreasing of the number and types of stable isotopes of any particular element. The parity of protons and neutrons in nucleus atoms of isotopes of light elements makes 1:1. Increasing of the nuclear mass of the elements in periodic table accompanied by increase the number of neutrons and the heaviest elements are approximately 1.6 times higher then the number of neutrons in comparison with the number of protons. 70 isotopes of 25 elements are unstable. It is supposed that they are still in the process of formation. This process comprises any possible nuclear transformations accompanied by emission of nuclear ionizing radiation.

Nuclear transformations (radioactive decay) involve a transition from a definite quantum state of the original nuclide to a definite quantum state of the product nuclide. The energy difference between the two quantum levels involved in the transition corresponds to the decay energy. This decay energy appears in the form of electromagnetic radiation and is the kinetic energy of the products.

In turn, the stable isotope can be transformed in radioactive one at absorption by a nucleus of atom energy from the outside with following decay and release of energy, emitting elementary particles and quanta. For this reason alongside with a *natural radioactivity* an *artificial radioactivity* takes place. By present about 1880 artificial radioactive isotopes of the practically all chemical elements obtained by their special irradiation (bombardment) by high-energy particles or in nuclear reactors are known.

Thus, *the radioactivity is considered as a spontaneous or artificial transformation of nucleus of atom of unstable isotopes of a chemical element from the basic state in other isotope of this or other element that is accompanied by emitting of energy of elementary particles or nucleus*. Such nucleus and corresponding atoms are considered to be as radioactive. Radioactive decay is a spontaneous nuclear transformation that is characterized to be unaffected by pressure, temperature, chemical form, etc.

Since ionizing radiation is a consequence of radioactive isotope decay, it causes gradual increase in number of atoms. Radioactive decay is a random process. Among the atoms in a sample of undergoing decay it is not possible to identify which specific atom will be the next to decay. *The law of radioactive decay* asserts that the identical portion of available nucleus disintegrates per unit time. The measure of the number of disintegrations per unit time is called the *decay rate*. The decay rate is proportional to the number of radioactive atoms present. The ratio of the number of nuclei at any time to the original number at a given time is plotted on both a linear and logarithmic scale as a function of time. The linearity of the decay curve in the semi-logarithmic graph illustrates the exponential nature of radioactive decay (Fig. 4).



Time	N
0	1,000,000
$t_{1/2}$	500,000
$2t_{1/2}$	250,000
$3t_{1/2}$	125,000
$4t_{1/2}$	62,500
$5t_{1/2}$	31,250
$6t_{1/2}$	15,625
$7t_{1/2}$	7,813
$8t_{1/2}$	3,906
$9t_{1/2}$	1,953
$10t_{1/2}$	977

Fig. 4. The exponential radioactive decay curve. In one half-life $t_{1/2}$, the number decreases to half of its original value, half of what remains decay in the next half-life, etc https://courses.lumenlearning.com

Mentioned above insensitivity to extra nuclear conditions allows characterizing radioactive nuclei by their decay period and their mode and energy of decay without regard to their physical or chemical condition. The time dependence of radioactive decay is expressed in terms of the half-life ($T_{1/2}$) which is the time required for one-half of the radioactive atoms in a sample to undergo decay. In practice this is the time for the measured radioactive intensity (or simply radioactivity of a sample) to decrease to one-half of its previous value. The *half-life period is the time during which the quantity of atoms of a radioactive isotope decreases twice.*

Half-lives vary from millions of years to fractions of seconds. In this connection they are subdivided on short-lived (fractions of seconds, seconds, minutes, hours, days), middle-lived (weeks, months, some years) and long-lived (tens and more years) isotopes. The shortest measurable half-life today is about 10^{-18} seconds and considered to be instantaneous. At the other extreme, if the half-life of the radioactive decay exceeds 10^{15} years, the decay usually cannot be observed above the normal signal background present in the detectors. Therefore, nuclides which may have half-lives greater than 10^{15} years are normally considered to be stable to radioactive decay.

However, it is necessary to mention the number of very important terminological features.

In both scientific and educational radiobiological literature (this manual is not an exception) the terms “radioactive isotope”, “radioactive element”, “radioactive substance”, “radionuclide’ to name the sources of ionizing radiation are quite often used as the equivalent concepts. In some cases it is justified and is not the big mistake. Nevertheless, they should be distinguished.

Isotopes as it was already mentioned are atoms of one element that has different mass numbers. *The radioactive isotope is an unstable isotope that undergoes decay.* Potassium element consists of three isotopes – ^{39}K, ^{40}K and ^{41}K. The first and the third isotopes are stable, and ^{40}K is radioactive. The terms “isotope” and “radioactive isotope” are usually used to denote atoms of the same element.

The radioactive element is a chemical element all isotopes of which are radioactive. For example, uranium that consists of three radioactive isotopes – ^{234}U, ^{235}U and ^{238}U and also thorium, polonium, radium, plutonium, americium and others comprise extremely radioactive isotopes.

The radioactive substance is a substance that comprises *a radioactive* *isotope.* The radioactive substances stand for chemical compounds, which include radioactive isotopes, for example, $^{40}KCl_2$, $^{235}UO_2$.

The term “nuclide” comprises terms “isotope” and “isobar”, i.e. atoms of an element having different number of nucleons in a nucleus or consisting of different number of protons and neutrons with identical number of nucleons. *The radionuclide or radioactive nuclide is unstable nuclide that undergoes decay*. The term “radionuclide” usually refers to radioactive atoms of radioactive substances, since radioactive isotopes are mainly present in various compounds rather then free elements, (for example, radionuclides ^{89}Sr and ^{90}Sr, ^{131}I and ^{133}I, ^{134}Cs and ^{137}Cs).

2.3. Types of nuclear transformations

In the beginning of this chapter we described the flow of electrons that is ionizing radiation resulting in various damages of substances. However, it is necessary to emphasize, that an initial source of radiation is a nucleus of an atom, but not atomic electron shells. It is obvious in the case of alpha-radiation, neutrons, and protons but is not absolutely clear in the case of beta particles that are not the part of a nucleus. These particles are produced in a nucleus as a result of decay at the transformation of neutrons into protons. Both the alpha- and beta-decays are accompanied by emitting of gamma-quanta. For this reason ionizing radiation sometimes is called as nuclear radiation. The main types of nuclear transformations or radioactive decay are alpha-decay, beta-decay (electronic and positronic), electronic capture (EC) and internal conversion.

Alpha- (α-) decay. Alpha decay is the emission of helium nuclei. Alpha particles are the nuclei of ^4He atoms, which consist of two protons and two neutrons. This configuration is particular stable. Thus, an alpha particle has a charge of 2^+ and a mass 4. The emission from initial nucleus (Z, A) is a process known as alpha decay. It leads to the formation of a product nucleus (Z-2, A-4). For example:

$$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + Q,$$

where Q is the energy emitted.

When a nucleus emits an α particle its atomic number falls by 2 and its mass number by 4. Alpha decay is observed for the elements heavier than lead and for a few nuclei as light as the lanthanide elements. Alpha particles are emitted from an energy state of the nucleus source, taking kinetic energy with them, which leave the nucleus product in a different energy state. In general, the energy of the most alpha particles from natural radioactivity is between about 4 and 11 MeV.

Beta-(β-) decay. The radioactive decay processes that are named by β-decay include electron emission (β^-), positron emission (β^+) and electron capture (EC). So, beta-decay is the creation and emission of either electrons or positrons, or the process of electron capture. It can occur in heavy and light elements. An example of natural beta-decay is the potassium isotope ^{40}K, which has a half-life of 1.28×10^9 years that is comparable with the age of the Earth. Beta "–" emission (electron emission) is produced by the conversion of a neutron to a proton inside the nucleus; hence an initial nucleus (Z, A) gives a product nucleus (Z+1, A). Similarly beta "+" emission (positron emission) is the conversion of a proton to a neutron and an initial nucleus (Z, A) gives a product nucleus (Z–1, A).

For example, the product of the beta-decay of ^{40}K (with 19 protons and 21 neutrons) is the stable calcium isotope ^{40}Ca (with 20 protons and 20 neutrons). The process is accompanied by emission of gamma-(γ-) radiation:

$$^{40}_{19}K \rightarrow \beta^- + ^{40}_{20}Ca + \gamma$$

In general, the isotopes of elements having nuclei with the neutron number greater than those having nuclei with greater proton number decay by beta "–" emission (β^-). The isotopes of elements having nuclei with the proton number greater than those having nuclei with greater neutron number decay by beta "+" emission (β^+). An example of such decay can be transformation of a radioactive isotope of phosphorus ^{30}P in a stable isotope of silicon ^{30}Si, making 3.05 % of all silicon available on a planet:

$$^{30}_{15}P \rightarrow \beta^+ + ^{30}_{14}Si + \gamma + Q.$$

In beta decay, the beta particles are emitted with a continuous energy spectrum, on the contrary to the discrete energy of alpha particle and gamma radiation decay. The maximum energy of spectrum, known as the endpoint energy, characterizes a particular radionuclide. Some radionuclides have a single spectrum and hence single endpoint energy and some have complex spectra with several endpoints energies. In order to explain the continuous spectrum observed in beta decay, the existence of the second emitted particle, the neutrino, which is virtually undetectable, was postulated. This is assumed to carry away a varying amount of energy so that the principle of conservation of energy is not violated. The neutrino is somewhat similar to the photon, which has neither mass, electric charge nor spin. However, while the photon readily interacts with matter, the neutrino does not. Beta-decay theory shows that neutrinos are emitted in positron decay, and antineutrinos are emitted in electron decay.

Electronic capture (EC). The EC decay process takes place when the electron from one of the inner orbit of the atom is captured by one of the protons of nucleus. The proton is thereby converted to a neutron γ-radiation is emitted. Depending on the electron shell from which the electron originates, the process is sometimes referred to as K-capture, L-capture, etc. The probability for the capture of an electron from the K-shell is several times greater than that for the capture of an electron from the L-shell, since the wave function of K-electrons is substantially larger at the nucleus than that of L-electrons. Similarly, the probabilities of capture of the electron in a higher order shells decreases with the quantum number of the electron shell. Electron capture is the predominant mode of decay for neutron deficient nuclei with the atomic number greater than 80.

Typical example of electronic capture is the absorption of an electron by nucleus of ^{40}K that in consequence turns to ^{40}Ar:

$$^{40}_{19}K + ^{0}_{1}e^{-} \rightarrow ^{40}_{18}Ar + \gamma.$$

EC decay is accompanied by release of γ-radiation.

Thus, the natural isotope ^{40}K can simultaneously undergo β-decay, producing β-and γ-radiations (88%), and electronic capture, producing γ-radiation (12%).

Internal conversion. The alpha and beta decay may leave the daughter nucleus in an excited state, i.e. a state of higher energy than the ground or zero energy state. This excitation energy is removed either by γ-ray emission or by a process called internal conversion and the nucleolus stays in the ground state. This process may occur in a single γ-ray emission, but there may also be multiple emissions with a cascade of γ-rays emitted each of which is associated with intermediate excited states between the initial state and the ground state. In such cases, the sum of the multiple γ-ray energy states is equal to the difference between the initial and the final energy states. In addition, γ-radiation can also be the sole mechanism for the de-excitation of an excited nuclear state. In this case, the product nuclide is the same as the initial one.

In some cases the initial excited state decays to a state close to the ground state, which has a relatively long half-life before finally decay to the ground state. It is known as an isometric (or metastable) state symbolized by a letter m placed after the mass number. A well-known example in the environmental radioactivity is the decay of ^{137}Cs that result from beta emission to ^{137m}Ba (an isomer of ^{137}Ba). The isometric state decays with the emission of a 0.662 MeV γ-ray that is usually used to determine the ^{137}Cs activity.

2.4. Types of ionizing radiation

There are two types of ionizing radiation originated from natural and artificial sources: electromagnetic and corpuscular.

2.4.1. Electromagnetic ionizing radiation

Electromagnetic, or photon, ionizing radiation is a stream of periodic electric and magnetic fluctuations that have shorter wavelength and higher energy as compared with the radio-waves, visible light and ultra-violet light. Inversely proportional relationship exists between wavelength and energy (Fig. 6). Among the types of the electromagnetic ionizing radiation, X- and γ-radiation of radioactive isotopes as well as the decelerated radiation arising when accelerated charged particles are passing through the substance is widely used in radiobiological researches and practice.

X-radiation is the electromagnetic radiation that is in a spectral area between γ- and ultra-violet radiations within a range of wavelength from 10^{-11} up to 10^{-7} m. However, X- radiation may be of a shorter wavelength up to 10^{-14} m. Conditionally X-radiation with wave length less than 2 angstroms (2×10^{-10} m) is called hard X-radiation and with wave length more than 2 angstroms is called soft X-radiation. Sometimes so-called super-hard X-radiation with shorter wavelength and, accordingly, higher energy up to 1 MeV is distinguished. These names are widely used in practical radiobiology, first of all radiation medicine.

γ-radiation – is one of the types of ionizing radiation which is emitted by nucleus both natural (^{226}Ra) and artificial (^{60}Co, ^{137}Cs) radioactive isotopes when a nucleolus changes from a more to a less excited state. Gamma rays are similar to X-rays that are also of electromagnetic radiation emitted when the electrons surrounding atoms change more to less excited state. γ-radiation is electromagnetic radiation which is characterized by extremely small wavelength – 10^{-12}–10^{-11} m and even less. On the scale of electromagnetic waves showed on

Fig. 5, γ-radiation borders with hard X-radiation and overlaps it a little, occupying an area of the shortest waves.

Accordingly, energy of X-radiation varies between several tens hundreds up to hundreds thousand, and γ-radiation varies from tens thousand up to millions of electron-volt.

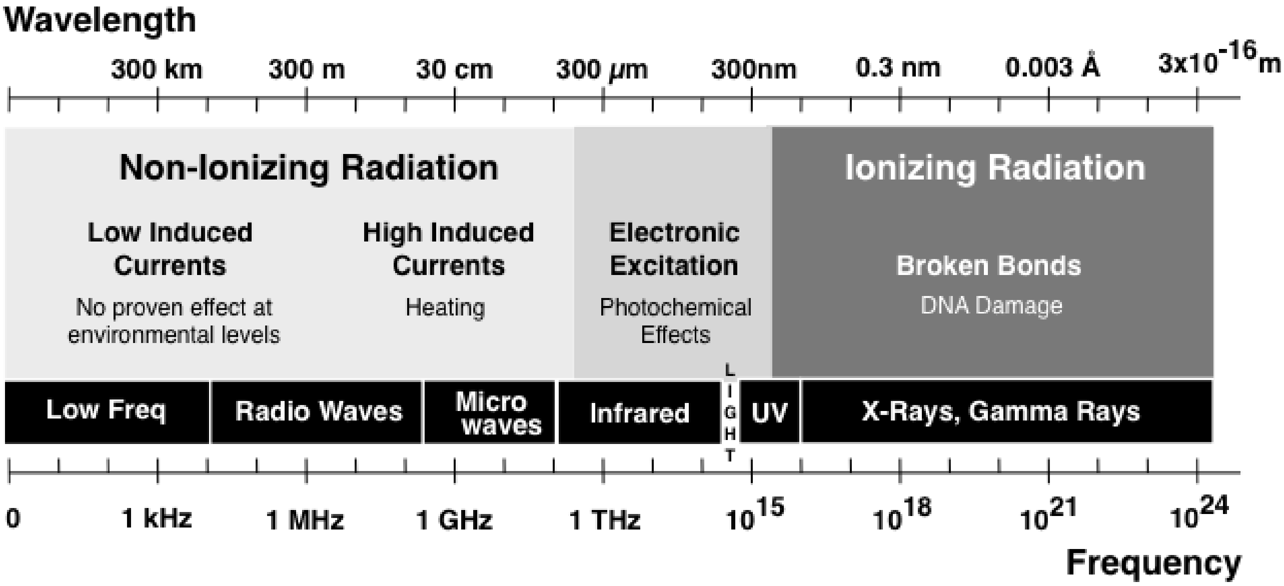


Fig. 5. Relations between non-ionizing and ionizing radiation. (https://copradar.com/chapts/chapt8/ch8d1.html).

Deceleration radiation appears when harged particles or fission products formed during spontaneous and artificial splitting of nucleus of uranium and plutonium, and some other nuclear reactions that result in decelerating in a matter. A classical example of deceleration radiation is the X-radiation of an X-ray tube arising at sharp decelerating of an electron stream, accelerated up to energies higher than 12 кeV, and its collision with atoms of tungsten of which the anode is made.

2.4.2. Corpuscular ionizing radiation

Corpuscular ionizing radiation is a stream of particles (corpuscles) that characterized by energy, mass and electric. Depending on the last two properties, particles are subdivided to *light* and *heavy*, *charged* and *neutral.*

Alpha-particles (α). Alpha-particles are considered to be heavy particles. Alpha particles are the nuclei of ^{4}He atoms that consist of two protons and two neutrons having, accordingly, two elementary positive charges.

Beta-particles (***β, e***$^{-}$). It is a stream of electrons that are the easiest negatively charged elementary particles which are emitted by a nucleus.

The substance can become a source of electrons if enough energy will be applied to it. So, if an electric field which is created in a vacuum is applied to tungsten cathode heated up to white heat, it begins to emit electrons. It will be a stream of electrons, but not β-particles. Although at the equal energy states they will interact with matter in the same manner.

Positrons (e^{+}***)***. They are the light elementary particles that are emitted by a nucleus. Positrons have similar properties to that of the electron; the only difference is that positrons have only a positive electric charge. In contrast to β-particle that is called as beta-minus-particle, a positron is called as beta-plus-particle.

Protons (p). They are the heavy positively charged elementary particles (the nucleus of ^{1}H atoms) that penetrate into nucleus of all chemical elements. The proton bears an electric charge, which is identical with such positron but has a mass 1836 times greater. The proton inside a nucleus can turn to the neutron when nucleus absorbs energy from the outside, and subsequent decay occurs. This process is accompanied by an appearance of the positron and the neutrino that is the elementary particle and has an electric charge of 0 and a mass ≈ 0.

Neutrons (n). These are heavy elementary particles that have an electric charge of 0, and a mass similar to that of proton. The neutron is considered to be a particle, which strongly interacts with matter, and is compared with heavy charged particles (α-particles, protons, deuterons) easily penetrates deeply into atoms and, reaching atomic nucleus, is absorbed or dissipated. When neutrons are absorbed by nucleus, the last become unstable and, in the subsequent decaying emit protons, α-particles, γ-radiation, i.e. acquire *artificial* or name *induced radioactivity*.

Depending on the energy the following conditional classification of neutrons is accepted: ultra cold neutrons (up to 10^{-7} eV), very cold (10^{-7}–10^{-4} eV), cold (10^{-4}–5×10^{-3} eV), thermal (5×10^{-3}–0,5 eV), resonant (0,5–10^{4} eV), intermediate (10^{4}–10^{5} eV), fast (10^{5}–10^{8} eV), high-energy (10^{8}–10^{10} eV) and relativistic neutrons (more than 10^{10} eV). Slow *neutrons* are called neutrons having energy up to 10^{5} eV. The *fast neutrons* are mostly used in radiobiological studies.

Deuterons (d). Deuterons are heavy positively charged particles, the nucleus of ^{2}H atoms. Deuterons are the simplest nuclear system known in nature that includes two particles – a proton and a neutron bound by a intranuclear forces.

The main physical characteristics of the major types of ionizing radiation widely used in radiobiological researches are shown in Table 1.

2.5. Interaction of ionizing radiation with matter

Penetrating ability of ionizing radiation, i.e. the depth of their penetration into matter, depends on the above-mentioned characteristics as well as on the structure and density of irradiating matter. Penetration depth is minimal in materials having high density, i.e. steel, lead that is usually used as a protection against radiation, and maximal in an air and other gases.

Table 1. Physical characteristics of the major types of ionizing radiation

Type	Symbol	Energy, eV	Wave length, m	Charge, C	Mass, g
Electromagnetic radiation					
X-radiation	X	5×10^1–5×10^5	10^{-11}–10^{-7}	–	–
Gamma-radiation	γ	5×10^5–5×10^6	10^{-12}–10^{-11}	–	–
Deceleration radiation	$X+\gamma$	10^4–10^6	10^{-11}–10^{-9}	–	–
Corpuscular radiation					
Beta-particles (electrons)	e^- (β^-)	10^3–1.7×10^6	–	-1.6×10^{-19}	9.31×10^{-28}
Positrons	$e^+(\beta^+)$	10^3–1.7×10^6	–	$+1.6\times10^{-19}$	9.31×10^{-28}
Protons	p	2–8×10^6	–	$+1.6\times10^{-19}$	1.67×10^{-24}
Neutrons	n	10^5–10^8	–	0	1.67×10^{-24}
Deuterons	d	5×10^5–10^7	–	$+1.6\times10^{-19}$	3.34×10^{-24}
Alpha-particles	α	3–5×10^6	–	$+3.2\times10^{-19}$	6.68×10^{-24}

When ionizing radiation penetrates into the substance it interacts with atoms and molecules. Thus the major part of energy is spent for ionization of atoms and molecules of substance and excitation of electrons. By passing through the matter ionizing radiation energy transforms in kinetic energy of secondary electrons of atomic electron shell as mentioned in the beginning of this chapter.

It has to be emphasized that corpuscular radiation causes ionization of matter itself. Electromagnetic X- or γ-radiation causes irradiation of matter indirectly; ionizing particles appear as a result of interaction of their photons with matter.

2.5.1. Interaction of electromagnetic radiation with matter

Since they are without charge, gamma rays are not deflected by electric or magnetic fields and hence their penetration in matter is much greater then that of charged particles. According to Beer's law, when a mono-energetic beam of gamma rays of the intensity I is incident up on a flat plate of matter, the intensity I after the beam travels a distance x through the plate is given by

$$I_x = I_0 \exp(-\mu x),$$

where μ is called the linear absorption coefficient of the plate material. Values absorption coefficients are shown in the Table 2. The straight line of the intensity of X- or γ-radiation against the thickness of the absorber allows obtaining accurately a quantity known as the "half value thickness" or "half value layer" (HVL). It is the thickness of the absorber that will reduce the intensity of a beam of X- or γ-radiation by 50%.

Table 2. The absorption coefficient of γ-radiation various energy states

Substance or material	Density, $g \cdot cm^{-3}$	Energy, MeV		
		1	2	3
Air	0.0013	0.00008	0.00006	0.00004
Wood (oak)	0.77	0.0521	0.0293	0.0203
Paraffin	0.89	0.0646	0.0369	0.0246
Robber	0.915	0.0662	0.0370	0.0254
Human tissues	1.0	0.0699	0.0393	0.0274
Water	1.0	0.07	0.05	0,04
Brick	1.78	0.113	0.0646	0.0473
Carbon	2.25	0.143	0.0801	0.0590
Concrete	2.4	0.154	0.0878	0.0646
Aluminium	2.7	0.16	0.12	0.09
Steel	7.83	0.460	0.276	0.234
Lead	11.34	0.77	0.51	0.47

In general, the value of μ depends on the absorbing material and on the initial energy of gamma rays, increasing from heavier elements and decreasing to higher-energy gamma rays. As a rule the ratio of μ to the density of the absorbing material is roughly constant, so that the mass of different materials required decreasing the γ-radiation intensity by the same fraction is approximately the same. The parameter μ is the result of three interactions described below.

There are three main mechanisms for the interaction of γ-rays with matter:

- photoelectric absorption (photo-effect);
- Compton scattering (effect of Compton, or Compton-effect);
- electron-positron pair production (Fig. 6).

In photoelectric absorption the photon energy is transferred to an orbit electron that is ejected from its atom. This process tends to predominate at low energy (below about 500 keV for lead absorbers). At higher energy (from about 500 keV to 5 MeV for lead absorbers), Compton scattering tends to predominate. In living tissues the photoelectric absorption is usually observed when low-energy electromagnetic radiation (long-wave X- and γ-radiations) with energy states up to 100 keV are applied.

Compton scattering takes place when after colliding with an atomic electron, the photon is deflected through an angle with its original direction and at a lower energy. The electron carries away the energy lost by the γ-radiation. As a result of scattering the narrow beam of radiation becomes wider and radiation consequently softer (long-wave).

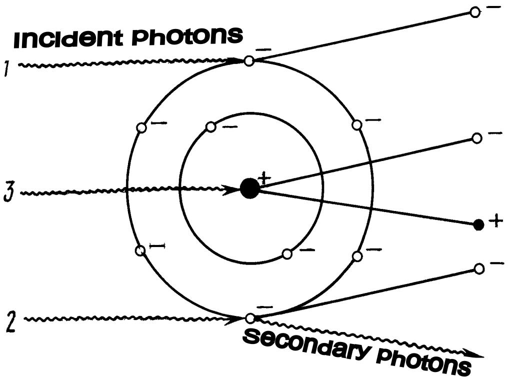


Fig. 6. The schematic description of the three main processes taking into consideration γ-radiation interaction and absorption: photoelectric absorption (1), Compton scattering (2) and electron-positron pair production (3).

The production of an electron-positron pair can occur if the γ-radiation energy is equal to or greater than the rest mass energy equivalent of the pair, which is 1.02 MeV. In this process a γ-ray of a sufficient energy disappears while in the electric field of a nucleus, an electron and a positron are created. Two particles of opposite charge must be formed for charge to be conserved. After this the positron disappears (annihilates) and two photons with energy 0.511 MeV are created. In a lead absorber, the probability of an interaction by pair production is greater than by Compton scattering at about 5 MeV and increases at higher energy. A minor interaction mechanism for γ-radiation and matter is the nuclear photoelectric effect, in which high-energy gamma rays may transfer their energy to a nucleus, and if it is greater than the neutron or the proton binding energy, one of these particles may be emitted.

The energy of the electromagnetic radiation of the majority of natural and artificial radioactive isotopes as well as X- and γ-radiation used in radiobiology varies between 0.2 to 2.2 MeV. The most probable mechanism of an irradiation interaction of plants and animals is Compton scattering and the electron-positron pair production.

2.5.2. Interaction of corpuscular radiation with matter

Generally, any type of charged corpuscular particles loses their energy primarily by the same mechanism. However, there are some differences. Interaction of α- particles with matter occurs mainly with atomic electrons. Each collision involves some kinetic energy transfer from the α-particle, which can ionize the atoms, i.e. one or more electrons are freed up from their orbits becoming free negative particles, leaving the atoms as positively charged particles. The transfer associated with an individual collision is relatively small, and so the α-particle continues to move in a straight line, making collisions until its energy is dissipated. A small proportion of α-particles undergo Coulomb scattering in matter, in which they are significantly deflected from their original path by interaction with the positive charge of the atomic nuclei.

When α-particles pass through low-density matter, such as gases, their range (distance travelled) depends on their energy. The range increases approximately as $E^{3/2}$. In high-density of solid material, the chance of a collision is greatly increased and the ionization per unit distance travelled is very high. Consequently the alpha particle range is very short and is usually described in units of mass per unit area, kg m^2. So, α-particles with huge energy of 5–10

MeV owing to the big sizes and positive charge will penetrate into living tissues to depth of 30–100 microns. This accounts for the fact that the exposure hazards by alpha particles for men are insignificant if the exposure is external, since a thin layer of clothing or the outer layer of skin absorbs their energy. However, if the exposure is internal, from inhalation or ingestion of the alpha-active material or its entry through an open wound, the alpha energy may be deposited in sensitive internal organs and the hazard may be significant.

Beta-particles are similar to α-particles because their principal mechanism of the interaction with matter is in making collisions with atomic electrons. The beta particles emitted can be negative (electrons) or positive (positrons) depending mainly on whether the unstable nucleus has an excess of neutrons or protons. Positrons, after being slowed down, interact with electrons with the disappearance of both particles and with the formation of two photons moving in opposite directions. Each photon has energy of 0.511 MeV. The energy is the equivalent of the mass of an electron at rest, according to the mass-energy relationship $E = mc^2$, where E is energy, m is mass and c is the velocity of light. The photons are known as annihilation radiation, where radioactive decay processes involve the emission of positrons; the associated gamma-ray spectra usually include a strong peak at 0.511 MeV due to the presence of annihilation radiation. Beta-particles produce much less ionization per unit length of path than α-particles do, so that whereas a 3 MeV α-particle has a range in air of about 28 mm, a 3 MeV β-particle has a range of about 10 m. So, the air is an inconvenient absorbing medium for beta particles. However, solids are practical absorbers and the range of a 1 MeV β-particle in aluminum is about 4 kg m^2 (or 1.5 mm).

It has to be emphasized that X- and γ-radiation cause regular ionization on their way in matter. As the α-particle penetrates deeper into the media more and more interactions (ionizations and excitations) occur, thus, reducing its speed, which in turn increases opportunities for further interactions. Eventually, a peak, often referred to as the Bragg ionization peak, is reached (Fig. 7) and followed by a decline to zero, when all the α-particle energy is dissipated. The exhausted particle attracts two electrons and becomes a neutral helium atom.

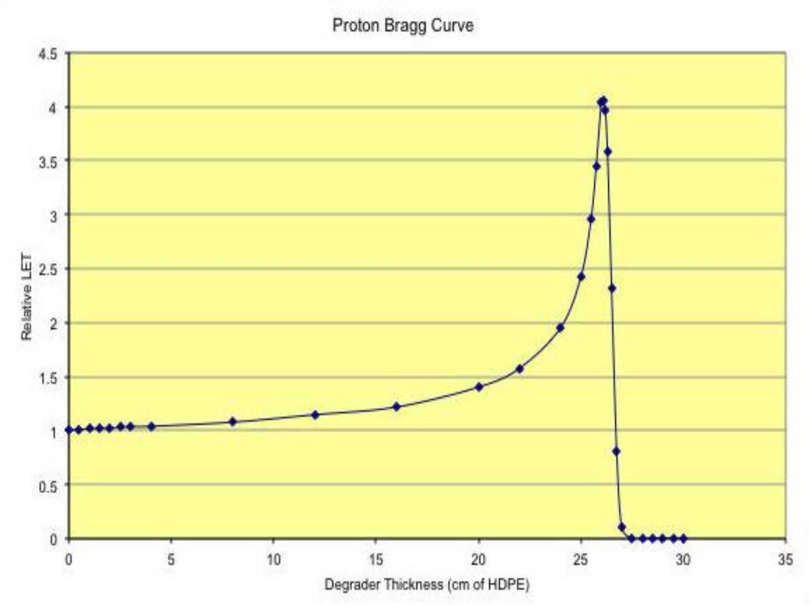


Fig. 7. Bragg Curve for 205 MeV protons. HDPE - high density polyethylene, ρ = 0.97 g/cm^3 (https://www.bnl.gov)

Number of ion pairs produced per path unit of a particle or a photon in a matter is called density of ionization or specific ionization. Alpha-particles produce the highest specific ionization. By passing distance in air up to 10 cm each α- particle produces some ten thousand pairs of ions per 1 cm of path while high-energy β-particle, for example ^{32}P, passing in air up to 25 m, produces only 50–100 pairs of ions per each centimeter. Photons of X- and γ-radiation that are passing hundreds meters in air are induced at about the same degree of ionization.

2.5.3. Linear energy transfer of ionizing radiation and their relative biological efficiency

Although all ionizing radiation interacts with living matter in a similar way, different types of radiation differ in their effectiveness or efficiency in damaging a biological system. The "relative biological effectiveness" (RBE) of a type of radiation is always expressed in relation to a dose of a standard type of radiation.

The most important factor that influences the RBE of a type of radiation is the distribution of the ionizations and excitations in its tracks. The idea of specific ionization was mentioned above. In order to accommodate the excitation and ionization events, the term liner energy transfer (LET) was created. So, LET is a *transfer of energy of ionizing radiation on the all length of path of a particle or a photon*. LET is expressed to explain energy released in keV per micrometer (μm) of the tissue traversed (keV mkm^{-1}). As mention above in the case of specific ionization, the velocity and the charge of the ionizing particle will affect the LET. Alpha-particles, neutrons and protons are high LET of radiation, X- and γ-radiation and fast electrons are low LET of radiation. Since the biological effectiveness of a particle is related to the amount of ionization and the distribution of it in its track, particles with high LETs will make more damage per dose unit than low LET of radiation. Alpha particles, protons and neutrons therefore have a higher RBE than X-radiation, γ-radiation and electrons. The RBE of radiation increases with the increase of LET that, however, does not hold at very high values of LET. The dependence between relative biological efficiency (RBE) of ionizing radiation and linear transfer energy (LET) of particles or photons is presented in Fig. 8.

In the case of high density of ionization, much more energy is deposited in the biological system than it is necessary to produce an effect. Since much of the energy is ”wasted“, the relative biological effectiveness falls.

X-radiation with energy of 180–250 keV or γ-radiation ^{60}Co or ^{137}Cs that produces approximately 100 pairs of ions per 1 μm of path in water is usually used as a standard. Therefore, RBE = D_O/D_X , where D_O is a dose of standard radiation and D_X is a dose of investigated radiation. Values of RBE for some types of ionizing radiation are shown in Table 3.

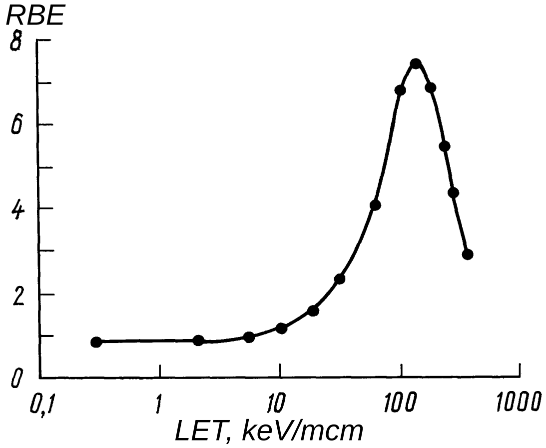


Fig. 8. Dependence of relative biological efficiency (RBE) of ionizing radiation on linear energy transfer (LET) of particles or photons.

To obtain the biological effective dose for different types of radiation we must use the concept of ”dose equivalence“ or so-called *quality factor*. The concept of ”dose equivalence“ is most useful in radiation protection where mixtures of radiation have to be considered because the difference in the relative effectiveness of different radiation is taken into account. Equivalent dose (Sievert) is numerically equal to an absorbed dose (Gray) multiplied on quality factor (Q). The Table 4 lists the quality factors that are specified by the International Commission on Radiological Protection (ICRP) and the LET values that should carry these quality factors.

Beta-particles, as well as X- and γ-radiation result in from several tens up to hundred ionizations on 1 mcm of path in water, and, hence, in living tissues due to similar density values in those media. They are called *sparse-ionizing radiation*. Losses of their energy do not exceed 3–5 keV mcm^{-1}, and their value of RBE is close to 1.

Protons, as well as deuterons and neutrons similar energy result in up to several hundreds ionizations and lose on 3–5 keV per μm of path. RBE for those particles reaches 3–5 and even 10. α-particles induce very dense ionization, and they have very high LET value. So, one α-particle with energy of 4 MeV that appears when boron or lithium is bombarded by neutrons, produces more than 9 000 pairs of ions in a tissue on 1 μm of path. Thus, losses of energy make up to 300 keV mcm^{-1} and RBE reaches 20. Nuclear radiation of uranium causes up to 130 thousand ionizations on 1 micron of path. These types of radiation are called *dense-ionizing radiation.*

Table 3. Relative biological efficiency (RBE) of various types of ionizing radiation

Type of radiation	Energy, MeV	Average number of ionization in 1 mcm of run	Average loss of energy, keV mcm^{-1}	RBE
X- and γ-radiation	to 3	100	3	1
β-particles, electrons, positrons	to 3	100	3	1
Slow neutrons	to 0.5	300	10	3
Fast and intermediate neutrons	to 10	800–1100	25–35	10
Protons and neutrons	0.5–10	700–1000	30	10
α-particles	5–10	10000	300	20
Nucleus of uranium division	5–20	130000	4000	20

Table 4. The dependence of quality factors (Q) on LET for some types of radiation

LET in water (keV mm^{-1})	Quality factors	Radiation
3.5	1	X-, γ-radiation or electrons
7	2	
23	5	protons, neutrons
53	10	
175	20	a particles, heavy recoil nuclei

Schematic picture of the length of the trajectory in the substance of sparse- and dense-ionizing radiation of the same energy is shown in Fig. 9.

Finally, it should be emphasized that knowledge of RBE factors of various types of radiation is extremely important for a prediction of probability of occurrence of those or other radiobiological effects, a degree of radiation damage, an estimation of a degree of risk at an irradiation, forecasting of level of radiation diseases and many other situations.

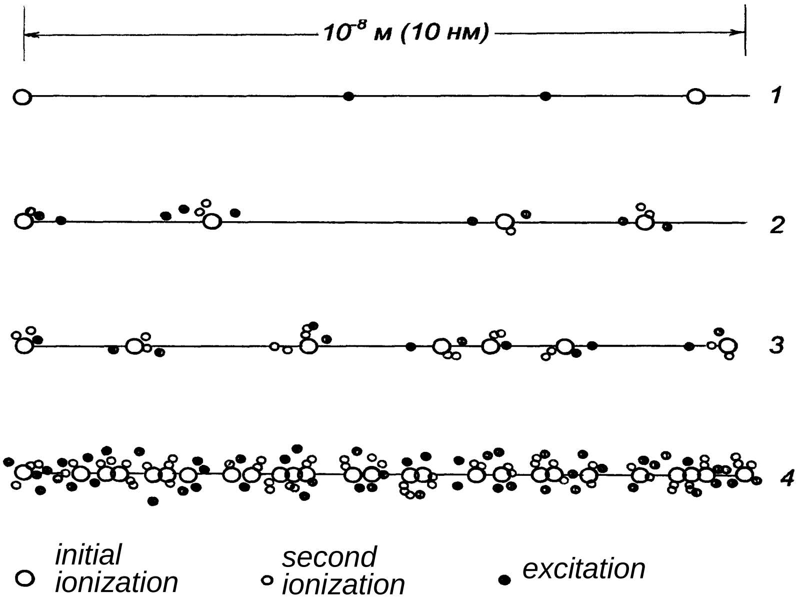


Fig. 9. Schematic picture of the length of run trajectory in substance of sparse- and dense-ionizing radiation of the same energy: 1 – β-particles, 2 – protons, 3 – deuterons and 4 – α-particles.

2.6. Radiometry and dosimetry of ionizing radiation. Units of radioactivity and doses

Uranium ore and other minerals, the mineral fertilizers created on their basis, building materials, as well as a ground, plants, water, air and many other substances and objects in the environment contain natural radioactive isotopes. In case of radioactive contamination listed above objects can contain certain amount of artificially produced radioactive isotopes. The level of radioactivity is estimated by various methods of radiometry. *Radiometry is a set of methods that define the activity and concentration of radioactive substances as well as types of their radiation in the sources of ionizing radiation and in the environmental objects*. The main task of radiometry is the quantitative estimation of a radioactivity of a sample, i.e. the number of radioactive transformations, or decays, for a time unit.

The SI unit of radioactivity is *Becquerel (Bq)* and the activity is given in reciprocal seconds, s^{-1}:

1 Becquerel (Bq) = 1 (disintegration) s^{-1}.

The decay rate is usually expressed as disintegrations per second (dps) or disintegrations per minute (dpm). In measuring radioactive decay, it is difficult to count every disintegration. However, the absolute disintegration rate A and the observed decay rate proportionally exist for any particular detection system:

$R = \psi A$

where R is the observed decay or count rate and ψ the proportionality constant, known as *counting efficiency*.

The measured count rate R is given in counts per second (cps) or per minute (cpm).

The earlier unit is the Curie unit (abbreviated Ci) that is still in some use and defined as:

1 Curie (Ci) = 3.7×10^{10} s^{-1} (Bq)

The Curie unit was originally defined as the number of decays per time unit and gram of ^{226}Ra, assuming its half-life to be 1580 years.

The *specific radioactivity* is defined as the decay rate A per unit amount w of an element or compound, $S = A/w$.

The *surface radioactivity* is defined as the decay rate per area unit.

The SI unit of specific radioactivity is Bq kg^{-1}. For practical purpose it is sometimes also defined as dpm g^{-1} or dpm $mole^{-1}$. *Activity concentration* (or “radioactive concentration”) is given in Bq m^{-3} or Bq l^{-1}. While the half-life is 1599±4 years, the specific activity per gram of ^{226}Ra is 0.988 Ci or 3.65×10^{10} Bq or 2.19×10^{12} dpm. The specific activity of the longer-lived naturally occurring radioactive substances is: K, 31.3 kBq kg^{-1}; ^{232}Th, 4.05 MBq kg^{-1}; ^{238}U, 12.4 MBq kg^{-1}. Accordingly, the specific radioactivity may by estimated in Bq kg^{-1}, and surface radioactivity is Bq m^2 or other equivalent units – kBq kg^{-1}, Bq cm^2, etc.

The radioactive substance or material containing radioactive elements creates a certain field of the radioactivity. It forms a dose of an irradiation of various objects, including living organisms. *Dosimetry is a measurement of energy of fields of ionizing radiation in the objects of an environment created by sources of a radioactivity.* The basic task of dosimetry in radiobiology is to define a dose of ionizing radiation in the environment as well as in a living organism. A dose is created as a result of ionizing radiation interaction with tissues for a certain time as at external exposure, when the source of a radioactivity is outside of an organism, and at internal exposure, when the radioactive substances are located inside the organism.

It is necessary to distinguish between radiation energy, directed at irradiated object from outside and the energy absorbed by object with the following physical influence. Therefore in radiobiology, as well as in nuclear physics, it should be distinguished between *expositive or physical dose (Dx)* and *absorbed dose (Dp)*. In radiobiology, however, in contrast to nuclear physics, it is necessary to deal with doses of lower orders.

The expositive dose is a dose that is formed in air on the certain distance from a source of radioactivity. In other words, it is an energy applied to object of irradiation.

Up to 1975, the two units of dosimetry, commonly used in radiation biology were the roentgen (R) and the rad. The standard unit of an expositive dose *roentgen (R)* was determined as a dose at which there is such quantity of ions, that their total charge is equal to 1 electrostatic unit of quantity of an electricity of each charge in 1 cm^3 of air. As it was mentioned in the beginning of the chapter, a dose 1 R corresponds to the formation of 2.08×10^9 ion pairs in 1 cm^3 of air. In SI system the unit of the expositive dose is *coulomb per kilogram (C/kg). 1 C/kg = 3876 R*. The roentgen that is defined as the quantity of X- or γ-radiation so that the associated secondary emitted electrons produce ions of the same sign carrying a charge of 2.58×10^{-4} coulomb per kilogram of air. The associated electrons are the photoelectrons or recoil electrons. The *rad* (from Radiation Absorbed Dose) was most useful unit for radiobiological purposes since it was a measure of the radiation energy actually absorbed by the tissue. One rad was defined as the absorption of 10^{-2} joule of radiation energy per kilogram of a material (0.01 J kg^{-1}).

Since the energy absorbed in tissue corresponding to an exposure to one roentgen is 0.0095 joules per kilogram, it follows that one roentgen gives an absorbed dose of 0.95 rad in tissue. So, in practice these quantities were often considered interchangeable.


L.H. Gray
(1905–1965)

Even if the biological effects of ionizing radiation are to be estimated the quantity of radiation energy passed through an object of irradiation, i.e. the total dose absorbed by an object, is of more important value. *The absorbed dose is a total quantity of ionizing radiation energy which is absorbed by object of irradiation.*

The SI unit of absorbed dose is *gray (Gy)* called to honor of eminent English physics and radiobiologist Luis Harold Gray and it is defined as 1 joule per kilogram (1 J kg^{-1}) and is thus a hundred times larger than rad (1 Gy = 1 J kg^{-1} = 100 rad). In terms of rad: *1 rad = 0.01 J/kg*, and *1 Gy = 100 rad*.

Undoubtedly, absorbed dose *Dp* depends on expositive dose *Dx*. If expositive dose and factor of absorption of matter *f* are known, the absorbed dose can be calculated under the simple formula: $Dp = Do \cdot f$. For electromagnetic radiation with energy of 0.4–2 MeV such factor for water, plants and animals tissues vary within the limits of 0.93–0.97. When expositive dose 1 R is applied to plants and animals, it corresponds to the absorbed dose of 0.93–0.97 rad that is practically the same, taking into account the possible error of dosimeter devices of 5–15%.

However, normally living organisms are exposed to a simultaneous irradiation by various types of ionizing radiation both natural and artificial radioactive isotopes, for example, γ- (^{40}K, ^{137}Cs, ^{226}Ra), β- (^{40}K, ^{90}Sr), α- (^{222}Rn, ^{239}Pu, ^{241}Am) and many others which have various RBE. To estimate the biological effects for different types of radiation as well as unidentified ionizing

R.M. Sievert
(1896–1966)

radiation, the special dose is called the *equivalent dose*. *The equivalent dose is a dose of irradiation of living organism by mixed or unknown types of ionizing radiation which biological efficiency is equivalent to the unit of absorbed dose.* An earlier unit of an equivalent dose was the *rem* that is the abbreviation of *rad equivalent man*. One *rem* corresponds to such radiation dose of a given type or a beam of ionizing radiation applied to organism when observed biological effect is equal to the effect observed at a dose of X- or γ-irradiation (standard) in 1 R.

The SI unit of equivalent dose is *sievert (Sv)* called to honor of eminent Sweden physics and radiobiologist Rolf Maximillian Sievert*; 1 Sv = 100 rem*.

Mentioned above SI-system and out-of-system units of radioactivity, doses of ionizing radiation and correlation between them are shown in Table 5.

Table 5. Units of radioactivity and doses of ionizing radiation

Unit	Name of unit		Correlation between units
	out-of-system	SI system	
Radioactivity	curie (Ci)	becquerel (Bq)	1 Ci = 3.7×10^{10} Bq 1 Bq = 2.7×10^{-11} Ci
Expositive dose	roentgen (R)	coulomb per kilogram (C/kg)	1 R = 2.58×10^{-4} C/kg 1 C/kg = 3876 R
Absorbed dose	rad	gray (Gy)	1 rad = 0.01 Gy 1 Gy = 100 rad
Equivalent dose	rem	sievert (Sv)	1 rem = 0.01 Sv 1 Sv = 100 rem

2.7. Relations between radioactivity and dose of radiation

Units of radioactivity and doses being of different physical values are connected among themselves as the certain radioactivity causes a certain dose at certain distance from the source. In radiometry there is some kinds of a model of such relationships or dependence: at standard conditions (0°C, 760 mm mercury column), radioactivity of 1 Ci ^{226}Ra creates during 1 hour on a distance of 1 m an expositive dose 1 R.

There is also the dependence between an expositive dose and radioactivity of a radiation source. In the certain situations such dependence allows to use classical dosimeters- roentgenometers for an estimation of radioactive pollution of various objects. So, during accident on the Chernobyl Nuclear Power Plant in 1986, dosimeters and roentgenometers were widely used for the control of radionuclide pollution of various buildings, techniques, overalls, diverse objects of an environment and even people and foodstuffs.

There is a certain relation between radiation background, i.e. the capacity of the expositive dose in the environment, and radionuclide pollution density of a ground surface. A number of relationships based on empirical estimations that may be used in many situations are proposed. One example of such dependence is shown in Fig. 10.

However, relationships between radioactivity of a source and a dose formed depend on various factors, many of which (isotope structure of a source of a radioactivity and, accordingly, types of radiation, a physical and chemical state of a source and the environment and many others) very difficult or even impossible to account. Therefore any estimation of a dose based on radioactivity, on the contrary, is rather rough and gives only approximate representation about real radiation conditions.

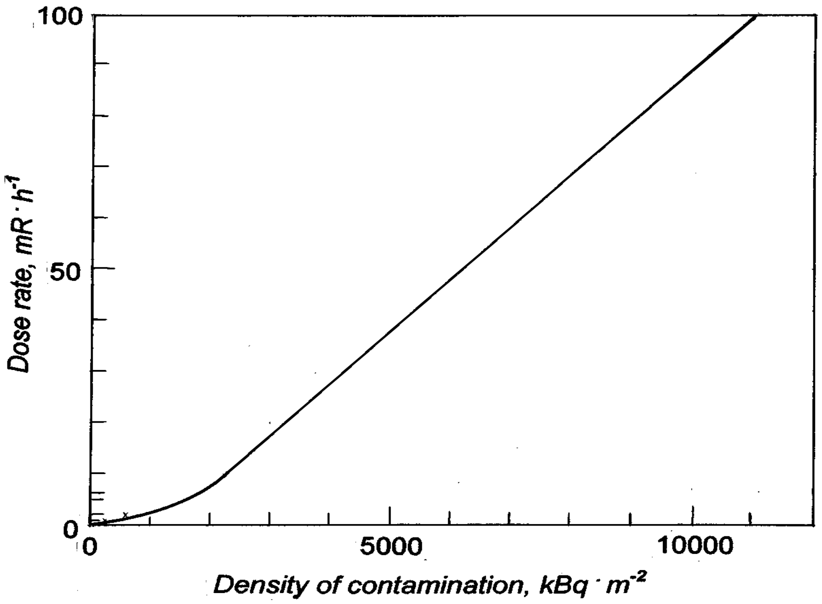


Fig. 10. The relationship between a density of soil radionuclide contamination and dose rate of radiation background.

2.8. Forms of irradiation

In order to characterize how the ionizing radiation is distributed with time so called *dose rate* has to be used. The dose rate is an amount of energy of radiation absorbed by the substance per time unit. Depending on the dose rate two forms of irradiation are distinguished – *acute* and *prolonged.*

An *acute irradiation* referred to a situation when an organism due to high dose rate applied (tens, hundreds *gray* per minute or hour) receives very high dose.

A *prolonged irradiation* means continuation of irradiation during hours, days, weeks, months at low dose rate (small fraction of *gray* per hour or day).

A *chronic irradiation* is considered as a special case of prolonged irradiation, when dose formation at very few fractions of gray per hour continues months, years, vegetation period of plants, life-time of animals and men or, at least, the period comprising a significant part of ontogenesis.

In terms of biological efficiency the identical dose of *prolonged irradiation*, as a rule, essentially exceeds a dose of an *acute irradiation* that is defined by a degree of prolongation, i.e. a difference in dose rate. The dose of a chronic irradiation of annual plants during the vegetative period (100–120 days) is between 3 to 6 times and more higher a dose of an acute irradiation at equal biological effects.

Single and *fractional (repeated) irradiation* is also distinguished. In the first case the dose is given during one continuous act of irradiation. In the second the dose is divided into two and more fractions, interchanging with non-irradiated period. Biological effects of radiation at fractional irradiation depend essentially on the quantity of fractions of a dose, on the one hand, and the duration of an interval between them, on the other hand. In both cases effects decrease with the interval increase (Fig. 11) due to the restoration period between fractions, when various structures and functions of cells and an organism as a whole may be restored.

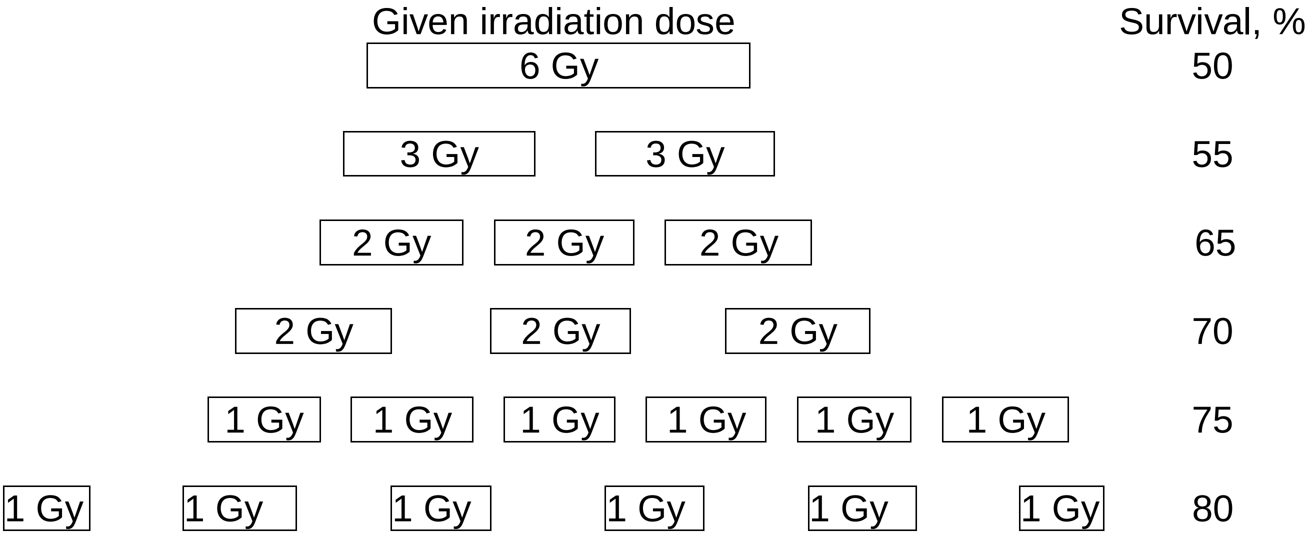


Fig. 11. Increasing of mice survival with increase of the dose fractions and the time at the same quantity of X-radiation dose (6 Gy).

The decrease of the efficiency of irradiation with reduction of dose power and dose fractionation is one of proofs of existence of processes of postradiation recovery of living organisms which will be discussed in chapter 11.

Physical properties and characteristics of ionizing radiation define radiochemical and radiobiochemical processes in cells and tissues of the irradiated organisms, and in total form of its certain radiobiological reaction to radiation or radiobiological effects. Depending on the type of radiation, the quantity of dose, various distortions and the diversified reactions at various levels of the organization of living organisms are observed. The subsequent chapters are devoted to the consideration of these phenomena.

Control points to chapter 2:

1. The nature of radioactivity.
2. The law of radioactive decay.
3. Terms “radioactive isotope”, “radioactive element”, “radioactive matter” and “radionuclide”.
4. Types of nuclear transformations.
5. Types of ionizing radiation.
6. Kinds and general physical characteristics of electromagnetic ionizing radiation.
7. Kinds and general physical characteristics of corpuscular ionizing radiation.
8. Comparative penetrating ability of ionizing radiation.
9. The basic processes occurring at interaction electromagnetic ionizing radiation with the substance.
10. Linear energy transfer (LET) of radiation. Sparse- and dense-ionizing radiation.
11. Relative biological efficiency (RBE) of ionizing radiation.
12. The expositive, absorbed and equivalent doses of ionizing radiation.
13. Units of radioactivity and doses of ionizing radiation.
14. Transition from out-of-system units of radioactivity and doses to units of SI-system.
15. Dependence of the biological efficiency of ionizing irradiation from the factor time of irradiation.
16. Forms of irradiation.

3. SOURCES OF IONIZING RADIATION IN THE ENVIRONMENT

3.1. Cosmic radiation. 3.2. Radiation of radionuclides. 3.2.1. Radiation of natural radionuclides 3.2.2. Radiation of artificial radionuclides. 3.3. Generators of ionizing radiation. 3.4. The contribution of various sources of ionizing radiation to dose formation for a man.

The ionizing radiation is not unusual or new factor on the Earth. All living organisms as well as non-living matter was exposed to the radiation during our planet history. Moreover, it is assumed that in the beginning of the Earth history, when active tectonic processes of the Earth formation took place and first forms of life appeared, intensity of ionizing radiation was even much higher.

Two main sources of ionizing radiation such as cosmic radiation and radiation of radionuclides are distinguished (Fig. 12). Cosmic radiation consists of galactic and solar radiation. Radiation of radionuclides includes radiation of natural and artificial radionuclides. Altogether first three sources form so-called *natural radiation background*. Apart of this there is radiation of artificial generators.

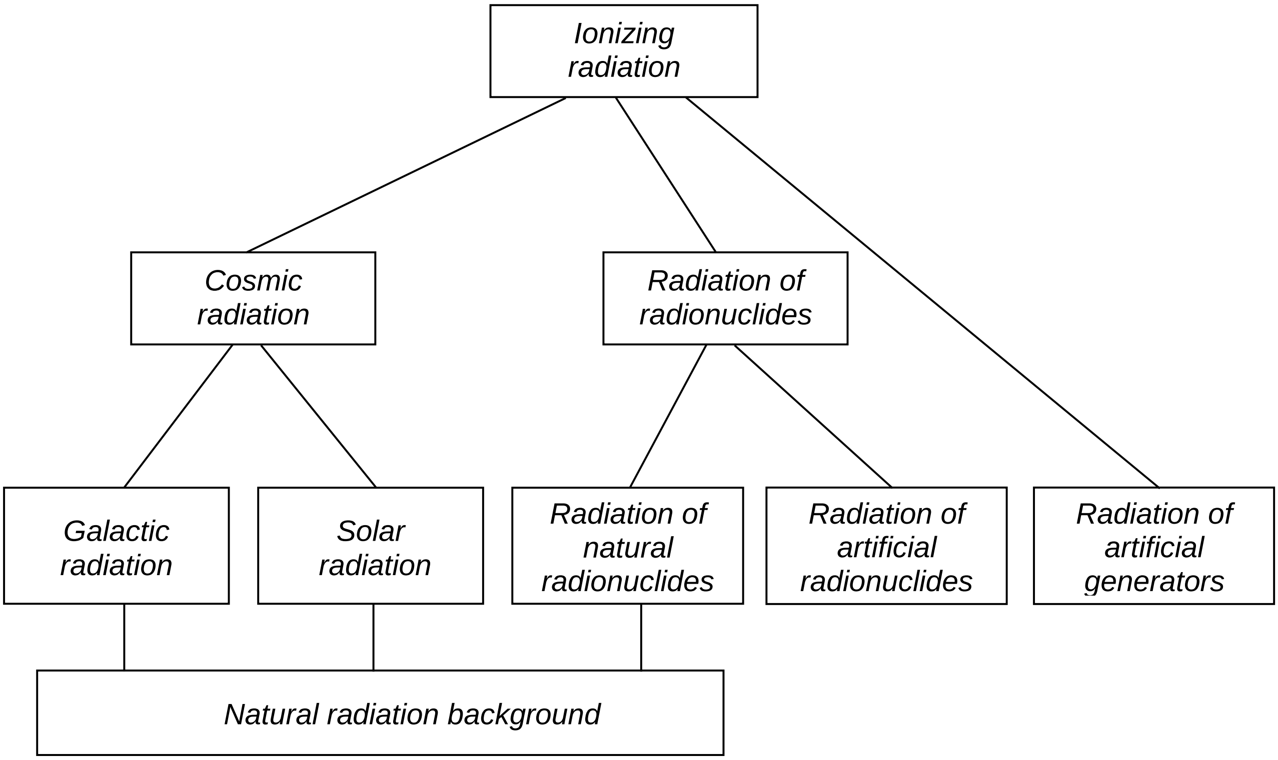


Fig. 12. Sources of ionizing radiation on the Earth.

3.1. Cosmic radiation

Cosmic radiation includes galactic and solar radiation. Primary and secondary radiation is also distinguished among cosmic radiation. The primary cosmic radiation comes to the Earth mainly from outer space but also includes a contribution from the sun, particularly during solar flares. It consists principally of high-energy charged particles, mainly protons (approximately 79%) and α-particles (about 20%), the passage of which can be deflected by the Earth's magnetic field. Hence, some of the effects on the Earth are related to the geomagnetic latitude. Neutrons, electrons, nucleus of some light and heavy elements as well as quanta are also present here, however, in immeasurably smaller quantities.

The main part of primary cosmic radiation appears in our Galaxy as a result of nuclear and thermonuclear processes that are accompanied by eruption and transpiration of matter during star explosions and formation of new stars. It is *galactic radiation*.

The mean value of cosmic radiation energy is 10^9 eV, however, it may reach 10^{17}–10^{21} eV. It is assumed, that particles of so high energy come to the Earth from outside of Galaxy – metagalaxy, getting such high energy due to the acceleration in various electromagnetic fields of celestial bodies, cosmic dust clouds as well as in shells of new stars.

Cosmic radiation has lower energy (up to 4×10^{10} eV) in comparison with galactic radiation. It is worth noting that X-rays and γ radiation that are usually used in radiobiological studies have energy of 0.12–12×10^3 and 1.2–5×10^6 eV correspondingly.

The age of galactic radiation, i.e. the time of its way from Galaxy to the Earth, is about 10^6–10^7 years. It explains the fact that galactic radiation completely lacks of neutrons that are produced in a great amount of all nuclear processes. The neutrons break down during such a long time. Low content of electrons and quanta in galactic radiation is due to its uptake by a cosmic dust clouds in Galaxy.

Secondary cosmic radiation is formed when the primary cosmic particles enter the atmosphere. It consists practically of all known to the present time fundamental particles – protons, electrons, neutrons, pions, mions, mesons and many others. Their energies are also great enough to induce the further nuclear transformations.

Cosmic radiation is most intensive mainly outside the Earth's atmosphere and prevails at the height of 40–50 km. The peak intensity of secondary radiation is observed at the height of 20–25 km. With the decreasing of the height the intensity of radiation also diminishes and reaches a minimum above sea level. Therefore, it is quite natural, that the dose of an irradiation due to cosmic radiation increases with height. At the Earth surface the dose rate due to cosmic radiation is 0.02–0.04 mcSv h^{-1} and increases approximately twice per each 1.5 km within the height of 10 km (Fig. 13). People, living in the high-mountainous settlements located at height of 2–5 km, receive 5–10 times higher doses in comparison with those living in the same area above sea level. At the height of 10–12 km (superhigh-altitude planes airways) dose rate reaches 3–5 mcSv h^{-1}. At the height of 20 km (supersonic speed planes such as “Concord” airways) dose rate depends on geomagnetic latitude of area and varies between 5–15 mcSv h^{-1}.

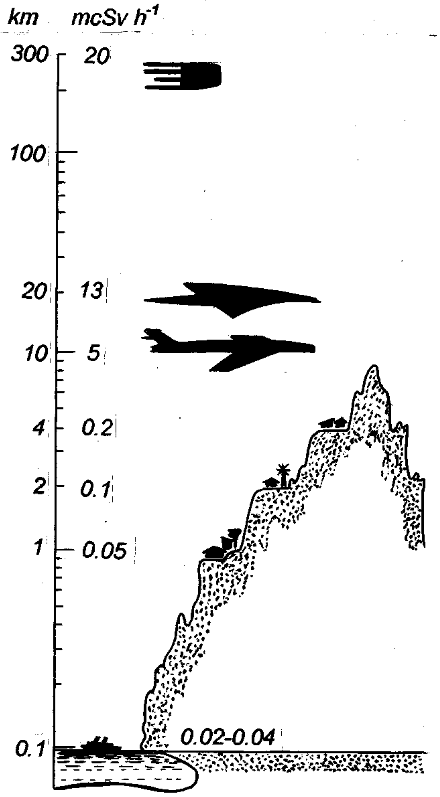


Fig. 13. The increase of dose rate of cosmic radiation with the height above sea level.

3.2. Radiation of radionuclides

There are *natural* and *artificial* radionuclides (Fig. 14). About 1950 radioactive nuclides (isotopes) known nowadays and only 70 among them are considered to be natural and the rest (approximately 1880) have artificial origin.

3.2.1. Radiation of natural radionuclides

According to current theories of nucleogenesis the Earth is composed of both radioactive and stable chemical elements. They were produced in nuclear reactions that took place in stars. As we mentioned above the elements that occur on the Earth's surface today include the stable elements and radionuclides having half-lives in comparison with the age of the Earth (estimated to be about 5×10^9 years). Their decay products are usually known as the terrestrial or primordial source of natural radioactivity. 70 terrestrial radionuclides belong to 25 chemical elements and are divided into two groups. The first group consists of heavy nuclides that occur in three radioactive series, where a radionuclide successfully decays to become another radionuclide until a stable nuclide is reached.

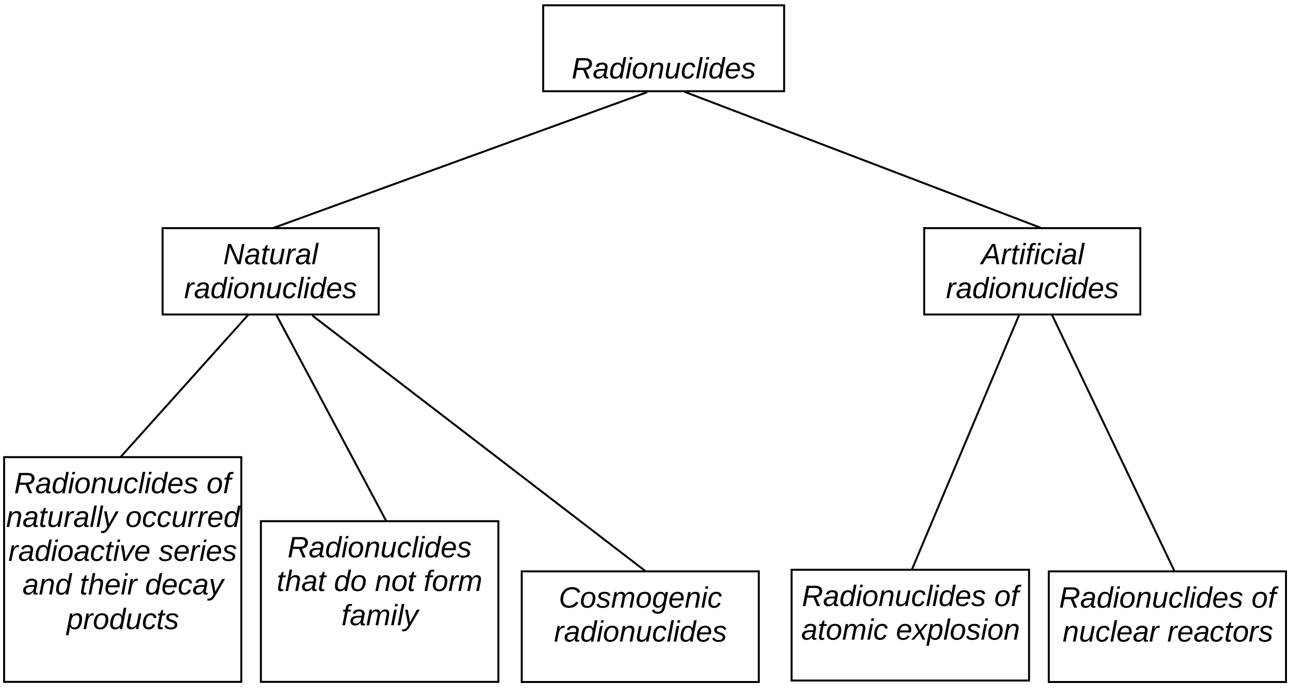


Fig. 14. Sources of radionuclides on the Earth.

Radionuclides of naturally occurred radioactive series and their decay products. Each of the radioactive series includes both α- and β-active radionuclides with half-lives varying from small fractions of the second to thousands of years. Three naturally occurred radioactive series are the uranium series headed by ^{238}U, the actinium series headed by ^{235}U and the thorium series headed by ^{232}Th. Each of them is the ancestor of radionuclides family. Being exposed to a many-stage cycle of α- and β-decays they form a series of radioactive isotopes.

The parent isotope of uranium series ^{238}U as a result of 8 α- and 6 β-decays transfers in a stable isotope of lead ^{206}Pb (Fig. 15, a). Due to the presence of ^{226}Ra isotope, this series is often called as uranium – radium series.

The isotope of uranium ^{235}U is the ancestor of actinium family. This series is known as the actinium (or action-uranium) series due to the presence of actinium ^{227}Ac in a change of decays. ^{227}Ac is the main element among the large group of radioactive elements – actinides, or actinoids. Decay series headed by ^{235}U through the chain of decays comes to the end with a stable isotope of lead ^{207}Pb (Fig. 15, b).

Decay series of thorium ^{232}Th through a 6 α- and 4 β-decays comes to the end with a stable isotope of lead ^{208}Pb (Fig. 15, c).

As we mentioned above, all three ancestors are characterized by very long half-lives (Table 6). The elements uranium and thorium and, hence, their decay products, show wide variations in concentration all over the world, and tend to have high concentrations in igneous and sedimentary rocks.

Tens isotopes that belong to different elements are produced during their radioactive transformations. Each of series includes an isotope of the inert gas radon, ^{222}Rn (frequently, the name radon is applied to this particular isotope), ^{219}Rn and ^{220}Rn (often called thoron) for the uranium, actinium and thorium series respectively during their radioactive transmutations. From a radiological point of view, these nuclides are of great importance. They and their decay products provide the largest single contribution to the radiation dose of the human population. Since they are gases, they tend to diffuse away from their points of formation in the matrix. The descendants of radon isotopes are not gases, but they are mainly the chemical elements such as polonium, lead and bismuth that are metals (although polonium is volatile).

Table 6. The radionuclides of naturally occurred radioactive series and their decay products

Radionuclide	Half-life	Prevailing radiation	Energy, MeV
^{210}Po	138.4 days	α	5.290
^{210}Pb	19.4 years	β	0.018
^{214}Pb	26.8 minutes	β	0.291
^{214}Bi	19.9 minutes	α, (β)	4.313 (0.648)
^{218}At	2 seconds	α	4.270
^{220}Rn	55.6 seconds	α	6.280
^{222}Rn	3.8 days	α	5.490
^{223}Fr	21.8 minutes	β	0.391
^{226}Ra	1620 years	α	4.860
^{227}Ac	21.7 years	α, (β)	4.900 (0.460)
^{228}Th	1.9 years	α	4.300
^{232}Th	1.41×10^{10} years	α	4.070
^{234}Pa	6.7 hours	β	0.422
^{235}U	7.1×10^{8} years	α	4.470
^{238}U	4.5×10^{9} years	α	4.260

Such decay products as ^{219}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, are all short-lived and are conveniently considered as a group, the radiation dose of which comes to a human organism mainly via the inhalation pathway. All decay products from ^{220}Rn (thoron) to stable ^{208}Pb also have relatively short half-lives, and may be considered as a single group, the radiation dose of which comes to a human organism in a similar way. In outside air, the concentration of ^{222}Rn and its short-lived products varies widely depending on the geographical location, having mean values from 0.01 to 9 Bq m^{-3}. The typical concentrations for ^{220}Rn and its products are perhaps a factor 20 lower than those of ^{222}Rn.

Radionuclides unassociated with each others. This group includes isotopes of chemical elements that are usually considered to be non-radioactive due to the relative abundance of radioactive isotopes in their mixture and, as a rule, comprises very small part. Many of them are of little importance because of their long half-lives. Among them are potassium ^{40}K, calcium ^{48}Ca, rubidium ^{87}Rb, zirconium ^{96}Zr, lanthanum ^{138}La, samarium ^{147}Sm and lutetium ^{176}Lu (Table 7). Two of them ^{40}K and ^{87}Rb, having half-lives of 1.28×10^{9} and 4.8×10^{10} years, are of principal significance. Potassium ^{40}K, abundance of which in an intermixture of isotopes of potassium makes only 0.012 % (^{39}K and ^{41}K – 93.22 and 6.77%, accordingly) and emits both gamma radiation and β-particles. ^{87}Rb emits only β-particles.

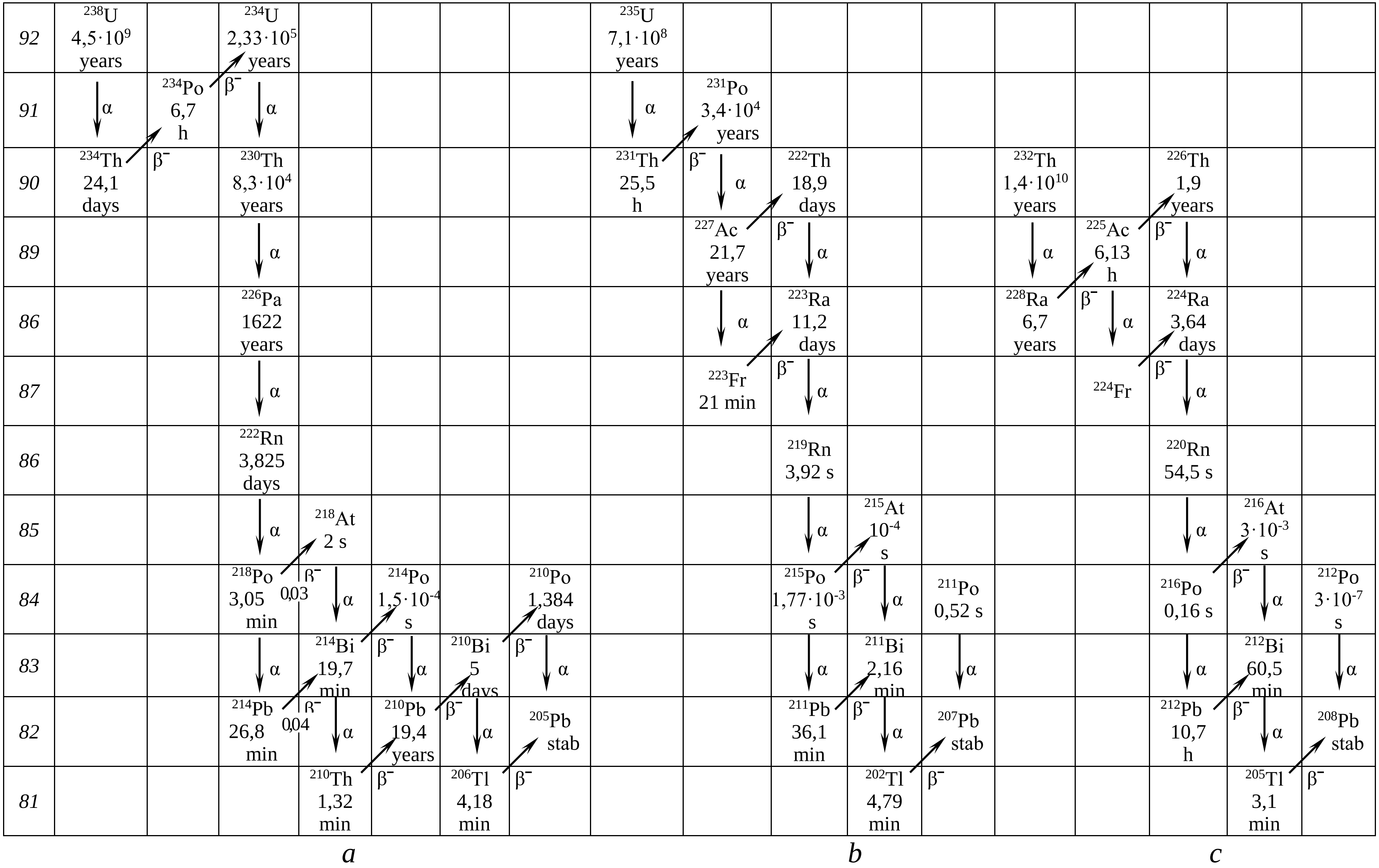


Fig. 15. The schemes of decay of radionuclides of naturally occurred radioactive series

Table 7. Nuclides unassociated with each other

Radionuclide	Half-life, years	Prevailing radiation type	Energy, MeV
^{40}K	1.28×10^{9}	β (γ)	1.325 (1.459)
^{48}Ca	1×10^{16}	β	0.077
^{87}Rb	6.15×10^{10}	β (γ)	0.275 (0.394)
^{96}Zr	6.2×10^{16}	β	3.400
^{115}In	6×10^{14}	β	0.630
^{124}Sn	1.51×10^{17}	β	1.500
^{130}Te	1.4×10^{21}	β	0.226
^{138}La	7×10^{10}	γ	0.535
^{147}Sm	1.05×10^{11}	α	4.500
^{150}Nd	5×10^{10}	β	0.011
^{176}Lu	2.4×10^{10}	β (γ)	0.215 (0.180)
^{180}W	2.2×10^{17}	β (γ)	0.4–3.2 (0.270)
^{187}Re	4×10^{12}	β	0.040
^{209}Bi	2.7×10^{7}	β	3.150

As we mentioned above these radionuclides exist in nature with fairly constant isotopic abundance. The abundance of ^{40}K and ^{87}Rb elements in crusted rock equals 2.59×10^{4} and 90 mg kg^{-1} correspondingly. As potassium is an essential element in the body and is under homeostatic control, its concentration in the body is rather constant, the ^{40}K average concentration is about 60 Bq kg^{-1}. Behaviour of rubidium is less known, but the average ^{87}Rb concentration in the body is about 8.5 Bq kg^{-1}.

Cosmogenic radionuclides. Cosmogenic radionuclides appear mainly in the atmosphere, when high energy cosmic radiation interacts with the atmospheric gases. When the primary cosmic particles enter the atmosphere, reactions occur with the nuclei of the components of the atmosphere and the secondary particles and gamma radiation are produced.

High energy neutrons and protons interact with N_2, O_2, Ar etc, and result in the production of radioactive nuclides. Many radionuclides can be formed in these reactions with half-lives ranging from very short to very long. The six isotopes (^{3}H, ^{7}Be, ^{10}Be, ^{14}C, ^{22}Na and ^{24}Na) that are listed in Table 8 are examples of cosmogenic radionuclides that have some environmental significance. These nuclides are produced at the constant rates and are brought to the Earth surface by rainwater. The reaction rate depends on the intensity of the incoming radiation that tends to be attenuated as it passes through the atmosphere, and on the density of atmospheric gases that diminish with increasing distance from the Earth. Consequently, the rates tend to increase with altitude to a maximum value and then decrease. For example, the production rates per unit mass of air for ^{7}Be and ^{24}Na increase in four orders of magnitude from ground level to 20 km at latitude 46° north, where they slowly decrease.

Table 8. Natural concentration of cosmogenic radionuclides in the environment
(E. Stricht, R. Kirchmann, 2001)

Nuclide	Medium	Concentration
^{3}H	surface water	0.2–0.9 Bq l^{-1}
	seawater	0.1 Bq l^{-1}
^{7}Be	air	0.001–0.004 Bq m^{-3}
^{14}C	Carbon	227 Bq kg^{-1}
	human body	52 Bq kg^{-1}
^{22}Na	air	0.0003 Bq m^{-3}

Though they are formed in extremely low concentrations, the global inventory is by no means small. Equilibrium is assumed to be established between the production rate and the main residence time of these radionuclides in terrestrial reservoirs (the atmosphere, the sea, lakes, soil, plants, etc) leading to constant specific radioactivities of the elements in each reservoir.

One of the most widely spread radionuclides of cosmogenic origins is tritium (^{3}H), or heavy hydrogen. Satellite measurement showed that the Earth receives some of the tritium ejected from the sun, however, larger amounts are formed in the atmosphere through nuclear reaction; e.g., between fast neutrons and nitrogen atoms

$$n\ (\text{fast}) + {}^{14}N \rightarrow {}^{12}C + {}^{3}H$$

About 2500 atoms of tritium per second per square meter of the Earth’s surface are formed from this reaction. Their global inventory is, therefore, about 1.3×10^{18} Bq. They rapidly incorporate in water, entering the global hydrological cycle. Their average residence time in the atmosphere is about two years that is a small fraction of the half-life. The tritiated water reaches the low troposphere and rains out in 5–20 days.

The second radionuclide of cosmogenic origins is ^{14}C. Carbon ^{14}C is produced in the atmosphere by the variety of reactions; the most important one is the reaction between thermalized neutrons from cosmic radiation and nitrogen atoms

$$\text{n (slow)} + {}^{14}\text{N} \rightarrow {}^{14}\text{C} + {}^{1}\text{H}$$

This reaction involves approximately 22 000 atoms of ^{14}C formed per s. and m^{2} on the Earth's surface; the global annual production rate is ~1 PBq, and global inventory is ~8 500 PBq corresponding to ~75 tons. Among this amount ~140 PBq remain in the atmosphere while the rest is incorporated in terrestrial material. All living materials (incl. body tissue) have a ^{14}C concentration of ~227 Bq kg^{-1}. The cosmogenic ^{14}C changes places with stable carbon and forms CO_2 in the atmosphere, after which the normal CO_2 movements follow.

Cosmogenic radionuclides together with gaseous form of radioactive by-products of uranium and thorium decay, first of all a radon, define radioactivity of an atmosphere. Most of the cosmogenic radionuclides have rather large half-lives measured by years – millennia and some of them have very short half-lives measured by seconds and even microseconds (Table 9).

The content of natural radionuclides in an environment. The content of radionuclides in the Earth's crust and, hence, in water varies widely and is defined, mainly, their concentration in ground bed-rock. As we mentioned above, uranium and thorium elements and, hence, their radioactive products tend to have higher concentrations in igneous rocks, sedimentary rocks, e.g. some shale and phosphate rocks. Sedimentary rock such as clay, limestone, coal, as a rule, are feebly radioactive. Volcanic rocks such as granite and basalts contain much more radioactive elements. Relatively high concentration of thorium and radium was found in monazite sands that are mainly composed by monazite minerals, e.g. phosphates of rare Earth elements belonging to cerium group.

The radioactive water sources are also known.

There are so called *light* and *heavy* natural radionuclides. *Heavy* natural radionuclides are those that belong to radioactive series (radioactive elements and isotopes having nuclear mass above 200). The rest is considered as *light* radionuclides. The concentration of the most important radionuclides in soils, plants and animals are given in Table 10.

The mass abundance of natural radioactive elements, as well as radioactive isotopes of stable elements in the Earth's crust, and, hence, in water, plants and animals, is low. The concentration of radium in soils is $1–13\times10^{-11}$ %, uranium – $2.6–4\times10^{-4}$%, thorium – $5–12\times10^{-4}$%. Concentration of ^{14}C in soil varies in the range 1–30×10^{-9}%, ^{40}К – 1–5×10^{-4}%. The content of ^{3}H in waters makes about 10^{-18} of hydrogen (^{1}H) content.

Table 9. Some radionuclides of cosmogenic origins

Radionuclide	Half-life	Prevailing radiation type	Energy, MeV
^{3}H	12.34 years	β	0.019
^{7}Be	53.6 days	γ	0.480
^{10}Be	2.4×10^{6} years	β	0.555
^{14}C	5 730 years	β	0.155
^{22}Na	2.6 years	β^{+}	0.545
^{24}Na	15.06 hours	β	1.389
^{26}Al	7.4×10^{5} years	β^{+}	1.165
^{28}Mg	21.2 hours	β	0.460
^{32}Si	700 years	β	0.210
^{32}P	14.3 days	β	1.710
^{35}S	87.1 days	β	0.167
^{36}Cl	4.4×10^{5} years	β	0.714
^{39}Ar	270 years	β	0.565

Table 10. The concentration of some natural radionuclides in soils, plants and animals, Bq kg^{-1}

Object	^{40}К	^{226}Ra	^{232}Th	^{238}U
Soil (0–25 cm)	90–720	2–2500	7–50	10–50
Plants	95–500	1.9×10^{-2}–0.5	4×10^{-3}	2.4–6.0×10^{-3}
Animal (muscles)	70	1.6–7.4×10^{-2}	4×10^{-3}	4.9×10^{-3}–1.2×10^{-2}

Natural radiation background. The natural sources of ionizing radiation provide rather constant radioactive field on the Earth that is *natural radiation background*. It means *a level of the ionizing radiation on the Earth surface, in above ground layers of the atmosphere and other objects of an environment which is formed due to radiation of both natural radioactive isotopes as well as cosmic radiation.* This is a natural radioactive environment, where all living matters of our planet exist and develop at least for some millions years.

The mean value of natural radioactive background rate of our planet is about 0.1 mcSv h^{-1} or 10 mcR h^{-1} with the variation in different regions from 0.05 to 0.15 mcSv h^{-1}. The contribution of cosmic radiation depends on latitude, but at the sea level is more or less constant and equals 0.01–0.03 mcSv h^{-1}. The rest is determined by radiation of natural radionuclides that depends on their content in the Earth's crust and, hence, varies widely.

Natural radioactive background is thought to be one of the primary factors that plays the leading role in evolution of living organisms, and causes malignant tumours and hereditary diseases.

There are evidences that natural radioactive background increases from the beginning of 19th century in many countries and continents. It is due to the increased human activity and industrial growth, which results in an increased output of such minerals as coal, oil, building materials, metal ores, mineral fertilizers as well as natural radioactive isotopes from the Earth's crust to the environment.

In the middle of the 20th century, for example, the quantity of ^{226}Ra as the only source of γ-radiation that used in medicine, luminous paints production and for some other purposes in big cities and industrial centers increased by factor 50. In the places of fossil extraction of many minerals, which themselves are not radioactive ores the increased amounts of some natural radionuclides such as ^{226}Ra, ^{238}U, ^{232}Th, as a rule, are observed. Increased amounts of such radionuclides as ^{14}C, as well as ^{40}K, ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po and other natural radionuclides is observed in the radius of several tens kilometers from the thermal power plants, especially near there, where coal is used. Potassium ^{40}K and uranium ^{238}U concentration in the environment increases as a result of potassium and phosphorus fertilizers application, since phosphorites deposits, as a rule, contain high amounts of ^{238}U and its decay products. Elevated level of natural ionizing radiation caused by increased human activity is called technogenic radiation background.

Natural radionuclide anomalies *are places of high concentration of natural radionuclides* (usually uranium, thorium and their decay products) *where the natural radioactive background level is many times higher the ordinary level.*

Such radionuclide anomalies are well known on the Earth: Ramser, Iran (natural radioactive background reaches 5–10 mcSv h^{-1}), the Kerala state, India (up to 1 mcSv h^{-1}), the cities of Guarapuava and Posus-de-Kandas, Brazil (1–2 mcSv h^{-1}). No provinces with such high radioactivity are found within the territory of the former USSR, but there are places, where natural radioactive background reaches 0.5–0.6 mcSv h^{-1}. It is the region of IssykKul lake (Kirghizia), Navoi region (Uzbekistan), Shevchenko region (Kazakhstan), some regions in the Southern Ural and Ukhta region (Russia).

No regions of elevated natural radioactive background level were found in Ukraine. However, almost half of its territory on the east is under the Ukrainian crystalline board – a volcanic rock, enriched with uranium and its decay products. Radionuclide anomalies appeared as a result of uranium extraction as well as other mine works. The most well known among them are situated in Yellow Waters located in Dnepropetrovsk region, as well as in some areas in Kropyvnytskyi, Zhitomir and Donetsk regions.

Nowadays the radioactive background within the territory of Ukraine after the direct effect of Chernobyl accident ranges from 0.10 to 0.18 mcSv h^{-1} (before the accident 0.06–0.10 mcSv h^{-1}, or 6–10 mcR h^{-1}). Such acceleration of the radioactive factor rate is caused by artificial radionuclides entrance in the environment. In this case the concept of radioactive background should be used instead.

3.2.2. Radiation of artificial radionuclides

Fission of heavy nuclides is the most important process as a source of environmental artificial radioactivity. E. Fermi obtained the Nobel Prize in physics for his work on transuranium elements obtained by irradiation of uranium with slow neutrons in 1938. It was found that the uranium nucleus might break up into smaller nuclei. To describe this process the term fission was introduced by analogy with cell division. Radionuclides such as ^{233}U, ^{235}U, ^{239}Pu and ^{241}Am undergo fission with thermal (slow) and with fast neutrons whereas fission, e.g. ^{232}Th and ^{238}U, always requires fast neutrons. To cause fission by bombarding of a target (isotopes of naturally occurred stable elements), the bombarding particles (neutrons) have to be of high energy from several millions up to tens billions of electron volts. By using α-particles, neutrons, and protons as well as accelerated on the nuclear reactors charged particles, and accelerated light particles and heavy ions, more than 1880 radioactive isotopes that belong to 80 chemical elements, which are used in various areas of human activity were obtained. Reactions of heavy nuclides fission are similar to those occurred in the atmosphere when cosmogenic radionuclides are produced. Some of the artificial radionuclides are listed in Table 11.

However, the main sources of artificial radionuclides and, hence, additional sources of irradiation are radionuclides produced during nuclear weapon military tests and radionuclides of nuclear reactors.

Radionuclides produced during nuclear weapon military tests. The great amount of radioactive isotopes was injected into the environment as a result of nuclear bomb tests. Above 1 600 tests have been carried out in the world since 1945. The nuclear bomb is such type of explosive weapon that has a charge of extremely destructive power that is based on the chain of the self- developing reaction of uranium ^{235}U or ^{239}Pu fission (Fig. 16). The occurrence and proceeding of such reaction is caused by penetrating of high energy particle, e.g. a neutron that can be natural cosmic or artificially obtained, in a nucleus of ^{235}U or ^{239}Pu followed by fission of a nucleus and emission of 2 or 3 new neutrons. Having high enough energy each of them capable to interact and cause new fissions. The following generation of neutrons induces fission of the next group of nucleus and, thus, results in avalanche like the development of the reaction (Fig. 17).

Table 11. Some of the artificial radionuclides

Radionuclide	Half-life	Prevailing radiation type	Energy, MeV
^{3}H	12.34 years	β	0.019
^{14}C	5 568 years	β	0.155
^{32}P	14.3 days	β	1.710
^{35}S	87.1 days	β	0.167
^{42}K	12.36 hours	β	1.430
^{45}Ca	163 days	β	
^{54}Mn	312.3 days	γ	0.830
^{55}Fe	2.6 years	γ	0.006
^{59}Fe	45.1 days	β (γ)	1.560 (1.290)
^{60}Co	5.272 years	β (γ)	1.478 (1.330)
^{65}Zn	244.1 days	β (γ)	0.325 (1.110)
^{89}Sr	50.5 days	β	1.463
^{90}Sr	29 years	β	0.544
^{93}Zr	64.05 days	β (γ)	0.890 (0.756)
^{95}Nb	35.1 days	β	0.160
^{103}Ru	39.35 days	β (γ)	0.710 (0.610)
^{106}Ru	368.2 days	β	0.039
^{129}I	1.57×10^{7} years	β	0.150
^{131}I	8.04 days	β (γ)	0.608 (0.723)
^{134}Cs	2.06 years	β (γ)	0.512 (1.367)
^{137}Cs	30.17 years	β (γ)	0.520 (0.662)
^{140}Ba	12.78 days	β (γ)	1.010 (0.537)
^{140}La	40.22 hours	β (γ)	2.200 (2.520)
^{141}Ce	32.5 days	β (γ)	0.580 (0.145)
^{144}Ce	284.3 days	β (γ)	0.320 (0.134)
^{144}Pr	17.3 minutes	β (γ)	2.994 (2.650)

^{237}Np	2.14×10^{6} years	α	4.787
^{239}Pu	2.41×10^{4} years	α	5.580
^{241}Am	432.8 years	α	5.570
^{242}Cm	163 day	α	6.200
^{243}Cm	32 years	α	6.060

Assuming each fission act produces only two neutrons, which in their turn interact again, after 80 of such fissions all the atoms of 1 kg of ^{235}U (approximately 10^{20} atoms) will undergo decay during million parts of a second. This process is accompanied by release of a great quantity of energy.

It is to be mentioned that not all neutrons cause usually fission of nucleus. The part of them is lost outside volumetric mass of uranium or plutonium. Chain reactions slow down and stop, if such losses are too great. Such probability increases with the decrease of the mass and linear size of a matter. A *critical mass is the least quantity of a matter undergoing decay at which the self-supported chain reaction of nucleus fission can proceed*. It determines the amount of a nuclear charge in a nuclear bomb or another nuclear weapon, which is about 20–25 kg ^{235}U or 4–8 kg ^{239}Pu.

To prevent an explosion the total mass of ^{235}U or ^{239}Pu in atomic bomb is divided in 2–3 parts and keeps apart. At the moment of an explosion all the mass is mixed by means of an ordinary explosive material. The chain reaction begins.

Fig. 16. Chinese atomic bomb.
https://www.atomicheritage.org

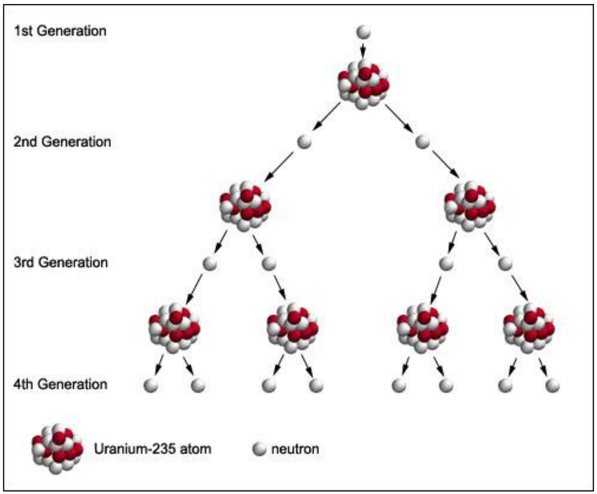


Fig. 17. Nuclear Chain Reactions in ^{235}U.
http://www.atomicarchive.com/

As we mentioned above natural uranium consists of intermixture of three isotopes: ^{238}U, ^{235}U and ^{234}U, whose isotopic abundance is 99.2745%, 0.7200%

and 0.0055% respectively. Chain nuclear reaction can occur only in pure ^{235}U. Therefore, to achieve chain reaction 40–60% ^{235}U is needed, which in turn requires application of sophisticated technological equipment. As to ^{239}Pu, it is an artificial element and does not exist in nature (only trace amount is found). Thus, *chain nuclear reaction on the Earth is possible only in simulated conditions*.

An explosion of a nuclear bomb is simultaneously accompanied by an action of very powerful airwave, extremely intensive light radiation and injection of big quantities of the heat and ionizing radiation with the following fallout of radioactive substances on the Earth's surface.

When ^{235}U or ^{239}Pu undergo fission some hundreds various radioactive isotopes are produced. Among them there are three groups of artificial radionuclides. The first group of radionuclides is produced as result of ^{235}U and ^{239}Pu nuclei fission. The most important elements among them are ^{89}Sr and ^{90}Sr, ^{95}Nb, ^{95}Zr, ^{103}Ru and ^{106}Ru, ^{129}I and ^{131}I, ^{134}Cs and ^{137}Cs, ^{140}Ba, ^{140}La, ^{141}Ce and ^{144}Ce. The second group of radionuclides is produced by capture of neutrons or other particles in construction materials in nuclear reactors or in warheads body. ^{54}Mn, ^{55}Fe and ^{59}Fe, ^{60}Co, ^{65}Zn belong to the second group. ^{60}Co and ^{65}Zn are typical examples of corrosion products of environmental concern. ^{54}Mn and ^{58}Co are not neutron activation products and are produced by other nuclear reactions that occur as a result of fission. The third group is presented by radioactive transuranic elements. They are produced during successive interaction of neutrons and γ radiation with nuclei of fission matter and followed by radioactive decay of super heavy nuclei that appears at this process. Radionuclides of this group are mainly α emitters such as ^{237}Np, $^{238–241}$Pu, ^{241}Am and ^{243}Am, $^{242–244}$Cm that are characterized by high radiotoxicity and have long half-lives.

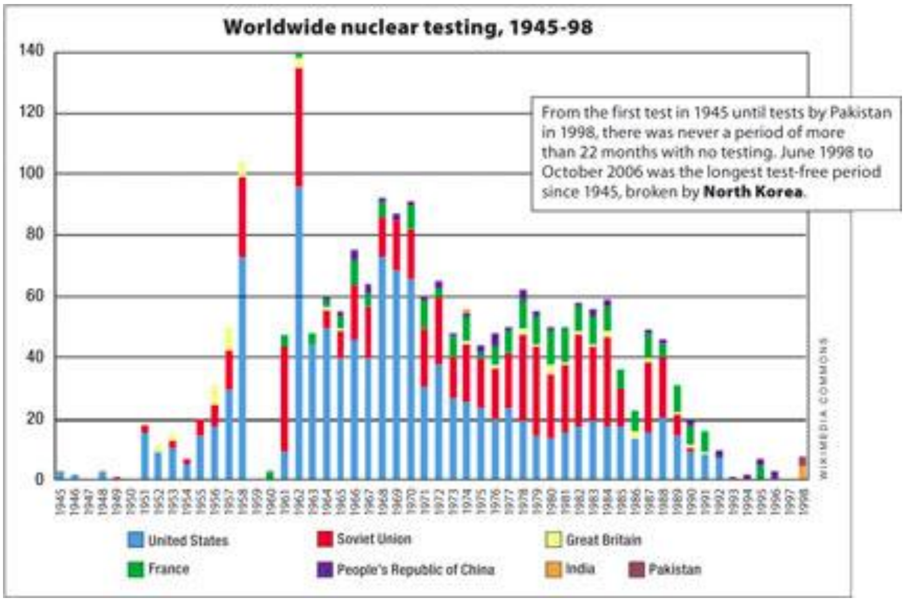
However, the majority of artificial radionuclides produced during nuclear weapon military tests are short-lived and in case of the atmospheric tests they break up before reaching the Earth's surface. In the following 1.5–2 years the major part of middle-lived radionuclides break up as well. Therefore, the radioactive fallouts mainly contain long-lived isotopes of ^{90}Sr and ^{137}Cs (half-life of 29 and 30 years) as well as mentioned above transuranic elements.

As a whole, due to nuclear bomb tests the great amount of long-lived artificial radioactive isotopes was injected into the environment such as ^{3}H – 2.4×10^{20} Bq (much more than in nature), ^{14}C – 2.2×10^{17} Bq, ^{90}Sr – 6.0×10^{17} Bq, ^{95}Zr – 1.4×10^{20} Bq, ^{106}Ru – 1.2×10^{19} Bq, ^{137}Cs – 9.1×10^{17}, ^{144}Ce – 3.0×10^{19} Bq, ^{239}Pu – 6.5×10^{15} Bq.

Hundreds of aboveground blasts took place around the world in the period between 1945 and 1963, when the limited test ban treaty was signed by the United States, the Soviet Union and Great Britain in 1963 (Fig 18). Some aboveground weapons testing by other countries continued until 1980.

In spite of the nuclear test suspension (underground nuclear tests is still going on) many long-lived radionuclides still are in the environment causing additional irradiation of all living organisms on the Earth. The risk levels, however, are far below the regulatory limits.

Radionuclides of nuclear reactors. In 70s and early 80s, the most important source of radionuclide environmental contamination from the enterprises of nuclear power engineering was nuclear reprocessing. The work of such enterprises involves an extraction of uranium ore, the enrichment of ^{235}U nuclear fuel, the manufacturing of fuel elements, obtaining energy in nuclear reactors and the processing of fuel wastes for following use (regeneration, utilization and a burial of radioactive wastes). These operations make so-called *nuclear fuel cycle*.


Worldwide nuclear testing, 1945-98

From the first test in 1945 until tests by Pakistan in 1998, there was never a period of more than 22 months with no testing. June 1998 to October 2006 was the longest test-free period since 1945, broken by **North Korea**.

Fig. 18. Worldwide nuclear testing. https://newint.org

The lost of radioactive substances at each stage of nuclear fuel cycle is not excluded. However, possible effects and intensity of radioactive factors on the biosphere objects might be different. At the stages of an extraction and processing of raw uranium material and fuel elements manufacturing, only natural fission products of uranium can penetrate into surroundings. However, the intensity of radioactive factors may increase on the stage of nuclear reactor operation and fuel wastes processing, when artificial radionuclides are formed. On the stage of storage and burial of radioactive wastes the probability of radionuclides release into the environments might be even higher.

Under normal operation of nuclear power plants or experimental reactors, the authorities regulate the discharge of radioactive substances into the environment. The releases are kept low in order to protect people and the environment and the doses received from normal operation of nuclear plants are in general negligible. The discharges are made both to the atmosphere and to the aquatic environment. The discharges from nuclear reactors to the atmosphere mostly consist of noble gases viz. ^{41}Ar, ^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe and ^{138}Xe. All these radionuclides are short-lived except ^{85}Kr with a half-life of 10.8 years. They are not of radioecological interest as the main pathway to human being is inhalation and external radiation from the clouds.

The releases of ^{3}H and ^{14}C are of more interests. In nuclear reactors tritium is produced by means of ternary fission and from neutron activation reactions with lithium and boron isotopes. Tritium is also the dominating radionuclide in liquid wastes from nuclear reactors. As the airborne discharges the average of normalized release from light water graphite reactors of tritium is about 3 TBq per giga-watt-electric-year and it is nearly 500 T Bq per giga-watt-electric-year from heavy water graphite reactors. Large amounts of tritium were injected in the atmosphere when the hydrogen bomb tests conducted. Carbon ^{14}C is produced in nuclear reactors by (n, p) reactions with ^{14}N presented in the fuel as impurities or by (n, α) reactions with ^{17}O presented in oxide fuel. For ^{14}C the average of normalized airborne discharges are 120 GBq per giga-watt-electric-year for pressurized water reactors, 450 for boiling water reactors and 4 800 for heavy water graphite reactors. All living material (incl. body tissue) has a ^{14}C concentration of ~227 Bq kg^{-1}.

Iodine ^{131}I, which is the most important fission product in radioecology, is released with airbone effluents from nuclear reactors. The average of normalized release varies from 0.19 to 14 GBq per giga-watt-electric-year depending on the reactor type. Particulates mostly consisting of corrosion and fission products are also discharged from nuclear reactors to the atmosphere, amounting 0.2–12 GBq per giga-watt-electric-year depending on the reactor type

The low level and intermediate level wastes arising from the nuclear fuel cycle are mostly deposited by shallow burial although some of those wastes also have been dumped into the ocean until 1982, namely, in shallow waters in

Arctic close to Novaya Zemlya. The future permanent disposal of high level wastes may be a potential source of the groundwater contamination.

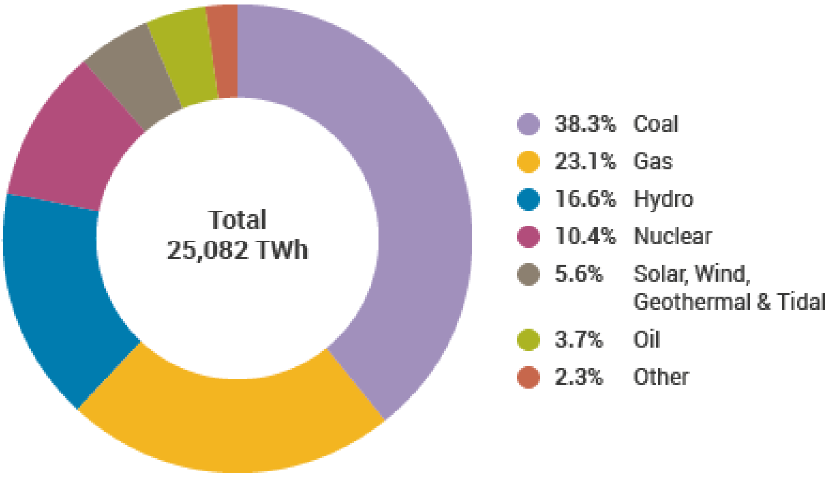
According to European Nuclear Society data today (2016) in 31 countries there are 450 nuclear power plant units in operation with an installed electric net capacity of about 392 GW. 60 plants with an installed capacity of 60 GW are in 16 countries under construction (Table 12).

Table 12. The number of nuclear power plant units in operation and under construction (https://www.euronuclear.org)

Country	In operation		Under construction	
	Number	Electr. net output MW	Number	Electr. net output MW
Argentina	3	1.632	1	25
Armenia	1	375	-	-
Belarus	-	-	2	2.218
Belgium	7	5.913	-	-
Brazil	2	1.884	1	1.245
Bulgaria	2	1.926	-	-
Canada	19	13.524	-	-
China	36	31.402	20	20.500
Czech Republic	6	3.930	-	-
Finland	4	2.752	1	1.600
France	58	63.130	1	1.630
Germany	8	10.799	-	-
Hungary	4	1.889	-	-
India	22	6.225	5	2.990
Iran	1	915	-	-
Japan	43	40.290	2	2.650
Korea, Republic	25	23.133	3	4.020
Mexico	2	1.440	-	-
Netherlands	1	482	-	-
Pakistan	4	1.005	3	2.343
Romania	2	1.300	-	-
Russian Federation	36	26.557	7	5.468
Slovakian Republic	4	1.814	2	880
Slovenia	1	688	-	-
South Africa	2	1.860	-	-

Spain	7	7.121	-	-
Sweden	10	9.651	-	-
Switzerland	5	3.333	-	-
Taiwan, China	6	5.052	2	2.600
Ukraine	15	13.107	2	1.900
UAE	-	-	4	5.380
UK	15	8.918	-	-
USA	99	98.868	4	4.468
Total	450	391.915	60	59.917

Nuclear power plants in 2016 provided around 10.4% of worldwide electricity production (Fig. 19), while generation from combustible fuels accounted for 67.3% of total world gross electricity production. Ukraine gets more than half from nuclear power plants.



Source: IEA Electricity Information 2018

Fig. 19. World electricity production by source 2016 (https://www.iea.org/statistics/)

Unlike fossil sources of energy (oil, coal, gas etc.), whose stocks are gradually decreasing, uranium total world resources even are not known exactly, virtually only began to be used. It is believed that the world nuclear energy production will increase in the future.

Data in Table 13 shows uranium reserves by country in 2017. Ukraine among them ranks 13th and the first in Europe, apart of Russia, whose main uranium reserves are in the Asian part.

Accidental release of radionuclides. Accidents that result in releases of radioactive materials into the environment have occurred throughout years. On April, 26, 1986 the most serious accident in the history of the nuclear industry occurred at the Chernobyl NPP. As a result of the accident, the rector was destroyed and in ensuing 10 days, large quantities of radionuclides were injected into the environment. The total activity of released radioactive material is estimated today to be 12×10^{18} Bq, including noble gases (from 6 to 7×10^{18} Bq). The amount released was about 3 to 4% of the used fuel present in the reactor at that time, as well as up to 100% of noble gases and 20–60% of volatile radionuclides.

The release had a complex composition of radionuclides. The radioactive isotopes of iodine and caesium were of special radiological importance. The iodine with their short half-lives had greater radiological impact for the short term; the caesium with half-lives of tens of years will have greater radiological impact for the long term.

Table 13. Uranium resources by country in 2017 (http://www.world-nuclear.org)

Country	Tonnes U	Percentage of world	Country	Tonnes U	Percentage of world
Australia	1,818,300	30	Uzbekistan	139,200	2
Kazakhstan	842,200	14	Ukraine	114,100	2
Canada	514,400	8	Mongolia	113,500	2
Russia	485,600	8	Botswana	73,500	1
Namibia	442,100	7	Tanzania	58,200	1
South Africa	322,400	5	USA	47,200	1
China	290,400	5	Jordan	43,500	1
Niger	280,000	5	Other	280,600	4
Brazil	276,800	5	World total	**6,142,600**	-

The current estimates of the activity of the releases of these elements are the following: ^{131}I ~2×10^{18} Bq, ^{134}Cs ~0.06×10^{18} Bq and ^{137}Cs ~0.09×10^{18} Bq. These values represent about 50–60% of the radioactive iodine in the reactor core at the time of the accident, and about 20–40% of the radioactive caesium. Material released into the atmosphere dispersed and eventually deposited back on the surface of the Earth. Most of the material was deposited in the regions around the plant site with great variations in deposition density. The surrounding territories of Belarus, Ukraine and Russia contaminated by ^{137}Cs with the deposition level of 185 kBq m^{2} and higher are estimated as 16 500 km^{2}, 4 600 km^{2} and 8 100 km^{2} respectively. These territories were designated as affected areas, or “areas of strict control”. The 200 000 persons who participated in “liquidation” of the accident received average doses in the order of a hundred mSv. About 10% of these received doses of 250 mcSv, a few percent received doses greater than 500 mSv, while perhaps several tens of the people who responded initially to the accident received lethal doses. Among the public, the 116 000 people were evacuated from the exclusion zone in 1986. Among them there were people who received the highest doses (10% received more then 50 mSv and 5% more then 100 mSv).

The other nuclear reactor accident of environmental concern was the Windscale accident (Great Britain) in October 1957. A military air-cooled graphite-moderate natural uranium reactor used for plutonium production caught fire during the scheduled release of the energy stored in the graphite. Emission lasted for 18 hours. Approximately 0.6–1 PBq ^{131}I, 22–94 TBq ^{137}Cs, 5 TBq ^{89}Sr, 0.22 TBq ^{90}Sr, 8.8 TBq ^{210}Po, 5 PBq ^{3}H and 1.6 GBq ^{239}Pu were released. The activity was found in most parts of Western Europe.

In 40s, the plutonium production for military use started in the territory somewhere between Chelyabinsk and Yekaterinburg in Russia. High levels of radwastes such as nitrates and acetates resulted from the plutonium production were stored in large water-cooled tanks at plant called Chelyabinsk-40. It was located near Kyshtym. A failure in the cooling system dried out the waste in one of the tanks and on September, 29, 1957 an explosion that resulted in the total deposition of 74 PBq occurred. Most of the activity consisted of short-lived fission products ^{95}Zn and ^{144}Ce. About 2 PBq of ^{90}Sr and 30 TBq of ^{137}Cs were also released by the accident. The deposition occurred to the distance of a few hundred kilometers including regions of the Chelyabinsk, Yekaterinburg and Tyumen provinces.

A number of reservoirs for disposal of high level radwastes were established for Chelyabinsk–40. One of them was the 0.25 km^{2} Lake Karachy, contained 4 EBq of ^{90}Sr and ^{137}Cs. Dust from the shore line of the lake was dispersed by the wind over an area of 1 800 km^{2} and to the distance of 75 km in the summer of 1967. As a result of the great amount of radioactive wastes was dispersed in the environment.

The most of the accidents resulted in releases into the atmosphere, however, a few accidents resulted in radionuclides released directly into the sea. In 1968, a B–52 aircraft from the US Air Force crashed during an emergency landing on the sea to the west of Tuline, the airbase NW, Greenland. About 1.3 TBq of $^{239+240}$Pu contaminated the marine environment.

A similar accident occurred at Palomeras, SE, Spain, 1966. The radioactive debris was mainly deposited on land, but relatively large inventories are also found in the marine environment.

In 1964, a nuclear powered satellite containing 0.6 PBq of ^{238}Pu re-entered the atmosphere over the Mozambique Channel. It resulted in the appearance of enhanced ^{238}Pu/$^{239+240}$Pu ratios globally, especially over the Southern Hemisphere.

The loss of submarines and their seabed disposal had minor effects on concentrations in the marine environment. The US lost two submarines and the former USSR lost six ones. Most losses occurred in the North Atlantic. In April, 1989, 180 km to the south west of Bear Island in the Barents Sea the submarine “Komsomolets” (the USSR Navy) sank at 1 500 m depth. The core inventory in this submarine was 2.8 PBq of ^{90}Sr and 3.1 PBq of ^{137}Cs. In the morning of August 12th 2000, a Russian submarine sank in international waters eastwards of Rybatschi Peninsula in the Barents Sea. To the northeast of Murmansk about 250 km from Norway and 80 km from the cost of Kola the submarine sank at 116 meters depth . The Komsomolets contains only one nuclear reactor with the inventory of long-lived radioactive substances that are estimated to be about: 2.8×10^{15} Bq of ^{90}Sr and 3.1×10^{15} Bq of ^{137}Cs.

3.3. Generators of ionizing radiation

The cathode tube that became the source of X-radiation received Röentgen name stimulated production of X-devices. Such devices are widely used in many areas of science and industry but mainly in medicine for diagnosis of many diseases and injuries as well as for the radiotherapeutic treatment of neoplasms, mainly cancer. *The X-radiation apparatus was the first artificial generator of ionizing radiation that provided the additional dose to a human organism.*

Nowadays simple X-radiation apparatuses that are used in disease-preventive service, provide the highest additional dose in comparison with other artificial sources of ionizing radiation. Such disease-preventive service contributes approximately 20% above of natural background level. However, in some developed countries doses due to the application of disease-preventive service may reach the natural background level or even exceed it. At radiotherapeutic procedures as well as procedures for diagnostic of different organs the pharmaceutical preparations with radioactive isotopes are used. The preparations penetrate inside the organism and therefore give considerably higher doses of irradiation.

A gas ^{222}Rn isolated from the parent substance ^{226}Ra is sometimes used for the radiotherapeutic treatment of cancer. The radiotherapeutic value of ^{222}Rn in the tissue is due to irradiation by γ-rays of its decay daughters ^{214}Pb and ^{214}Bi that reach radioactive equilibrium extremely rapidly with the ^{222}Rn.

^{99m}Tc is used for diagnostic purposes for liver, spleen, and thyroid scanning.

The development of high-energy physics led to the creation of special installations, i.e. the accelerators of charged particles capable to cause ionization of a matter such as linear accelerators, microtrons, betatrons, cyclotrons, synchrotron accelerators, phazotrons, synchrophazotrons up to the most modern supercolayders that are the sources of electrons, protons, deuterons and ions with energy up to millions of electron-volts. Physicians pay attention to these generators of ionizing radiation because of their convenience in the operation and high accuracy of dosimetry, providing wide opportunities for localization of a dose in the definite places inside of the organism. Undoubtedly, such devices cannot be competed with ordinary X-rays apparatuses and γ-installations. New specialized accelerators and other modern diagnostic and therapeutic complexes based on both X-rays apparatuses and γ-installations are adopted for the medical purposes in many countries. It is worth mentioning that improvement of existing X-rays apparatuses, the use of new methods for diagnostics of internal organs and new types of irradiation for radiotherapy decreases the radiation dose. The modern X-rays apparatuses allow reducing a radiation dose during a séance by factor 5–10 in comparison with those ones, used 30–50 years ago. An application of a computer tomography when X-rays don’t penetrate into the body but only reach a certain depth allows in some cases decreasing radiation dose by factor 20–50. Increased sensitivity of radiometers allows reducing isotope concentrations at radiodiagnostic procedures. An application of specialized accelerators of charged particles and some other types of radiation in radiotherapeutic treatment of cancer allows avoiding treatment of undamaged tissues due to precise beam localization in damaged tissues.

Displays of colour TV sets, PC monitors and other devices also generate X-rays. However, as a rule, they are not registered on the distance of more that 50 cm. The radiation dose from the modern models of these devices is absolutely inappreciable, if the screen is properly adjusted and used.

3.4. The contribution of various sources of ionizing radiation to formation a radiation dose for man

Thus, all living organisms as well as lifeless matters on the Earth are subjected to the ionizing radiation of various natural and artificial sources. However, there are well known doses that may induce noticeable physical and chemical alterations in mentioned above objects, and that thousand and tens thousand times higher than the natural radioactive background. It means that the possible effect of irradiation doses due to the natural background can be neglected. Concerning living organisms the effects of radiation may be observed even at the dose rate corresponding to the natural radioactive background. When radioactive background is elevated the probability of radiation effects increase.

The general index of the irradiation dose dynamics of the Earth population in the second half of the 20th century is shown in Fig. 20

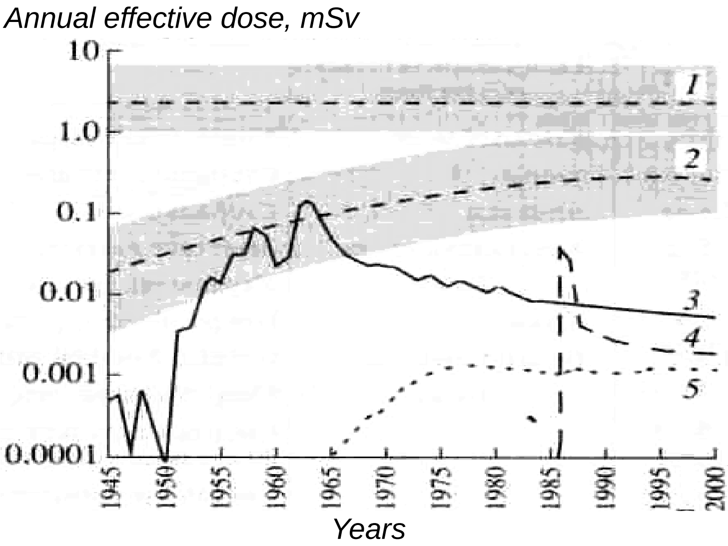


Fig. 20. Dynamics of the formation of human irradiation dose from different sources of ionizing irradiation: 1 – natural radiation background, 2 – medical X-radiation examinations, 3 – nuclear tests in atmosphere, 4 – accident in Chernobyl NNP and 5 – production of nuclear energy (shading parts are showing of the dose diapasons; R. Alexakhin, 2000).

1

It is an annual average dose per man depending on habitat, diet and other factors that differ significantly. Thus, it represents the relative contribution of the main sources to a total dose. The natural radioactive background is the main source of radiation. Nowadays, the average radiation dose due to the natural radioactive background equals 2.2 mcSv y^{-1}. It is also quite clear, that this value may vary widely over the regions of the planet. However, for a definite country it is more or less constant. Radiation doses from artificial sources remain essentially lower.

Increase of the energy production and atomic energy provides an additional irradiation of people. In the beginning of this century doses due to this source were only 0.05% of the natural radioactive background.

The irradiation of the people and biota as a whole due to this source of radiation can be much higher only in the case of accident. The most typical example of such accident is the Chernobyl catastrophe when many people were subjected to high radiation doses. Extremely high radiation doses were observed in the area of the Chernobyl NPP. As a whole for the European region the radiation doses remain at low level. Only during the first year after the accident the average radiation doses in the Western Europe increased up to 50% in comparison with natural radioactive background. In the following years after the accident doses sharply reduced and now they do not exceed 0.1%.

The average ionizing radiation dose used in medicine is about 14% regarding natural radioactive background with variation (from 5 up to 50%) at different places.

Such average pattern is typical for the planet as a whole. In regions with anomalies other relationships between the components of radiation doses are observed. The radiological situation became worse in association with the accident on the Chernobyl atomic power plant for the population of Ukraine, especially who live in northern regions, Belarus, the western part of Russia. Population of these regions is exposed to elevated radiation doses due to external irradiation from radioactive fallout and internal irradiation caused by the incorporation of radioactive substances into a human body with food, water and air.

Control points to chapter 3:

1. Sources of ionizing radiation.
2. Natural sources of ionizing radiation.
3. An origin of cosmic radiation.
4. Original and cosmogenic radionuclides.
5. Categories of original radionuclides.
6. Components of natural radiation background.
7. Natural radionuclide anomalies.
8. Artificial sources of ionizing radiation.
9. Components of nuclear fuel cycle.
10. The largest nuclear accidents.

11. Characteristics of the Chernobyl NNP accident.
12. Generators of ionizing radiation.
13. The contribution of various sources of ionizing radiation to the formation of a dose for a man.

4. CHEMICAL AND BIOCHEMICAL INTERACTIONS OF IONIZING RADIATION WITH SUBSTANCES AND STRUCTURES OF CELLS

4.1. Direct and indirect actions of ionizing radiation on molecules. 4.2. Radiation-induced chemical transformations of molecules in water solution. 4.3. Radiation-induced damages of biologically important molecules. 4.4. Radiation-induced damages of membranes. 4.5. Structural-metabolic hypothesis of ionizing radiation effects on living organisms. 4.6. Comparative radiosensitivity of various types of cells and cellular structures.

There is a number of theories and hypothesis that explains the biological effects of ionizing radiation. Some of them were formulated during 1920s and 1930s. They are fundamental and still topical nowadays. The most important is “target” theory and the theory of direct and indirect actions of ionizing radiation. This chapter describes the interaction of ionizing radiation and living matter. The biological effects of ionizing radiation are caused by the absorption of the radiation energy in the tissues and by the distribution of that energy in living matter. Some of the basic physical phenomenon and chemical reactions that precede the biological effects of radiation are discussed. The chapter also examines the effects of radiation at biophysical, biochemical and subcellular levels that might be a basis for interpreting the radiobiological damage in tissues and of a whole organism.

4.1. Direct and indirect actions of ionizing radiation on molecules

The effects of the physical deposition of radiation energy are quite well understood. The biological effects of radiation will be discussed later in this book. There is the lack of knowledge about the links between physical, chemical and biological effects of radiation.

Ionizations cause the majority of the immediate chemical changes in living material. This damage may be the direct result of an ionizing track or it may be due to the indirect action of free radicals. The radiation-induced transformations in biological systems are determined by two main mechanisms:

1. Direct action of ionizing radiation, which involves the simple interaction between the ionizing radiation and critical biological molecules.

2. Indirect action of ionizing radiation on molecules that occurs through ionization of free water radicals as the intermediaries in the transfer of radiation energy to biological molecules.

The initial stage of ionizing radiation action is the chain of the consequent events taking place in a living matter. The physical processes of interactions of photons and ionizing particles with matter occurred both in a living and in a non-living matter were discussed in previous chapter. These processes take extremely short time of 10^{-24}–10^{-14} seconds (Table 14). At this stage the energy of ionizing radiation is absorbed by matter with the following interaction.

Next steps in the chain may lead to a biological effect. The biological matter consists of molecules of various sizes, and each of them is composed of many atoms. The interaction of radiation with molecules is assumed to be similar to the interaction with individual atoms. The chain of chemical reactions that results in damage of critical biological molecules may take as little as 10^{-6} second. At this stage the interaction of ions and free radicals result in appearing of secondary free radicals and peroxides. Finally, all these products interact with matter and cell structures. Direct action of ionizing radiation mainly induces damages of such subcellular structures as molecules of DNA, aminoacids residues in protein molecules etc. The final stage of biological damage may take hours, days or even tens of years.

Table 14. Chain of events leading to radiation injury (J. Goggle, 1983)

Event	*Timescale*
Initial interactions	
Indirectly ionizing radiation [a]	10^{-24} – 10^{-14} s
Directly ionizing radiation [b]	10^{-16} – 10^{-14} s
Physico-chemical stage	
Energy deposition as primary track structure of ionizations	10^{-12} – 10^{-8} s
Chemical damage	
Free radicals, exited molecules to thermal equilibrium	10^{-7} s – hours
Biomolecular damage	
Proteins, nucleus acids, etc.	ms – hours
Early biological effects	
Cell death, animal death	hours – weeks
Later biological effects	years – centuries
Cancer induction, genetic effects	

[a] X-, γ-radiation, neutrons; [b] electrons, protons, α-particles

The physical absorption of energy (stages 1 and 2) and the biological effects of such absorption (stage 5 and 6) are better understood. It is less known about chemical and biochemical events and even less known about the relationships between stages 2, 3, 4, 5 and 6. The sequence of processes that links the physical absorption of energy with the resulting biological effects is impossible to be described in details. Processes observed at the stage 3 must be discussed in more detail.

Free radicals that appeared at the stage are electrically neutral atoms or molecules having an unpaired electron in their outer orbits. In stable atoms and molecules orbit electrons occur in pairs with opposite spin values (one of the number of the parameters that determines electron quantum and may have two values only). A free radical is formed by radiation when an atom is left by one of its outer orbit electrons unpaired with respect to spin. Free radicals are usually very reactive since they have a great tendency to pair the odd electron with a similar one of another radical or to eliminate the odd electron by an electron transfer reaction. Therefore, free radicals can be electron acceptors (oxidizing species) or electron donors (reducing species).

At the stage 2 and 3 molecules that are most abundant in living matter most likely will be ionized, since radiation produces excitations and ionizations at random. Taking into account the fact that living matter consists of 70–90% of water; water molecules will take up most of the absorbed energy. As a result of water radiolysis (breaking up of water molecules due to excitations and ionizations processes) and at the presence of oxygen in irradiated cells such free radicals as H^*, OH^*, HO_2^* and O^* are appeared. Such products may interact with molecules resulting in an inactivation and oxidizing; associate with each other as well as with other atoms providing new types of free radicals and hydrogen peroxides with highly oxidizing properties. Damages of macromolecules due to interaction of their parts and products of radiolysis are the result of indirect action of ionizing radiation.

From the point of view the biological damage it does not matter at all whether the critical molecule is damaged directly or indirectly. However, it seems that much radiobiological damage is a consequence of indirect action, since cells and tissues are composed of approximately 70–90% of water.

Direct and indirect actions of radiation upon important biological molecules result in the wide range of biological effects of irradiated living organisms. Functional properties of biologically important molecules alter due to direct as well as indirect action of ionizing radiation.

Stage 3 is very important, because the starting point of radiation-induced damages any biological system, organism, virus or mammal is inactivation of a number of macromolecules. As we mentioned above, the damage of DNA molecule is the most important process. Damaged DNA molecules induce synthesis of altered molecules of RNA and proteins, which might be involved in the metabolism processes providing various distortions and finally biological effects.

DNA macromolecule is the primary target for direct as well as for indirect action of ionizing radiation. The damage of DNA molecules may cause such unspecific reactions in irradiated cell as mutations, metabolism disorder and finally cell death. In radiobiology such state is interpreted as “hit principle” and “target theory”. It should be mentioned that “target theory” is not universal because the probability to hit in such sensitive volume (target) is relatively low even under doses causing radiobiological effects, or even death.

4.2. Radiation-induced chemical transformations of molecules in water solution

Absorption of radiation energy is determined mainly by the concentration of molecules in irradiated matter. We have already mentioned that living matter consists of 70–90% of water that means that the most of absorbed energy is taken up by the water molecules. Thus, for an understanding of radiobiological effects the radiation chemistry of water is of an extreme importance. If water is irradiated (radiolysis), it is ionized providing a fast moving of free electron and positively charged water molecule:

$$H_2O \xrightarrow{\text{radiation}} H_2O^+ + e^-$$

It is obvious that ionized molecules will be formed only in the case when the amount of radiation energy is enough to leave electron otherwise water molecule will be excited as follows:

$$H_2O \xrightarrow{\text{radiation}} H_2O^*$$

The electron (e^-) will travel through the water, losing energy during various processes. Finally it will be captured by another water molecule converting the latter into a negatively charged molecule:

$$e^- + H_2O \rightarrow H_2O^-$$

Since this process is relatively slow water molecules may surround the electron, i.e., hydrated. Hydration is a process, when the dipoles of several water molecules are orientated towards the negative charge of the electron. Such hydrated electron (e^-_{aq}) is stable enough at room temperature to give rise to a broad absorption spectrum with a maximum around 720 nm. Free hydrated electron (e^-_{aq}) may be attached to ionized or normal water molecule producing free radicals:

$$H_2O^+ + e^-_{aq} \rightarrow H_2O^*$$
$$e^-_{aq} \rightarrow H^\bullet + OH^-,$$

where the dot indicates the unpaired electron of the free radical.

Non-hydrated electrons (dry electrons), are capable to react with a wide range of solute molecules and such reactions occur better in high solute concentrations (between ~ 0.1 to 1.0 M) than in more dilute solutions where hydration of the electron is a competing process that is essentially complete in 10^{-11}s. Such electrons may be important since solute concentrations inside cells can be high enough.

Both neither ionized nor exited water molecules are stable and each dissociates to give an ion and a free radical:

$$H_2O^+ \rightarrow H^+ + OH^-$$
$$H_2O^- \rightarrow H^\bullet + OH^-$$
$$H_2O^* \rightarrow H^\bullet + OH^\bullet$$

Mentioned above reaction products are primary. It is known that for every 10^{-5} J of low linear energy transfer (LET) radiation energy absorbed by pure water the following new species are formed: 2.6 hydrated electrons, e^-_{aq}; 2.6 hydroxyl radicals, $OH^\bullet$; 0.4 hydrogen atoms $H^\bullet$; and a small amount of H_2 and H_2O_2. Hydrated electrons (e^-_{aq}), hydroxyl radicals ($OH^\bullet$) and hydrogen atoms ($H^\bullet$) are highly reactive and in the absence of other reactants they have lifetime up to several hundred microseconds. Such species can react with each other:

$$H^\bullet + H^\bullet \rightarrow H_2$$
$$OH^\bullet + OH^\bullet \rightarrow H_2O_2$$
$$H^\bullet + OH^\bullet \rightarrow H_2O$$

or they may react with other water molecules, or radicals may react with their own reaction products

$$H_2O + H^\bullet \rightarrow H_2 + OH^\bullet$$

$$H_2O_2 + OH^\bullet \rightarrow H_2O + HO_2^\bullet$$

where $HO_2^\bullet$ is the hydroperoxy radical.

Mentioned above reaction products are secondary ones.

The reactivity and rate constants for reactions of these species with many molecules are measured. Their chemical nature is similar to free radicals, and, therefore, they can abstract hydrogen from organic molecules, RH, resulting in new radical species:

$$RH + OH^\bullet \rightarrow R^\bullet + H_2O$$
$$RH + H^\bullet \rightarrow 0R^\bullet + H_2$$

The primary as well as secondary free radicals $R^\bullet$ can react with biologically important molecules and cause radiobiological damage. These reactions are generally held to be important in case of indirect action of ionizing radiation, because this action involves aqueous free radicals as intermediaries in the transfer of radiation energy to biological molecules. Many of these reactions lead to biologically harmful products, and others lead to the initiation of damaging chain reactions. There is strong conviction that the $OH^\bullet$ radical is involved in producing DNA single strand breaks, chromosome aberration, bacterial and mammalian cell killing. Many of such reactions are enhanced by the presence of oxygen.

The role of the oxygen in radiation injury. Free radicals may react with molecules of oxygen. Such reactions are of great radiobiological importance, because they may lead to the production of peroxide radicals both of hydrogen and of important organic molecules. Some of radicals are considered to be biologically damaging.

It is known that the effectiveness of radiation increases in the presence of oxygen. In radiobiology this phenomenon is known as the “oxygen effect”. It shows that the yield of free radicals increases in the presence of oxygen. The reaction of oxygen with aqueous free radicals such as H and e_{aq}^- leads to the production of relatively stable hydroperoxy radicals ($HO_2^\bullet$) and hydrogen peroxide:

$$O_2 + H^\bullet \rightarrow HO_2^\bullet$$
$$O_2 + e_{aq}^- \rightarrow O^-_2$$
$$O^-_2 + H^+ \rightarrow HO_2^\bullet$$

$$2HO_2^{\bullet} \rightarrow H_2O_2 + O_2$$

In the case if an organic biological molecule (RH) becomes a free radical either directly or indirectly it may interact with oxygen as follows:

$$R^{\bullet} + O_2 \rightarrow RO^{\bullet}_2 \text{ (an organic peroxy radical)}$$

A chain reaction may be generated involving more RH:

$$RO^{\bullet}_2 + RH \rightarrow RO_2H + R^{\bullet}$$

These reactions are tantamount to fixation of biological damage and occur at a rate thirty times faster than a competing reaction, e.g., $R^{\bullet}$ + cysteine or other hydrogen donor gives RH, i.e. reconstitution.

4.3. Radiation-induced damages of biologically important molecules

Radiation effects on nucleic acids. The living cell is extremely sensitive to ionizing radiation. It is established that the disturbance of DNA synthesis is a result of radiation effects on a living cell. However, knowledge of the molecular effects of radiation is based on the understanding of molecular biology in general. DNA macromolecule consists of two spiral strands twisted around one another to form the "double helix" (Fig. 21, a).

The unwound double helix resembles a step-ladder (Fig. 21 b), the sugar-phosphate "back-bone" (Fig. 21, c, d) and the rungs that are the combination of base pairs held together by hydrogen bonds (Fig. 21, e). The strands are composed of a "back-bone" of alternate phosphate and sugar groups attached to each sugar group so-called a nitrogenous base. The two strands are held together by hydrogen bonds that run from one base to another. There are four bases such as two pyrimidines (thymine and cytosine) and two purines (guanine and adenine). These pairs of bases always are opposite to one another (the number of adenine molecules equal to the number of thymine molecules and cytosine to guanine correspondingly) that make the strands be complementary to one another. It is suggested that DNA molecules hold the genetic information in the nucleus in the form of a linear sequence of base-genes. The information is in the form of a four-letter alphabet (the four bases), each "word" of the code has three letters. Each triplet of adjacent bases in the messenger of RNA (mRNA) has codes for a particular aminoacid. Therefore, a specific sequence of bases corresponds to a specific linear sequence of aminoacids, i.e. to a specific protein molecule. Thus, genes at a molecular level are a linear array of nucleotide sequences.

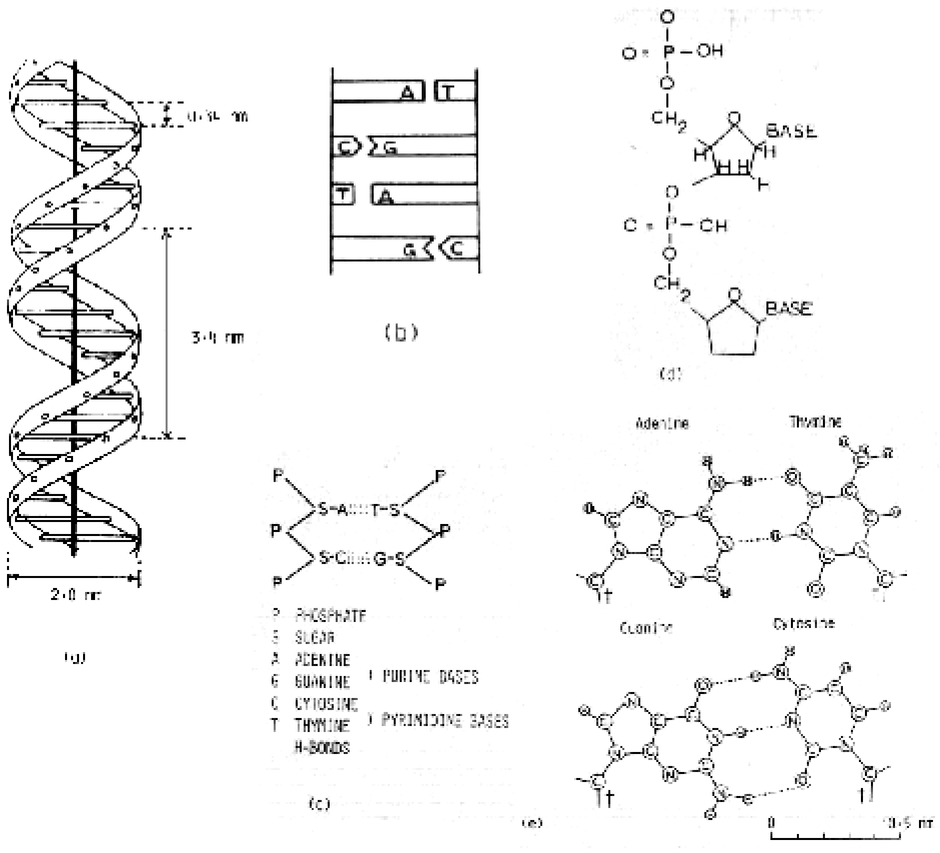


Fig. 21. The diagram of the basic structure of DNA (J. Goggle, 1983).

The aminoacid sequence that specifies a given protein is not built up directly on the base of DNA. Protein synthesis occurs in the cytoplasm. Intermediary molecules of mRNA are used in order to transfer the DNA code to the site of synthesis. A specific mRNA is a complementary copy of that part of the DNA that is to be transformed into a protein. The mRNA moves from the nucleus to the cytoplasmic site of protein synthesis. It joins ribosomes. Ribosomes are composed of protein and another species of RNA, ribosomal RNA (rRNA). In ribosome the mRNA is a mould (or template) for the synthesis of a specific protein. The individual aminoacid required to build up the protein are brought to the ribosomal site by a third RNA, transfer RNA (tRNA). Each aminoacid has its own tRNA in accordance with an anticodon.

The three types of RNA (messenger, ribosomal and transfer) have a structure comparable with a single strand of DNA, but uracil replaces thymine in RNA. Cells continuously produce new proteins and result in continuous process of RNA synthesis (RNA only ceases for a very short period of nuclear division – mitosis). On the contrary, the process of DNA replication is not continuous and occurs at a definite part or phase of the cell division cycle (S phase, Fig. 22).

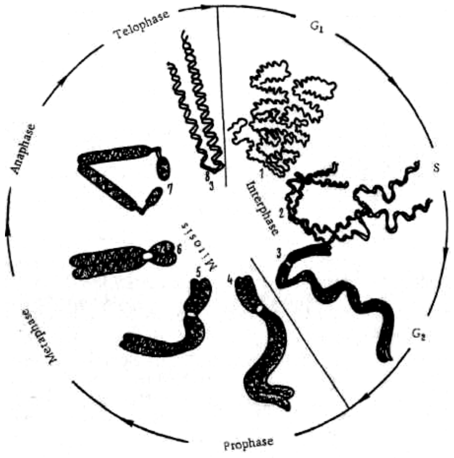


Fig. 22. The state of chromosomal DNA during different periods of interkinesis (1-3) and mitosis (4-8): 1) G_1 stage. The chromonemata are uncoiled and the DNA partly deprotonated (at the sites of synthesis of mRNA); 2) S stage. DNA replication is in progress, the replication part is in a strongly hydrated state (in the form of "nucleoplasm"); 3) G_2 stage. Distribution of the isologous daughter spiral nucleohistone helices into two isologous sets of sister chromatids; 4) prophase. Further twisting of the distributed helices in the chromonemata (supercoiling) and union into chromatids; 5) early metaphase. Distribution of the chromosomes in the "equatorial" plane of the nucleus; 6) metaphase chromosome composed of two sister chromatids; 7) anaphase chromosomes (diverging sister chromatids); 8) telophase. Uncoiling (backward development) of the chromosomes (N. Strazhevskaya, 1972).

During the replication (copying) the two strands of the RNA separate and two new strands are made using the complementary base pairings of the original two strands, thus, forming two new DNA molecules. The two new molecules will be eventually separated at mitosis (M), thus, allowing the transmission of the identical genetic information to two daughter cells.

The stage that is prior to S stage is called $G_{1.}$ The next is known as G_2. The G_1 stands for "gap" during which the cell marshals in the complex biochemical apparatus of small precursor molecules necessary to copy the DNA. It includes the four nucleosides 5^1 triphosphate precursors and enzymes such as endonucleases, DNA polymerases and ligases. The replication of DNA occurs from 10^3 to 10^4 sites (replicons) along the molecule at one time during the S stage. The replications at these growth points proceed simultaneously in two directions along the molecule until it links to the adjacent replicating points. Assuming the average cell life cycle is 24 hours, the respective duration of the stages is the following. The stage G_1 lasts about 14 hours. S stage lasts about 5 hours and is followed by G_2 before mitosis. DNA undergoes the complex coiling in G_2 stage. It leads to the formation of chromosomes. The duration of this stage is about 4 hours. Sometimes subpopulation of cells can go into a phase called G_0 (mitosis) where they are quiescent mode or “out of cycle”. The duration of this stage is about 1 hour.

Mitosis and cell division are among the most “radiation-sensitive” processes the cell performs. Obtaining a dose of radiation the cells lose their ability to complete mitosis and cell division. On the contrary, it is generally accepted that cells that are not divided remain largely unaffected by doses of radiation in comparison with cells that can be divided.

As we mentioned above the molecule of DNA is considered to be a “target”, thus, radiation-induced damage of it may cause the death of an organism.

The initial radiation-induced chemical transformations of the nucleic acids are determined by its interactions with such products of water radiolysis as hydrated electrons, e^-_{aq}; hydroxyl radicals, $OH^\bullet$; and hydrogen atoms $H^\bullet$. Hydrated electrons are involved in reduction as well as dissociative adhesion. Hydroxyl radicals are active in oxidative reactions and in the process of double-bond adhesion. They may chip hydrogen atoms from organic molecules. Hydrogen atoms are active in the process of reduction reactions, double-bond adhesion and may chip hydrogen atoms from organic molecules. Ions of oxygen ($O^-{}_2$) and radical $HO_2^\bullet$ might be formed in the presence of oxygen

Several transformations may occur when the molecule of DNA is irradiated. That is radiolysis of purine bases and break of pyrimidine ring followed by their separation from the polynuclear chain. Some of the bases may interact with water radiolysis products causing break of hydrogen bound. The last transformation might result in the loss of protein structure. Transformations of the nitrogenous bases cause violation of bases pairing, which in turn might lead to mistakes during the coding of the information. Radiation-induced alterations of the sugar groups result in break of phosphate and sugar groups bounds and finally in single strand break due to the interactions with water radiolysis products.

There are three major types of DNA damage: single- and double-strand breaks and base damage. The number of single-strand breaks is linearly related to the dose of radiation over a very wide dose range from less than 0.2 Gy to 60 000 Gy. The efficiency of induction of single-strand breaks varies from a number of biochemical factors and LET radiation from 10 to 20 eV per break is required. Fig. 23 shows the relative distribution of ionizing processes for high and low LET radiation in relation on the size of the DNA molecule.

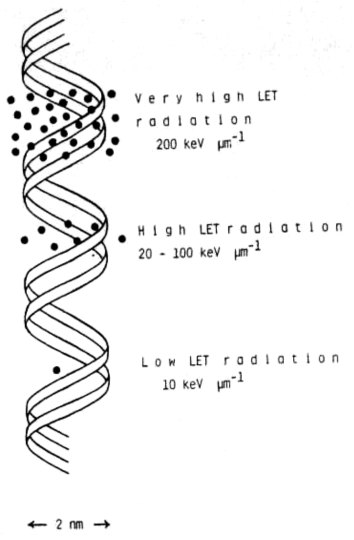


Fig. 23. The relative distribution of ionizing processes for high and low LET radiations (J. Goggle, 1983).

As we mentioned above, the significant proportion of single-strand breaks is induced via mechanism involving the $OH^{\bullet}$ radicals of water under normal conditions. The number of single-strand breaks induced by radiation in oxygenated mammalian cells is 3–4 times higher than those in cells irradiated under hypoxic conditions. It is assumed that single-strand breaks do not cause cell death. It seriously complicates the reading of information from DNA molecule.

Double-strand breaks can be formed either by a single ionizing process or by the coincidence of random single-strand breaks on the complementary strands. The relationship between the dose and the number of induced double-strand breaks is more complex in comparison with single-strand breaks. Some researchers find a simple linear response while others show that only the initial part of the curve at the lowest doses is linear and at higher doses the number of double-strand breaks increases with the increase of the dose, i.e. the dose effect curve is “linear quadratic”. Such response indicates that double-strand breaks may be produced by the passage of one ionizing process or as a result of two independent single-strand breaks. Double-strand breaks are especially dangerous for DNA molecule and often may lead to cell lethal end. At the same time newly formed ones providing chance for irradiated organism to survive might replace the limited number of damaged cells. However, if repairing mechanisms do not eliminate the part of damaged DNA such damage might be fixed resulting mutations in future generations.

Radiation damage of the purine and pyrimidine bases of DNA is linearly related to a dose and is thought to arise via interactions with aqueous free radicals such as $OH^{\bullet}$. Radiation-induced damage of thymine base is more frequent in mammalian cells than single-strand breaks. Non-repaired base damage is an important determinant of prokaryotes survival. There is evidence that similar damage may be important in higher cells.

The degree of the post-irradiation depression in DNA synthesis is not dose dependent only. It depends markedly on the phase of the cycle at which the radiation is given. The phases of radiation-induced defective synthesis (mitosis and the G_1/S border) are also the most sensitive for cell killing. That’s why in synthesis cells are less radiosensitive both for cell killing and the depression of DNA synthesis. RNA synthesis is less sensitive to delay and suppression than DNA synthesis. The radiation effects on RNA and protein synthesis are generally unimportant in radiobiology.

Damages of RNA molecules are generally the same as of DNA, i.e., single-strand breaks are the main outcome of irradiation. The main difference is that RNA is not unique subcellular structure in comparison with DNA. Thus, new molecules may be synthesized instead of damaged ones and RNA damages are thought less important.

It is generally accepted in radiobiology that the nucleus is the main target of the radiation lethal effect. If the dose to the cytoplasm is large, it will cause cell death. Although it is possible to kill cells and to produce other kinds of damage by irradiation of the cytoplasm, it is much easier to produce the same effects by irradiation of the nucleus. It is because many of the radiobiological damage criteria are related to the functions of the nucleus. That is chromosome damage, delay of the onset of mitosis, the cessation of mitosis and cell division and the inhibition of DNA synthesis. The major information of a cell resides in the nucleus, i.e., the genetic code of the DNA and it is expected that any damage to it will be of primary importance, whereas, the damage to the cytoplasm may be of secondary importance.

The radiation effects on amino acids. The following products may be formed when amino acids are irradiated: free radicals as a result of chipping of carboxylic group (COOH group attached to a carbon skeleton as in the carboxylic acids and fatty acids) (COOH – decarboxylation), aminogroup (NH_2 – deaminization), an atom of hydrogen that forms an atom of carbon or radicals of amino acids residue. Such radicals may interact with each other as well as with molecules of undamaged amino acids. It results in the formation of carbonic acids, amines and ammonia. In radiation-induced transformations of amino acids, the atom of sulphur is involved as the constituent of sulphuric acids.

The effects of radiation on proteins. When proteins are irradiated, following reactions are observed: free radicals appear as a result of chipping of hydrogen an atom from atom of carbon (bound C–H); the splitting off proteins and the release of amides and carbonyl compounds; the change of the initial structure of proteins; the release of amino acids during hydrolyses destruction and denaturalization of protein molecule.

Such changes result in: the fragmentation and splitting off the protein molecule; polymerization, i.e., the formation of macromolecule from low molecular mass of monomers; the appearing of amides and proteins denaturalization due to the loss of hydrogen bounds. Finally such damaged molecule loses an ability to form a structure of a higher order. However, under the low radiation doses and due to a great number of protein molecules, the newly synthesized molecules may be substituted for the damaged ones. Thus, radiation-induced damage of protein molecules is not so important, apart of the situation when such damaged molecules react with other biologically important molecules.

The effects of radiation on peptides. Peptides are between the proteins and amino acids by their structure and properties. The peptides are formed when enzymes are split off proteins (proteases, enzymes of hydrolase's group). When peptides are irradiated the following processes may be observed: reducing deaminization and release of ammonia and acetyl peptides; recombination of acetyl radicals, acetyl peptides and peptide radicals when C–H– bound is broken; recombination of two peptide radicals or radical and peptide molecule resulting in formation of neutral peptides; peptide carbonization.

The effects of radiation on lipids. Lipids are organic substances insoluble in water but soluble in benzene, ether and acetone. Some of the fatty acids are associated with a class of lipids found in cell membranes. They are called phospholipids. Phospholipids are complex molecules that belong to lipids containing a substituted phosphate group and two fatty acid chains of a glycerol basis. Lipids also contain phosphatides, cerebrosides, gangliosides, steroids, carotenoids, vitamins (A, D) and hormones. Lipids play role in building and functioning of biological membranes.

When lipids are irradiated the major radiation-induced chemical changes are observed in fatty acids that belong to aliphatic carbonic acids group that contains one or more carboxylic group (COOH). Radiolysis of carboxylic acids causes decarboxylation and formation of hydrocarbon radicals followed by the interaction of these radicals with hydroxyl radicals $OH^{\bullet}$ and the release of free radicals that in turn initiate the chain reaction of peroxide degradation of fatty acids molecules. Such chain reaction is held due to the recombination of some free radicals forming stable products but these products are in excited state. When such products return in stable state, photons of visible light are emitted.

Easily oxidizing lipid fractions are the unsaturated fatty acids that are subjected to peroxide oxidation due to the interaction with water radiolysis products. As a result peroxide lipid radical is formed which in turn interacts again with lipid molecules giving peroxide radial and so on. According to the law of branched chain reaction the amount of such active products increases. It is known that the quantum yield of reaction products in phospholipids is by 2–3 orders of magnitude higher in comparison with the yield of other irradiated organic compounds.

The final products of lipid oxidation are e.g. carboxylic compounds that contain carbonyl group >C=O. Such functional group is typical for aldehydes and ketones.

As we mentioned above polysaturated fatty acids and phospholipids are prone to easy oxidation by chain reaction mechanism. Thus, ionizing radiation together with other factors such as oxygen, ultra-violet light, short wave light etc. is a factor that causes and speeds up lipid oxidation.

Since lipids are included in the cell membrane, radiation induced damage of the last affects the functions of such structural components of the cell as the chloroplasts, nuclei, mitochondria etc.

It is considered that lipids are easily oxidizing material and when they are splitting off a great amount of energy is released. It is the nature of a cell to have some anti-oxidizing properties under the normal conditions. There is an interrelation between the lipids content and the speed of oxidizing reactions in lipids. If oxidizing reactions in lipids proceed to fast, fatty acids become enriched with more resistant to oxidation fractions, which in turn slow down the speed of reaction, and visa versa. If the speed of oxidizing reactions in lipids decreases to some level, the reactions become enriched with more easily oxidizing fractions and lipid splitting off increases. If a cell is irradiated, the anti-oxidizing ability of a cell may drop drastically.

The effects of radiation on carbohydrates. Carbohydrates belong to the natural organic compound group, which has a general formula $C_n(H_2O)$ or $C_nH_{2n}O_n$. There are simple carbohydrates, i.e., monosaccharides or sugars (glucose, fructose) and complex, i.e., polysaccharides that are low molecular disaccharides (saccharose, lactose) and high molecular carbohydrates (starch and cellulose). Being involved in the metabolic processes the carbohydrates content in a plant cell is about 80% and in animal cell is up to 2%. It is obvious that such compounds as nucleic acids, proteins and lipids form a high molecular mass complex incorporated as constituents in submolecular structures that are highly susceptible to physiochemical factors, including radiation.

The transformation of carbohydrates performed in dilute aqueous solutions under the influence of radiation constitutes a complex multistage process that depends not only on the conditions of irradiation but also on the structure of the particular sugar. The damage to carbohydrates results mainly from the action of the OH radical. The hydrated electron performs a comparatively minor role during the initial stages of damaging process.

The main radiation induced transformations in carbohydrates are: the break down of the molecule; newly formed radicals' reactions; ion-molecular reactions as well as interactions of released exited particles during recombination processes.

Monosaccharides radiolysis leads to the oxidation of hydroxylic group and to the appearance of the carbonyl groups $>C=O$ that are typical for aldehydes and ketones. First of all the initial spirits groups are oxidized, however, the oxidation of the secondary spirits group is also possible, resulting in the break down of C–C bounds and in the release of low molecular mass fragments of carbohydrates molecule. Oxidation of the aldehydes groups cause formation of organic acids.

When polysaccharides are irradiated some units of monosaccharides molecule may be transformed. Radiolysis of carbohydrate molecule under anaerobic conditions leads to the formation of polymers and dimers. The yield of radiation induced damage products of carbohydrates is low.

4.4. Radiation-induced damages of membranes

Such radiation effects as mitotic delay, the delay in DNA synthesis and the overall production in the amount of DNA synthesis are considered to be the result of DNA base damage and strand breakage. However, the recent studies show that the nuclear membrane is more likely subcellular target for division delay than the DNA. The G_2 blockage seems to be due to the interference with the chromatin condensation process that is essential for the formation of mitotic chromosomes and which occurs while the DNA is in close association with the nuclear envelope.

Membranes interconnect a cell, since there are suggestions that the outer cell membrane, the endoplasmatic reticulum, the mitochondrial, lysosomal and nuclear membranes as well as Golgi body are all in the intimate connection.

The cytoplasmic membrane is a fluid structure consisting of two layers of phospholipid molecules oriented so that the lipids face one another in the interior of the membrane. The interior of the membrane is hydrophobic while the inner and the outer surfaces are hydrophilic. The cell membrane is the site of many essential functions. The most important function of it is the transfer of nutrients and the maintaining potassium and sodium levels inside the cell.

Radiation may affect the outer membranes in several ways. The first and the foremost irradiation change is the permeability of the cell membrane that in turn affects metabolic activities of the cell and increases the concentration of toxins. The increased permeability of the cell membrane results in the release of various enzymes that are fixed in lisosomes mitochondria and other subcellular structures. Radiation damage of membrane causes the disorder of ion homeostasis, which in turn leads to the changes of cell membrane potential, increased by the flow of potassium ions from the cell and by the flow of sodium into the cell. It should be mentioned that potassium concentration in the cell is higher in comparison with the concentration of sodium under the normal conditions. Radiation causes a reduced amplitude and decreased conductivity of the nerve impulse in adult animals that is the result of the different diffusion of sodium and potassium ions across the membrane of the axon. Radiation-induced changes in the electrical conductivity of nerves indicate an increase in passive ion permeability of the nerve axon. However, such effects may be due to the primary radiation damage or indirectly to the release of toxins from other damaged tissues.

The properties of the cell membrane in the epithelial cells of the mammalian intestine after irradiation are thought to be due to the loss of the cell membrane ability to regulate electrolytes. Similar changes occur in the red blood and muscle cells.

4.5. Structural-metabolic hypothesis of ionizing radiation effects on living organisms

Radiotoxins hypothesis. The studies of the metabolic processes revealed toxins that are accumulated in the irradiated organisms. Some of them were named as radiotoxins. According to the hypothesis (B. Tarusov, Yu. Kudrjashov, 1962) such compounds belong to radiotoxin lipids. The hypothesis is based on the idea that lipids probably are the most suitable substrate for the development of the oxidation reactions chain, producing free radicals on the initial stages of radiation-induced damage. Since cell membranes comprise lipids, damage of the last will cause disorder in functioning of the cell and even death. Lipid radiotoxins that cease cell division, cause chromosomes damage, synthesis depression of many compounds and metabolic activity, were found in irradiated organisms during the first hours after the irradiation.

A. Kuzin et al. (1964) consider another group of toxic substances, formed in irradiated organisms. They are phenols and such their products as ortoquinones and semiquinones. The following sequence of events is proposed to explain the possible mechanism of formation and action of radiotoxins. First, free radicals of biosubstrates are formed at the moment of irradiation. This initiates oxidation reactions of phenols inside of the cell, first of all, tyrosine. Newly formed oxidation products activate tyrosinase and could possibly activate other enzymes. This in turn promotes formation of appreciable amount of ortoquinones. The quinonelike radiotoxins are absorbed by cell nucleus resulting in depression of DNA synthesis, cell division, cell growth and the development, appearance of mutations or even death of a cell or an organism depending on the dose. It was proved that phenol radiotoxins, elicited from plants and animals, have identical nature and toxic action. It was shown that compounds, being extracted from the irradiated plants and incorporated in non-irradiated organisms, induce radiobiological effects.

In 1980 A. Kuzin distinguished initial and secondary radiotoxins. Initial radiotoxins appear in cells of an irradiated organism in the process of irradiation or immediately after it. Such radiotoxins are able to cause various radiobiological effects. They are mainly lipidic and phenol-quinone by nature. Secondary radiotoxins are the various biologically active protein substances that may be accumulated and cause deep changes in metabolic processes. Such substances do not cause radiation damage but complete it.

A great number of compounds that are accumulated in irradiated organisms are considered as radiotoxins. The term “radiotoxins” does not mean any specific compound or complex formed in an irradiated organism, but ordinary metabolites that are accumulated when an organism is irradiated.

Structural-metabolic hypothesis of ionising radiation effects on living organisms. Structural-metabolic hypothesis is worked out and advanced by A. Kuzin on the base of radiotoxins hypothesis. The essence of the structural-metabolic hypothesis is that radiation-induced damage of an organism is developing due to the initial radiation-induced chemical reactions as well as due to the formation of toxic substances. It leads to the damage of biologically important macromolecules and first of all molecule of DNA. Thus, the major radiobiological effects are not only due to the occasional hit of particles or photons in unique structures or due to the interaction of radiolysis products with biologically important macromolecules, but also due to the radiation-induced biochemical processes that increase the concentration of biologically active substances and the interaction of the last with DNA of cell nuclei. The hypothesis proves that the energy absorption during the irradiation and the interaction of the initial oxidation products with cell substances is only the starting point for the development of the processes, which finally lead to metabolism disturbance and unspecific accumulation of toxic products, causing damage of unique subsellular structures. The probability of such events and the amount of the released products increases with a dose.

Thus, structural-metabolic hypothesis does not principally differ from that of radiotoxins hypothesis and is not an alternative to the classic ideas based on the “target theory”. The structural-metabolic hypothesis promotes the understanding of the radiation damage mechanism of an organism, and emphasizes the role of toxic factor in changes of the structural and metabolic organization due to radiation.

Finally it must be emphasised that all attempts to give a theoretical explanation of the mechanism of the radiation-induced biological effects are generally hypothetical and so far cannot give an answer about the nature of radiobiological paradox, i.e. the discrepancy of the amount of absorbed energy and reactions of an irradiated organism. They do not contradict each other, but explain the radiobiological effects on the different levels of the organisation of living matter from different points of view. All these approaches supplement each other to some extent. The main task of radiobiology is to explain the mechanism of various biological effects, different behavior of radiation damage processes in irradiated organism, which have different radiosensitivity.

4.6. Comparative radiosensitivity of various types of cells and cellular structures

It has been mentioned already in part 4.3 that mitosis and cell division are among the most “radiation-sensitive” cell processes. On the contrary, cells that are not divided stay largely unaffected by doses of radiation. We have also discussed that the DNA molecule of is considered to be a “target”. Thus, radiation-induced damage of it may cause the death of an organism.

This paragraph deals with radiosensitivity that is a very important notion in radiobiology. Understanding the “radiosensitivity” is the key factor for understanding radiobiological effects. There are two terms in radiobiology that are used to express the reaction of an organism to irradiation: radiosensitivity and radioresistance. Both notions are related to each other, because they determine the same phenomenon. Organisms having high radiosensitivity will show low radioresistance and visa versa. Thus, the “radiosensitivity” is the ability of an organism to react at low radiation doses and to catch the negligible levels of radiation by means of non-lethal radiobiological effects. The “radioresistance” is the ability of an organism to resist high levels of irradiation equated to semi-lethal and even lethal doses.

The lower dose that causes non-lethal radiobiological effects is the higher radiosensitivity of the irradiated organism and visa versa. The higher dose that causes lethal effects is the higher radioresistance of an irradiated organism. Thus, there are two dose levels: the low dose level is radiosensitivity and high level is radioresistance. The interval between them is a range of radiobiological or biologically effective doses.

Viruses survival curves. Viruses, bacteria, plant and animal cells can be killed by ionizing radiation. Regarding mammalian cells, radiation of a very high dose (tens of gray) can cause the rapid cessation of cellular metabolism and cellular disintegration. This type of death is often termed “non-mitotic death” or “interphase death”. Radiation of much lower doses can also “kill” cells by inhibiting their ability to divide. This failure to proliferate is termed “reproductive death”. Cells having a limited number of post radiation divisions that produce sterile progeny are defined as killed, though they may appear normal morphologically, physiologically and biochemically.

To assess the degree of radiation effects so-called effective dose is used. It may cause some biological effects, e.g. to induce stimulation due to morphological changes. Such doses may be semilethal (LD_{50}) or lethal (LD_{100}) causing death of 50 or 100% of irradiated organisms respectively.

Semilethal and lethal doses are determined by using dose-effect (or survival) curves that are the graphical presentation of the fraction of cells surviving against the received dose of radiation.

Fig. 24 shows the percentage of viruses killed by different doses of radiation. When the dose increases, the proportion of killed viruses approach, but never reaches 100%.

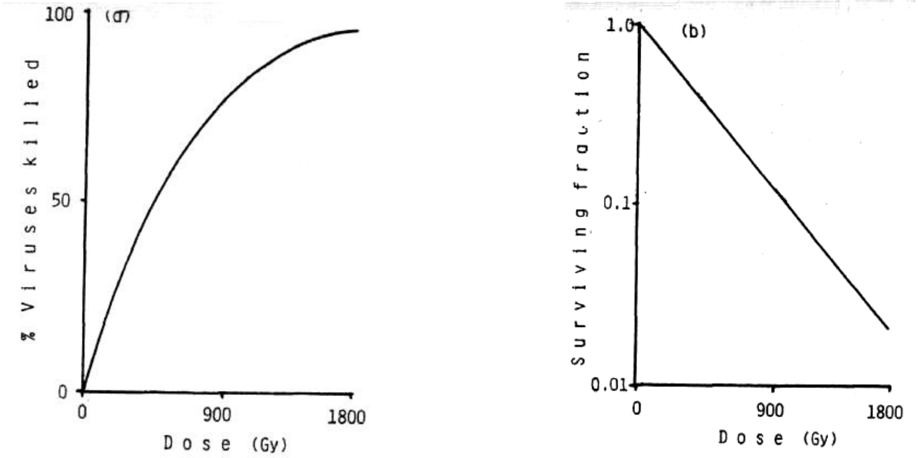


Fig. 24. (a) A linear plot of the percentage of viruses surviving against the radiation dose, Gy; (b) A semi-logarithmic plot of the percentage of viruses surviving against the radiation dose, Gy.

The curve in this figure can be transformed into a straight line by plotting the surviving percentage on the logarithmic scale. This semi-logarithmic plot shows that the relation between survival and a dose for viruses is exponential, i.e. any unit of a dose increase produces a corresponding decrease in survival. This type of relationship is considered to be typical in the case of the radiation inactivation of certain biological molecules such as enzymes, and of the survival of viruses, some bacteria and in some cases mammalian cells. However, survival curve for mammalian cells is a little more complex.

The direct hits at radiation sensitive targets could explain radiation inactivation of molecules and cells. This "target theory" tries to combine the physical facts about the absorption of radiation with the observed facts of the experimental shape of survival curves. The exponential shape of survival curve suggests the occurrence of a random process of killing. As it was mentioned above the radiation energy is dissipated in living matter by the random processes of ionization and excitation and it is considered to be the cause of biological damage. Besides, this target theory supposes that there are certain critical molecules inside the cell, critical sites or “targets” that must be inactivated by radiation and the cell is to be killed. If the target does not receive any hit, the cell will survive. Exponential survival curves in figure Fig. 25 can be derived in the theory if a single hit reaches a single target. Being strong enough, it may cause cell death. Such single-hit kinetics can be applied to molecules, viruses, and bacteria and, under some conditions, mammalian cells.

The exponential survival curve in Fig. 25 may be described by the equation

$$N = N_0e^{-D/D0}$$

where N_0 is the initial number of viruses; N is the number of viruses that remain unaffected after a dose of irradiation of D; D_0 is constant and gives an indication of the slope line. If one puts $D_0 = D$ in the equation this result in the term of e^{-1} that equals 0.37 so that

$$N = 0.37N_0$$

It means that D_0 is the dose required to reduce the population of viruses to 37 % of its initial value. According to the binominal distribution law, D_0 is the dose that requires putting one of an inactivating hit in each of the viruses. Some viruses will receive more than one hit and some will receive no hits. But approximately 63 % of the viruses will be inactivated and the rest (37 %) will survive. The D_0 for viruses varies up to the value of 500 Gy.

Bacteria survival curves**.** Different bacteria strains have different types of survival curves (Fig. 25).

A simple exponential curve (Fig. 25, a) is similar to that in Fig. 25, b for viruses. However, the D_0 that is the sensitivity parameter depends on the bacterial strain, and varies from 10 to 250 Gy. Thus, bacteria are more sensitive to radiation than viruses. The survival curve on Fig. 25. b is biophasic, indicating heterogeneity of irradiated bacterial population, e.g., due to the mixture of two different bacterial strains and different degree of the radiosensitivity, or the mixture of rapidly dividing cells (more radiosensitive) and stationary phase cells (less radiosensitive). The survival curve on Fig. 25, c has a “shoulder” at low doses and is typical for mammalian cells.

Mammalian cell survival curves. Radiation survival curve *in vitro* for mammalian cells was built up in 1956 year. The method of pipette is to get definite number of single cells, suspended in a liquid nutritive medium, onto a Petri dish. After about ten days of incubation small isolated colonies or clones of cells are seen as a result of individual cell division. If single cells are irradiated after being plated onto the Petri dishes, some of them will be killed resulting in the developing of fewer macroscopic colonies. A generalized survival curve for radiation-induced loss of reproductive capacity (cell death) in mammalian cells has a “shoulder” at low doses and only becomes exponential at higher doses (Fig. 26).

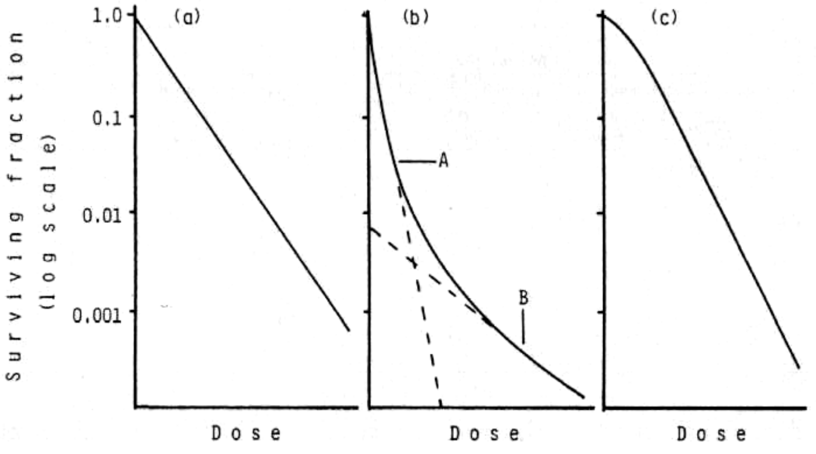


Fig. 25. Three types of bacterial cell survival curves, (a) Single-hit exponential survival curve; (6) Biphasic survival curve; (c) Multi-event survival curve.

The D_0 determines the slope of the linear part of the curve and indicates the dose that will reduce cell survival by a factor of 0.37. The experimental number (N) is derived by the extrapolating of the straight-line portion of the curve onto the survival axis and N is to be 3 (Fig. 24 b). The majority of mammalian cells curves, following the low LET radiation, have D_0 values from 1 to 2 Gy and the extrapolation number is about 1 to 5. However, the size of the shoulder and the slope of the curve can vary significantly depending on growth conditions. There is one more parameter D_q that is the quasi-threshold dose in Gray, where the exponential part of the curve crosses the 100 % survival of cells (Fig. 26). It is the measure of the size of the shoulder and its importance is related to the repair of radiation damage. It must be stressed that mammalian cell survival curves are more complex and generally fit so-called multi-event models.

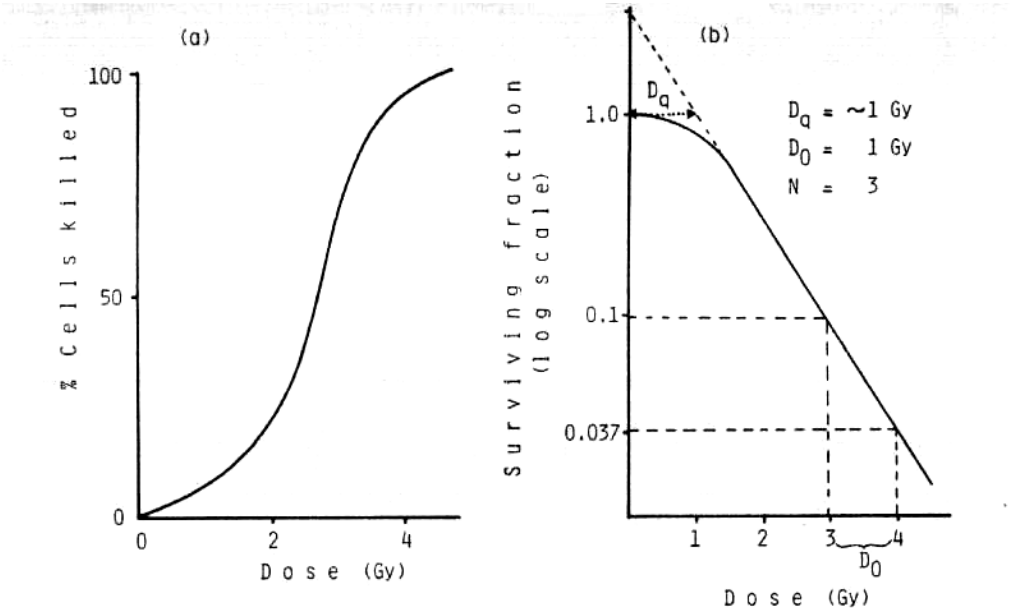


Fig. 26. The generalized survival curve for radiation-induced loss of reproductive capacity (”cell death“) in mammalian cells. (a) A linear plot of the percentage of cells killed against dose; (b) A semi-logarithmic plot of curve (a) with the fraction of surviving cells against dose.

Comparative radiosensitivity of cellular structures. The numbers of structural and functional factors determines the radiosensitivity of a cell. The structural factors are nuclei chromosome volume, a number of chromosomes and ploidy. The functional factors are the functional state of some cell structures, physiological state of genome, organogenesis stage, the content of different natural compounds, e.g., antioxidants, the ability to repair most of breaks, biological rhythms.

As we mentioned above DNA should be regarded as the most likely target for cell killing. It is likely that the inactivation of viruses and bacteriophages (bacterial viruses) is a result of damage of their DNA, i.e. double-strand breaks, unrepaired single-strand breaks, and some types of base damage. They are most likely to have lethal effect. However, in bacteria cell membranes may be the primary site of radiation damage. In more complex cells the identity of the target is a kind of an argument. However, in many cases DNA is considered to be the critical target for cell lethality, because the nuclear material is far more radiosensitive in relation to cell killing. Experimental data of ^{3}H and ^{125}I-labeled compounds incorporated into the DNA molecules showed that the cell killing effect implicates chromosomal material because most of electron energy of these isotopes is dissipated in the chromosomes. Data for fungi, insects, higher plants and animals indicate the connection between cell killing and ploidy that implicates DNA because ploidy is merely the word used to indicate the relative chromosome content of cells. Radiation-induced cell killing attributes to the damage of the genetic apparatus, especially of chromosome aberrations. The chromosome damage is the final stage of some forms of DNA damage. Cell death at the first mitosis after radiation and the presence of chromosome aberrations are very closely related. The correlation also exists between defective or altered DNA repair mechanisms and the enhanced sensitivity of cells to radiation.

The intimate association between DNA and nuclear membranes also highlights that nuclear membranes are the next critical targets for cell damage.

Control points to chapter 4:

1. The chain of events leading to radiation injury.
2. Direct action of ionizing radiation on molecules.
3. Indirect action of ionizing radiation on molecules.
4. Radiation-induced transformations of molecules in water solution.
5. Primary and secondary reaction products.
6. The role of the oxygen in radiation injury.
7. The effect of radiation on nucleic acids.
8. Types of DNA damage.
9. The effect of radiation on amino acids.
10. The effect of radiation on proteins.
11. The effect of radiation on lipids.
12. Radiation-induced damages of membranes.
13. Radiotoxins hypothesis.
14. Comparative radiosensitivity of cellular structures.

5. BIOLOGICAL EFFECTS OF IONIZING IRRADIATION

5.1. Somatic and genetic radiobiological effects. 5.1.1. Radiation stimulation. 5.1.2. Radiation-induced morphological changes. 5.1.3. Radiation sickness. 5.1.4. Ageing speeding up and lifespan shortening. 5.1.5. Organism death. 5.1.6. Genetic effects. 5.2. Deterministic (early) and stochastic (late) radiobiological effects. 5.3. Radiomimetic induced biological effects.

We have already mentioned that radiation-induced damage is a multi-stage process. The starting point of this process is direct or indirect action of ionizing radiation on molecules that we discussed in the previous chapter. This stage continues for very short time 10^{-24}–10^{-14} second. Physico-chemical and chemical stages that continue from 10^{-12} second to hours cause the appearance of free radicals and exited molecules. Biomolecular damage of proteins, nucleic acids, etc. takes time from milliseconds to some hours. We have also discussed that damages of some molecules are more important than others and the DNA molecule is regarded as the most likely target for cell killing. It is known that damage of some tens or hundreds of DNA molecules may cause severe biological effects or even cell killing. Processes of radiation-induced damage that take place inside the cell, generally, are the same for plant and animal organisms. Radiation-induced damages on the cell level are also typical for all eukaryotic cells, but due to the difference of plant and animal cell organisation such processes may be specific. However, the most visible differences in biological effects of ionizing irradiation of plants and animals are observed on the organism level. Until now radiobiologists have got a great number of data and evidences in the variety of living organism reactions as a response to irradiation. They are the anomalies of growth and the development of the organisms, morphological changes of some organs and organisms as whole, different breaks in physiological and biochemical reactions, different hereditary changes and, finally, death of an organism. All these processes are called radiobiological effects or biological effects of ionizing irradiation.

5.1. Somatic and genetic radiobiological effects

Under radiobiological effect we should understand the radiation-induced reaction of a living organism that can be characterized by changes of some of the signs and properties. There are two classes of effects somatic and genetic radiobiological ones. Somatic radiobiological effects are radiation-induced changes that can be watched during the ontogenesis. There are five major types of somatic radiobiological effects: radiation stimulation, morphological changes, radiation sickness, ageing speeding up and lifespan shortening and, finally, the organism death. Genetic effects are those that can be found out in future generations, i.e. they are handed down hereditary. Genetic or mutation radiobiological effects belong to the separate class.

5.1.1. Radiation stimulation

Radiation stimulation is a process of a radiation-induced speeding up of the growth and the development of an organism under doses that are many times lower normal ones and will cause inhibition of such processes.

Radiation-induced stimulation of plants. The first experiments on the speeding up of seeds germination under irradiation that drew attention of many scientists, working with ionizing radiation, were made in the end of the 19th century. A number of works appeared in this field during the following years, but many of them were based on an empirical base without definite knowledge and understanding of many factors that determine radiation stimulation (Fig. 27).

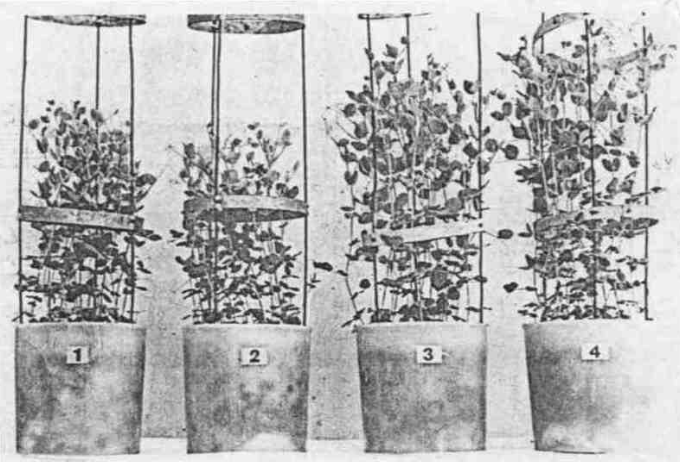


Fig. 27. Acceleration of growth in pea following γ-irradiation of the seeds in stimulating dose: 1 and 2 controls with no seed irradiation, 3 and 4 treated by dose at 3 Gy.

Thus, many studies on radiation stimulation of irradiated plants showed opposite results. Studies that were carried out during last decades using new methodological approaches, detailed records of dose applied, types of irradiation, individual radiosensitivity of irradiated objects, etc. proved the existence of radiation stimulation of plants. It must be stressed that applied doses vary significantly depending on the plant, species and even lot of seeds.

As a rule, doses that are applied for seedlings and vegetative plants are many times or even one order of magnitude lower in comparison with doses applied to seeds. Stimulating doses for some plant are shown in Table 15.

Table 15. Stimulating doses of γ-radiation for seeds and seedlings (vegetative plants) of some agricultural plants, Gy

Species	Seeds	Seedlings	Species	Seeds	Seedlings
Pine-tree	0.7–1	–	Wheat	5–8	1–1.5
Beans	1–1.5	0.1–0.2	Oats	8	1–1.5
Pea	3–5	0.35–0.5	Rye	8–10	1.5–2
Haricot	5–6	0.6–0.8	Tomatoes	5–10	0.5–1.5
Cucumber	3–5	1–2	Flax	7.5–10	2–3
Maize	5–10	0.5–2	Radish	10–15	3–4

Stimulating effect of radiation is usually registered only during first 4–6 days. Plant growth comprises cell division and its stretch. Therefore, when stimulating doses are applied, these processes are speeded up resulting in an increase of cells division in apex zone (Fig. 28). Irradiated seeds germinate faster, but 2–3 days later the difference between irradiated seeds and control seeds disappear. However, plants germinated from irradiated seeds show faster growth in comparison with control plants. Later, control plants catch up with experimental plants ant the difference in growth is at the same level. At the stage of buds formation the effect of radiation stimulation may be seen in an increasing number of buds of irradiated plants. Some days later the effect makes level again. Finally, due to a greater amount of buds and longer ripening period the yield is 10–20% higher in plants germinated from irradiated seeds in comparison with control ones.

The effect of radiation stimulation was also observed when plants were irradiated during a vegetation period. Reported stimulation doses vary from 0.00019–0.025 to 2.3–2.85 Gy per twenty-four hours. The lowest value is a magnitude of two orders higher than natural radiation background (10 μR h^{-1} or 0.0000024 Gy per twenty four hours). Some radiobiologists agreed that high yield of winter cereals in northern part of Ukraine in 1986 was a result of such stimulation.

The mechanism of radiation stimulation is not quite clear. Studies of the molecular-biochemical level showed that irradiation cause the activation of synthesis of nucleic acids, proteins and hormones, the activation of some enzyme systems, the increase of nutrient uptake, phosphorylation, photosynthesis and so on. However, it is the consequence. What is the primacy?

Stimulation effect is not a unique affinity of radiation. By applying some physical or chemical factors it is possible to speed up plants growth. Plants comprise very sensitive phytohormonal complex of substances-activators (inhibitors) that regulate (activate or suppress) growth processes. In this case it is radiation that primarily affects this complex, causing activation or suppression of plant growth. It was found that under stimulating by irradiation doses in plants the content of such plant hormones (phytohormones) as auxins, gibberellins and cytokinins increases. It activates metabolic processes and stimulates plants growth and their development. It was suggested (A. Kuzin, 1977) that an increasing activity of phytohormonal system is a result of radiation-induced unspecific suppression and activation of some genes. In radiobiology radiation-induced stimulation is denoted by a special term ”radiation hormesis“. It means that hormonal state of the metabolic processes under low doses plays the main role.

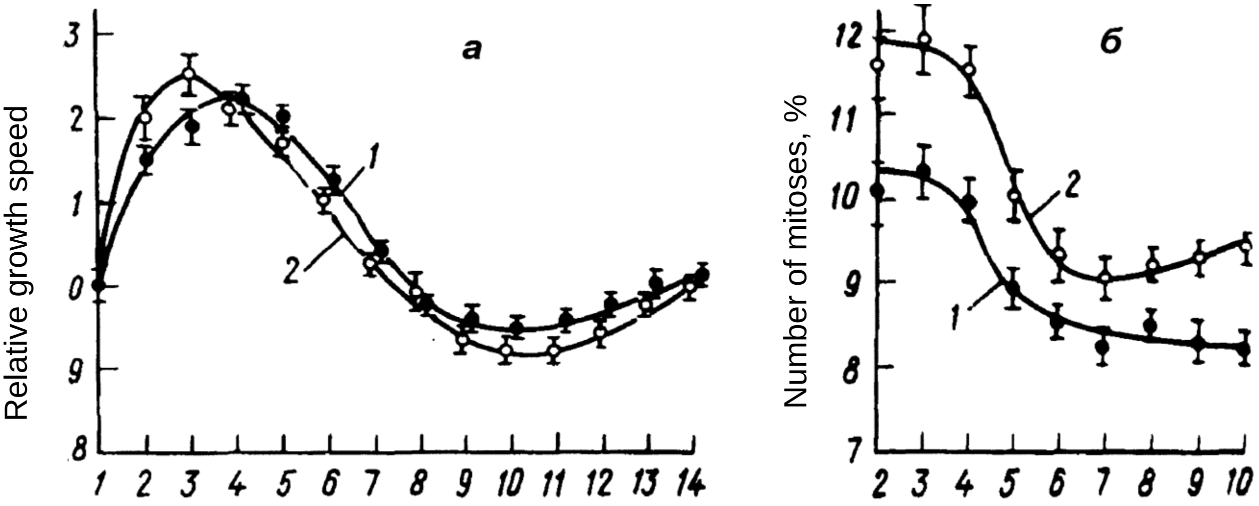


Fig. 28. The effect of γ-irradiation of pea (1) and maize seedlings (2) under stimulating doses (0.35 and 0.5 Gy, respectively) on the comparative rate of growth of roots (a) and mitotic activity of cells in meristem (b).

Radiation-induced stimulation of animals. The same approaches and criteria such as growth, development and productivity are used to study radiation-induced stimulation of animals. There are evidences that the application of low radiation doses (0.01–0.05 Gy) before incubation period increases chicken hatch with the following decrease of dying. Irradiated chickens begin laying eggs 10–12 days earlier in comparison with the control group. Irradiation of young chickens (0.25 Gy) increases their survival, speeds up growth, puberty and the beginning of laying eggs. Irradiation of a hen (0.05 Gy) increases laying eggs productivity.

The data of radiation-induced stimulation of mammalians are scarce, but there are some available data of fertility increasing, growth processes, body weight as well as stimulation of reproductive functions of rats. Experimental data also show radiation-induced stimulation of fresh water fish embryos. Doses of radiation-induced stimulation for some animals are shown in Table 16.

The effect of radiation on lifespan of animals is not well studied. However, radiation-induced stimulation of animals at low doses is likely to cause speeding up of life cycle processes and consequently lifespan shortening. At the same time data about lifespan shortening of animals are non-available. The reverse is true, because there are data showing lifespan prolongation of irradiated animals. Y. Lorenz (1980) reported that the lifespan prolongation of irradiated mice is from 703 to 761 days and of guinea-pigs is from 1400 to 1457 days at a constant obtained dose of 0.0011 Gy during the whole life time. L. Karlson (1957) revealed that the lifespan prolongation of irradiated rats is from 445 to 587 days at a constant obtained dose of 0.008 Gy during the whole lifetime. It shows that the radiation-induced stimulation mechanism in plants and animals at the molecular-biochemical level is the same. The role of specific animal's hormones, most likely steroid ones that induce some metabolic processes of an irradiated organism might be important.

Table 16. Stimulating doses of γ- or X-radiation for animals, Gy

Organism	Dose, Gy	Organism	Dose, Gy
Chicken eggs	0.01–0.05	Sucking pigs	0.1–0.25
Chickens	0.05–1	Laboratory rats	0.1–0.5
Hens	0.05	Laboratory mice	0.2–0.4
Fish caviar	0.1–0.05	Insects	10–45
Fish sperm	0.25–0.5	Protozoa	5–2000
Fish larva	0.1–0.5	Human cells *in vivo*	0.05
Chicken eggs	0.01–0.05	Sucking pigs	0.1–0.25

Radiation-induced stimulation of microorganisms. Data about radiation-induced stimulation of growth and activity of intestinal bacillus, *Aspergillus* and *Azotobacter* at chronic exposure dose of 0.03–0.6 Gy h^{-1} are available. Stimulation effect was also observed at acute exposure dose of tens and even hundreds of Gy.

Taking into account unsatisfactory data of radiation-induced stimulation experiments, lack of the scientific explanations of the mechanism of this phenomenon, some radiobiologists argue that radiation-induced stimulation is an artefact. Some researches argue that it is not a direct stimulation effect but a result of radiation-induced damage with the following repair, which in fact bears compensatory character. It is also worth mentioning that the attention to this research increases and decreases with time, but nowadays still there is a lack of knowledge of the mechanisms of the ”radiation hormesis“ that could explain this phenomenon.

5.1.2. Radiation-induced morphological changes

Morphological changes in this sense are radiation-induced changes of appearance of an organism, its organs, anatomic structure and other features that make difference between an organism and parent form.

However, it must be emphasized that changes of the appearance caused by the growth and the development of an organism do not concern radiation-induced changes. These changes concern, first of all, declinations of such natural properties of the organism that are considered to be peculiar to the definite organism, species, kind, race etc. Such properties are not considered to be hereditary. There are some kinds of radiation-induced declinations in comparison with the normal state, i.e. distortions, chimeras[1], terates[2], etc.

Radiation-induced morphological changes in plants. The great variety of radiation-induced declinations (changes) is observed in plants (Table 17). Most of those changes are considered to be the result of so called chimeras, which in turn are due to the radiation-induced changes in space oriented distribution of plant cells of specific organ of plant e.g., the appearance of cells with low division speed, chromosomes aberrations, falling out of tissue rows due to the

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[1] Chimaira (greek) – mythological monster with lion’s head, goat body and dragon tail; in biology – anomaly of development plants and animals.

[2] Terates (greek) – monster, freak.

death of some initials, induced division of some cells and tissues that were in the rest state, and other disorders. These processes cause changes of organs shape, intercepts, twists, wrinkledness, dichotomy, fasciations etc.

Table 17. Types of radiation-induced morphological changes of plant's organs

Organ	Morphological changes
Leaf	Increase or decrease of size and quantity
	Shape change
	Twists
	Wrinkledness
	Nervation break
	Asymmetry
	Thickening
	Leaf plates inosculation
	Fasciations
	Swellings
	Appearance of necrosis spots
	Loss of leaf plate
Stem	Speed up or inhibition of growth
	Curvature
	Phyllotaxis failure (order of leaf placing)
	Color change
	Taking down of apical dominance
	Dichotomy
	Fasciations
	Change of intercepts
	Swellings
	Appearance of aerial roots
Root	Speed up or inhibition of growth
	Splitting of main root
	Death of main root
	Trimming of meristem zone
	Absence of lateral roots
	Formation of secondary main root
	Swellings
	Twists
	Heliotropism break
Flowers	Speed up or inhibition of flowering
	Color change
	Increase or decrease of quantity
	Shape change

	Color change
	Defoliation of flowers and floscules
	Swellings
	Sterility
Fruits	Speed up or delay of ripening
	Color change
	Increase or decrease of size
	Shape change
	Trimming
	Premature defoliation
Seeds	Increase or decrease of size and quantity
	Shape and color change
	Wrinkledness
	Sterility

Such abnormalities as the increase of size and the quantity of organs are thought to be due to the hyperfunction of unaffected or less affected by radiation cells and tissues as well as due to the compensation mechanism, which starts when some organs loss their functions. Thus, when top buds, cells of which are divided actively, die taking down the apical domination, it causes wakening of axial buds that are in the rest state and are more radioresistant at normal conditions. Such buds produce extra shoots, leaves and flowers. Radiation-induced increase of fruit size may be due to the sterility of some flowers and floscules.

Radiation-induced dying of main root meristem in plants with pivotal root system causes more active development of lateral roots. It provokes the growth of some aboveground organs. Such swellings like excrescent may also appear on leaves, stems, roots, flowers and other organs as a result of irradiation (Fig. 29). The reason of this phenomenon is not well studied but it is assumed that it may be due to the appearance of mutated cells that have high ability to undergo division and to initiate excrescent in plants. There is also hypothesis that swelling like excrescent is the result of the damage of highly radiosensitive phytohormonal system. It causes the misbalance of phytohormonal activators and the inhibition of the growth.

Radiation-induced morphological changes in plants were observed in Chernobyl zone in 1986 (Fig. 30). In 1987 and the following years the number of such abnormalities increased and were observed mainly on coniferous trees, that change needles once a few years and on perennial organs (Fig. 32).

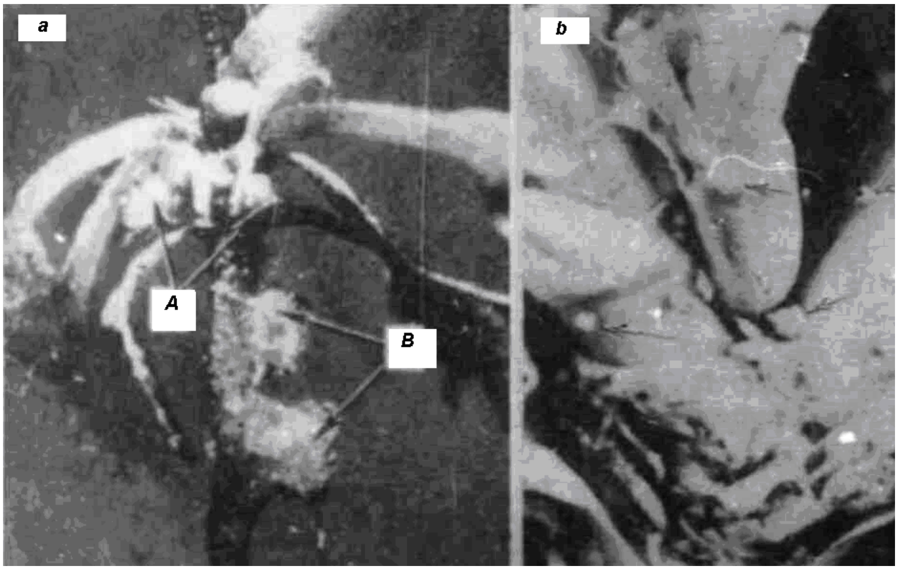

Fig. 29. Tumors in irradiated plants: a – on the epicotil (A) and on the hypocotil (B) of mouse-ear cress (*Arabidopsis thaliana [*L.*]* Heynh.) after X-irradiation (Y. Hirono et al., 1968); b – on the stem of lettuce (*Lactuca sativa* L.) after γ-irradiation (D. Bankes and A. Sparrow, 1969).

Various forms of ears – real freaks could be found in the self-seeding of wheat, collected in the fall of 1986 (Fig. 31).

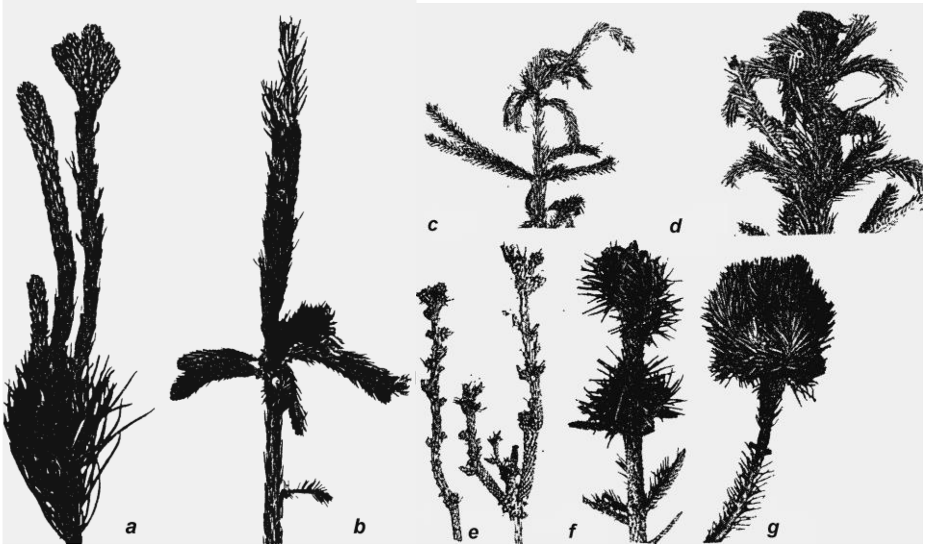

Fig. 30. Anomolies in the shoots of pine (*Pinus silvestris* L.; a, b) and spruce tree (*Picea exceisa* [Lam.] Link; c–g) that appeared in the forest near the Chernobyl nuclear power plant after the accident in 1986–1987 (G. Kozubov, A. Taskajev, 1990; D. Grodzinsky et al., 1971).

Fig. 31. Morphological changes of Mironovskaya 808 wheat in the exclusion zone of the Chernobyl NPP, found among self-seeding in the summer of 1987 (M. Kuzmenko, 2013).

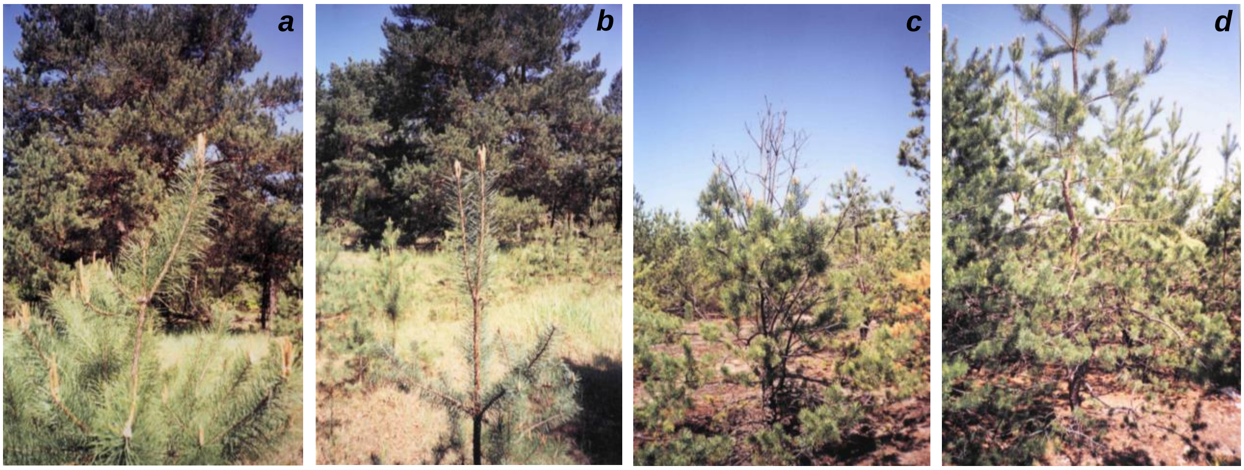

Fig. 32. Morphological changes a pine-tree observed in 10-kilimiters zone around Chernobyl NPP (2005): a – taking down of apical dominance, b – dichotomy, c – loss of needles, d – curvature of a stem (I. Gudkov, 2006).

Radiation-induced morphological changes of animals. Radiation-induced morphological changes of animals are not observed, however, various changes of some organs and tissues of animal developing after the irradiation are described rather well. Irradiation of animals during embryogenesis or in the early post embryogenesis period may cause a break of bone growth, disproportion in the development of some organs, and other changes resulting in appearing of various distortions (Fig. 33). Irradiation of adult animals causes the appearance of various ulcers followed by paunch’s appearance, skin and scalp pigmentation and depigmentation, the cease of their growth and death. Radiation may induce the cease of horny tissue growth and its exfoliation, appearing of cataracts, change of some organs, various degrees of dystrophya etc.

Radiation-induced morphological changes of animals appear in tissues. They have highly radiosensitive cells that divide actively. Uneven damage of cells in such tissues causes the growth disproportion, coming out of some formative cell sections from the development processes, the appearance of tissue mutations. Finally it causes the growth and development anomalies.

5.1.3. Radiation sickness

Radiation sickness is a complex of characteristics that show the damaging action of ionizing radiation on the organism. The diversity of such unspecific radiation-induced reactions is caused by a number of factors: the dose, mode and the conditions of irradiation, radiosensitivity etc.

Radiation sickness of plants. It is difficult to describe radiation sickness of plants. Many morphological changes discussed in the previous section may be considered to be a sign of radiation sickness. However, in this section we will concentrate mainly on such radiation-induced damages as cell division inhibition, cease of growth and development, break of various physiological and biochemical reactions.

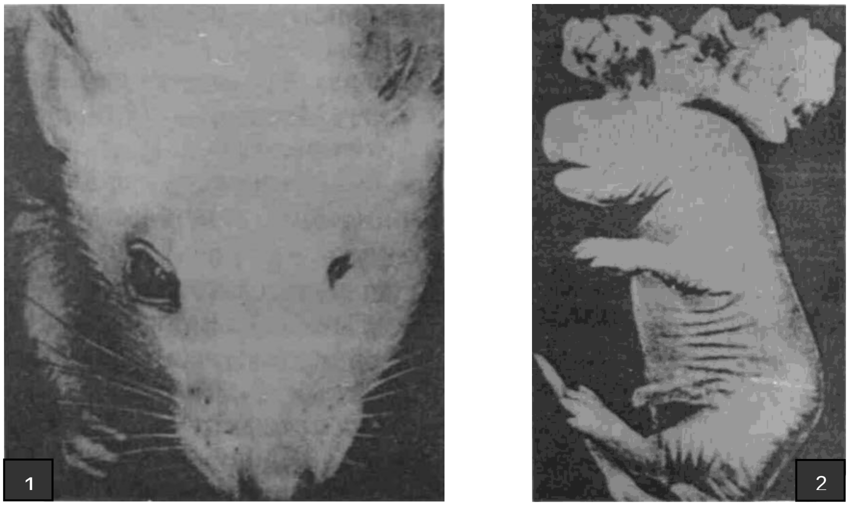

Fig. 33. Morphological changes of animals caused by γ-irradiation: 1 – microphtalmy of the left eye in a rat (right eye is normal) and 2 – the brain rupture in a mouse. In both cases, the irradiated animals during the ninth day of embryogenesis (P. Schwartz, 1963; D. Raf, 1990).

In this respect the inhibition of cell division of meristem tissue as well as some fast developing biochemical distortions is thought to be the first radiation-induced effects. Such effects may be registered as the delay of the next stage of mitosis cycle followed by the distortions of cytogenesis. The delay of mitosis cycle depends on the species radiosensitivity and the dose. Thus, the delay of the next phase of mitosis cycle (e.g. in horse beans and peas) may be observed after few hours after irradiation with the dose of 0.5–2 Gy.

Mitosis cycle delay results in the inhibition of some organs or the whole plant growth. These effects can be observed. However, the cell division inhibition and the growth cease is a secondary reaction of an organism followed by irradiation. The plant growth processes are coordinated and dependent on many factors that might be affected by radiation. The last makes difficult to reveal the real cause of the plant growth inhibition. That is why there are a number of hypotheses that explain the cause of the plant growth inhibition. Some researches consider the radiation-induced inhibition of plants to be due to the inhibition of growth activators. Others consider this process to be the accumulation of growth inhibitors and some other secondary metabolites. Another point of view is that radiation-induced growth inhibition is due to the break of the balance between activators and inhibitors. There is an opinion that DNA damage is the primary cause. However, there is no doubt that all phenomena listed are interconnected and occur in irradiated plant.

When a plant is irradiated metabolic processes are subjected to change. It affects biosynthesis processes. However, metabolism distortion is not the cause that results only in radiation sickness. Metabolism distortion reflects only direct or indirect action of radiation on definite tissues as well as meristem tissues. It, in turn, results in appearing of abnormal tissues.

Metabolism distortion of plants grown from irradiated seeds occurs, when shoots are developed. This reflects embryo cell damage, which was primary. In this case metabolism distortion might be caused by the accumulation of somatic mutations and the distortion of morphological and tissue structure of the plant organs.

Biochemical changes of irradiated growing plants are caused by the damage of fermentative systems and some organelles of different cells (ribosomal apparatus, mitochondria, plastids, endoplasmic reticulum, etc.) and by the distortion of regulatory bonds that determine correlative subordination of some organs, and, to some extend, formative cell distortion. Such changes may occur after a few hours after irradiation. The damage of apical meristem tissues is very important, since it causes distortion of bonds between various cells and tissue groups as well as between organs.

Mentioned above distortions occur rather soon under the semi-lethal dose (e.g. 4–12 Gy for some leguminous plants). Cells division and growth processes are slowing down drastically within a day after irradiation. However, photosynthesis, respiration and metabolism processes might be still observed during long time.

It was found out that radiation sickness symptoms in plants are accompanied by the increase of their sensitivity for infection sickness, the decrease of element uptake and resistance to harmful factors, potential reproduction and productivity.

There is an opinion that plants with radiation sickness damage cannot be used as a food or fodder, since it may cause damage to humans and animals. Nowadays high dose irradiation is used in many fields and technologies in order to protect and save plant and animal products, i.e. disinfection, sterilization, pasteurization, conservation. Medical tests did not find any danger for human health in such products.

Radiation sickness of animals. Such sicknesses occur in irradiated animals and are characterized by a complex of specific signs. There are acute and chronic forms of radiation sickness. *Acute radiation sickness* is caused by single irradiation with a high dose. There are four states of heaviness of radiation sickness: 1st degree is the light form, e.g. light form in pigs, that occur at a dose of 1–2 Gy; 2nd degree is of medium heaviness of radiation sickness, e.g. at a dose of 2–4 Gy; 3rd degree is a heavy form of radiation sickness, e.g. of 4–6 Gy; 4th degree is the very heavy form of radiation sickness, e.g. at a dose of 6 and more Gy. For radiosensitive animals (e.g. cattle) radiation sickness doses might be shifted to 0.5–5 Gy and for radioresistant animals (e.g. rabbits) such doses might be shifted to 6–12 Gy.

There are four phases (periods) in the developing of radiation sickness in animals. *First phase* – may be observed within few hours after irradiation and it lasts for 3–4 days. Characteristic symptoms are the following: the distortion of nervous system state, animal getting irritated, the suppression and the weakness. Such animals lose appetite. They have distortions of heart rhythms, short breath, diarrhea, vomiting, and possible increase of body temperature. Leukocytosis, absolute and relative lymphopenia and an increased amount of reticulocytes might be found in peripheral blood. Finally animal state improves.

Second phase is the latent period or phase of imaginary clinical prosperity. Depending on the heaviness of radiation sickness this period may last from few days to two weeks. Animal state seems to be satisfactory; however the imaginary clinical prosperity can be easily investigated by blood test, which shows lymphopenia, thrombocytopenia, the decreased amount of neutrofils and reticulocytes. The red bone marrow aplasia might be observed as well. The end of the second period is characterized by the hemorrhage on the mucous membrane, the distortion of gastrointestinal tract functions, bronchitis, pneumonia, hair receding. However, signs of regeneration appear in bone marrow at light and medium heaviness form of radiation sickness in the second half of the period.

Third phase means that sickness is in full swing and a clinical syndrome of acute radiation sickness becomes evident. Depending on the heaviness of radiation sickness this period takes from 1 to 4 weeks. The state of irradiated animals is getting worse: short-breath appears, functioning of the cardiovascular system and gastrointestinal tract becomes worse, i.e. animals lose appetite; diarrhea; and dystrophy processes in the mucous membrane of mouth might be observed as well as the decrease of body weight; short-term fever that can repeat, increasing the body temperature. The main characteristic feature of this period is hemorrhage (under skin, in the mucous membrane, gastrointestinal tract, bone marrow, heart, lung and other organs). By the end of this period progressive anemia appears. If semi-lethal dose is applied, in one half of irradiated animals full bone marrow and lymphatic knot aplasia causes death. In the second half of irradiated animals the sings of regeneration might be observed and sickness passes into the fourth period in 1–1.5 months.

Fourth phase is a recovering period of an organism in an easy form of radiation sickness that proceeds rather fast and is thought to be full. The state of animals improves rather soon, i.e. appetite appears, and the body temperature is normalized, blood parameters become normal.

The recovery period of the medium form of radiation sickness lasts from 2 to 2.5 weeks and animals recover after 3 to 6 months. The recovery period of the heavy form of radiation sickness may last up to 9 months and recovering is not full. There is a low immunity and the reproduction ability. Lifespan shortening might be observed. An acute form of radiation sickness often becomes chronic.

The very heavy acute form of radiation sickness of cattle may last from a few days to a few weeks and, finally, it ends with death of irradiated animals in the first or third period. At above semi-lethal doses animals die within 2–4 days. At doses 2–3 times higher of lethal dose animals die at once or within a few hours after irradiation. In this case the reason of death is a lack of oxygen that is due to the decrease of hemoglobin content in blood, the development of toxemia and lung oedema.

At the medium and heavy form of radiation sickness irradiated animals usually die in the third period mainly due to the mentioned above hemorrhage and dystrophy processes. Characteristic symptoms of acute radiation sickness of animals are given in Table 18.

Chronic radiation sickness of animals develops due to the irradiation of the entire body at low doses or penetration of radioactive substances inside the organism.

There are three forms of chronic radiation sickness: easy, moderate and heavy. Similarly to acute form the chronic radiation sickness occurs periodically. The easy form of radiation sickness, which is caused by relatively low doses and during limited period of time, is characterized by functional distortion of mainly nervous and reflector systems. However, these symptoms disappear rather soon. The distortion of regulatory systems, functional insufficiency of digestive apparatus, nervous and cardiovascular systems, and especially blood, are typical symptoms of medium form of radiation sickness. After an irradiation most of such distortions disappear due to the involving of repair mechanisms and regeneration processes in most injured (critical) tissues with following normalization of various functional disorders. Deep destructive morphological distortions of haemopoiesis organs, digestive apparatus, nervous and other systems characterize heavy chronic radiation sickness that is caused by prolonged irradiation. Sickness is accompanied by progressive indulgence of heart function, distortion of functions of endocrine glands, emaciation and the weakening of the immunity.

In the case of internal penetrating of radionuclides in animals, chronic radiation sickness is often caused by a prolonged irradiation of some organs depending on the distribution and accumulation pattern of such radionuclides inside the body.

Thus, ^{131}I is mainly accumulated in thyroid gland; causing irradiation of this important organ in mammals. It leads to seriously sickness. ^{90}Sr is mainly accumulated in bones causing irradiation of bone marrow, which in its turn affects haemopoiesis, i.e. the process by which the different cell types of the blood are produced.

Radiation sickness of a human is characterized by the evidence of the same symptoms and proceeds in the same way.

5.1.4. Ageing speeding up and lifespan shortening

Ageing speeding up and lifespan shortening is a radiobiological effect that is also universal for living organisms of various taxonomic groups. It is found that there is a direct relation between lifespan shortening and an irradiation dose (Fig. 34). However, gerontologists suggest that it is not necessary for ageing speeding up and lifespan shortening to be connected with any phenomena. Thus, ageing speeding up and lifespan shortening might occur due to radiation sickness, the induction of leukaemia, tumors, and immunity weakening and other damages. However, it is not related to the mechanism of real ageing.

Table 18. Characteristic symptoms of acute radiation sickness of animals
(V. Kirshin et al., 1986)

Symptoms	States of heaviness of radiation sickness			
	easy	medium	heavy	very heavy
The duration of initial reactions (first period), days	No or several hours	to 1	2–3	more 3
The duration of latent period (second period), days	2–7	10–15	8–12	5–10
The duration of heavy sickness period (third period), days	5–10	10–20	10–30	5–20
General state of animals	Slight depression	Noticeable depression	Depression, asthenia, unsteady gait	Strong depression, unsteady gait
Body temperature, ^{O}C	Without changes or heighten by 0.3–0.5	Without changes or heighten by 0.5–0.7	Heighten by 0.3–1	Heighten by 0.5–1.5
Digestive organs	Without noticeable changes	Thinning of excrement	Diarrhea	Diarrhea with mucus and blood
Yield of milk	Without changes	Decrease by 20–50%	Decrease by 50–80%	Lack
Hair cover	Without noticeable changes	Falling out of hairs in sheep	Balding of sheep including facial part of head and lower part of extremities	
Respiration organs	Light short breath	Short breath, discharge from nose	Short breath, crepitations, discharge from nose	Symptoms of pronounced bronchopneumonia
Leucocytes	Decreased by	Decreased by 50–	Decreased by	Decreased by

amount	30–40%	60%	50–75%	75–90%
Lymphocytes amount	Decreased by 30–40%	Decreased by 30–50%	Decreased by 50–80%	Decreased by 70–90%
Trombocytes amount	Decreased by 5–15%	Decreased by 5–25%	Decreased by 40–50%	Decreased by 40–60%
Erythrocytes amount	Without changes	Decreased by 10–20%	Decreased by 15–20%	Decreased by 20–30%
Prognosis	Favourable	Animal mortality up to 20%	Animal mortality up to 60%	Animal mortality up to 95–100%

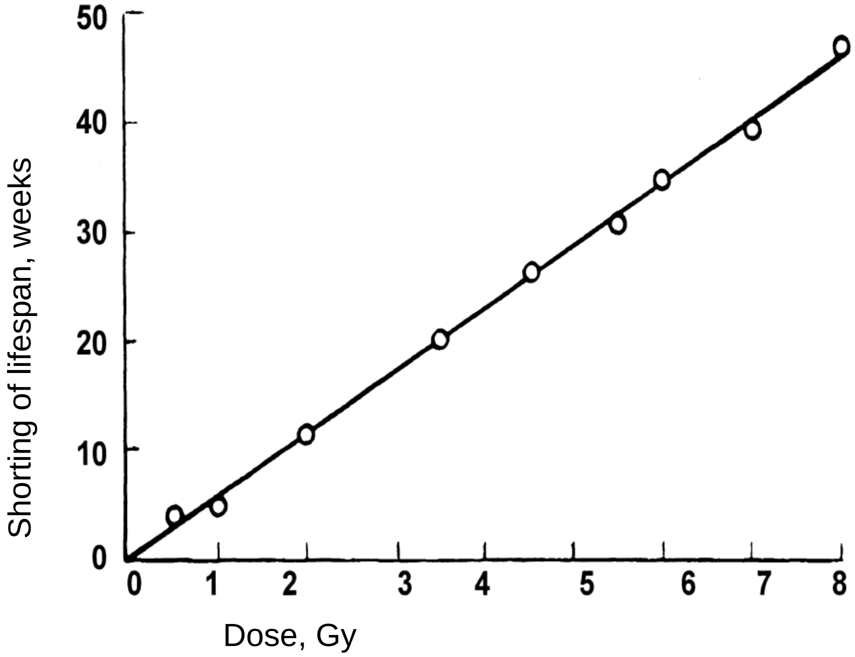

Fig. 34. Life span shortening of mice as an effect of γ-radiation doses
(D. Rosenblat, L. Lindon, 1961)

What is ageing? The classical definition of ageing is the following: ageing is a non-regulated process of age changes of an organism leading to the decrease of its adaptation possibilities and the increase of mortality. Ageing is natural for all living organisms at any life organization level: genetic, molecular, organism and population level.

On the molecular level ageing is accompanied by such changes: irreversible changes of DNA; uneven changes in synthesis of RNA and of various protein classes; changes during DNA synthesis; distortions in energy formation, the transfer and its use; decreasing of antioxidative system activity and microsomal oxidation; decreasing the intensity of mediators and hormone processes.

The major signs of ageing at cellular level are the decrease of mitochondria in cells, lysosomes destruction, and the change of electrical properties of membranes and ion transportation, the degradation of protoplasm colloids, the decrease of cell labiality and its reactions on the action of physiologically active substances. All these reasons decrease the cell division, the degradation and death of some cells, the devastation of forming cells.

At the organism level ageing of higher animals is revealed in mitigation of major physiological functions of the organism (e.g., nervous, endocrine, cardiovascular, digestive apparatus, etc.), in lowering the control of its activity, in the change of reactivity of hormone actions, in the distortions of the information entrance in nervous centres.

Ageing of plants at the organism level is characterized by mitigation of major physiological processes of an organism, i.e. photosynthesis, respiration, nutrient transportation, some metabolite transportation as well as disorder of regulatory systems, the change of reactivity to phytohormone actions.

Unfortunately, ageing speeding up of an organism is not well understood. There are some criteria that can be used for making decisions, whether ageing speeding up and lifespan shortening is due to irradiation or it is a naturally occurring process. In gerontology there is a rather interesting hypothesis, according to which ageing speeding up is a result of harmful somatic mutations accumulation that leads to destructive and degenerative processes mentioned above. At the same time an increase of radiation-induced somatic mutations, such as chromosome aberrations in cells of various plant and animal tissues, is well-known and used in radiobiology as one of the first criteria of radiation damage, which is easy to record.

Irradiation causes errors in RNA and the protein synthesis, in the synthesis of their molecules with lower molecular mass, increases the activity of proteolysis processes and many other signs of ageing. It makes possible to consider that the radiation damage is a factor of ageing speeding up.

Numbers of signs that are evidences of radiation-induced ageing speeding up were found out in higher plants. In comparison with non-irradiated plants irradiated ones show cellulose deposition on cell membrane, fast loss of growth zone, speeding up of cell differentiation rate, protoplasm regeneration, and the formation of big vacuoles. Irradiated plants often grow faster and are characterized by earlier flourishing and ripening. However, they usually have smaller size and lower productivity.

Though ageing speeding up of plants is similar to this process in animals, it differs in some specific features that make difficult to identify these signs in plants. On the one hand there are plant species all organs of which age and dying simultaneously (as in animals). At the same time there are plants, where there is a cyclical dying of certain organs, while others are still alive and active. On the other hand, many plant species have the ability to create new organs, including new shoots and even roots, which may repeat periodically through lifetime at a certain age and under certain conditions.

Therefore, when plants are irradiated at doses that cause death of actively dividing meristem, still there are meristem organs, which are in the rest state, e.g. axial buds that may produce new shoots. It is a kind of radiation-induced "rejuvenation". Such irradiated plants usually ripen later, because the germination of a new shoot from axial bud may be compared with the germination of a seed and the beginning of a plant growth.

Of course, there is no sense to speak about "rejuvenating" action of radiation; there should be secondary phenomenon, determined by the specific morphological and functional plant organization. For instance, shoots germinated from irradiated tissues have some signs of radiation damage.

Radiation-induced ageing speeding up of seeds that are in the rest state is of special interest. It was found, that the longer time passes between irradiation of seeds and its germination, the slower sprouting of irradiated seeds, its growth and the development in comparison with non irradiated ones. In radiobiology this phenomenon is known as "conservation effect". According to the hypothesis, it occurs due to the decay and the recombination of radiation-induced free radicals and biologically important molecules in post radiation period. However, mentioned above processes proceed relatively fast (during hours, weeks or a few month) and the effect of conservation may even increase in coming years.

It is known that ageing speeding up is a result of continuous oxidation of the cell component due to respiration. Such biochemical mechanism causes metabolic processes of mitigation and the loss of dry matter, since full oxidation of material results in death of a seed. Radiation induces a kind of displacement of most chemical and biochemical reactions to oxidation side, which is confirmed by an increase of respiration rate of irradiated seed and its ageing speeding up. It was also found out, that factors, which inhibit natural ageing speeding up, also mitigate preservation effect. Such effect also decreases at low oxygen content in the atmosphere and at the decrease of temperature and water content.

5.1.5. Organism death

The application of high radiation doses may cause organism death. Death of warm-blood animals, including agricultural animals, is caused first of all by the cessation of respiration and circulation of blood. There are two major stages of death: clinical and biological. During the clinical death there is a possibility to revive. However, irreversible changes and cessation of physiological processes begin on biological stage of organism's death.

As we mentioned above, various organs of many plant species die off at different time and many organs may reproduce themselves. It is difficult to estimate exactly when plant organism is dying off. Moreover, multicellular plant organisms comprise tissues and cells that vary significantly (up to a few orders of magnitude) in their radiosensitivity and, as a result, they lose the ability to perform their functions under different levels of irradiation. Thus, it is difficult to distinguish on the early stage of post radiation period, at which a plant organism loses ability to survive.

It is known that the resistance of differentiated cells of a leaf is much higher in comparison with meristem cells of a leaf. Thus, when a plant is irradiated, it may die, while differentiated cells of a leaf may survive and continue such functions as photosynthesis, respirations, and mineral and water metabolic processes. That's why it is difficult to observe any visible sign of a plant death within weeks or even months after irradiation. Obvious sings of so called "Red forest" close to Chernobyl NPP that reserved extremely high doses in April – May 1986, appeared only at the end of the year and became obvious only in spring 1987 (Fig. 35).

Even if the very high doses are applied, they inhibit complete cells division of all formative cells as well as growth processes. Such irradiated plants may preserve viable capacity of some systems that are still functioning. In such a way they obtain special sprouts (gamma-sprouts or gamma-plantlets) that are used for studying some physiological and chemical functions of plants, when dividing cells are absent.

Finally, when plants die due to formative cells dying off, the surviving of plants can be recorded. Within 2–3 days after irradiation, mitosis of meristem cells disappears. At the very high doses the blockade of a cell passage to mitosis can be observed in a few hours after irradiation. The meristem cell death may be observed within 6–10 days after irradiation, when root tips are getting brown and the growing zone is edged with fur; meristem shoots can be observed when covered leaves are opened (Fig. 36).

Fig. 35. Dead pine forest near Chernobyl NPP a year after the accident: study sites: a canopy of birches with higher radiosensitivity (foreground) and dead needles pine trees that have lost their needles (background).

When plants are irradiated under the doses of tens thousands Gy, their death may be observed a few hours later: the content of all cell types is degraded; the membrane exfoliates; the metabolic processes cease. Thus, the cell withers and dries up. This mentioned above kind of fast death is called “death-under-ray”.

Fig. 36. Death of pea seedlings in 6 days after γ-irradiation at a two-days age at a dose of 15 Gy; left – control, unirradiated seedlings.

5.1.6. Genetic effects

Radiation-induced damage of chromosomes is considered to be an especially dangerous effect of ionizing radiation, since it may cause the mutagenic effects in next generations, i.e. the heritable changes in the sequence of the pair bases in the DNA of an organism. Mutations occur spontaneously; however, the rate of mutation increases if an organism is exposed to X- or γ-radiation.

Three main types of mutations are distinguished:

1. Genetic or point mutations that are visible and involve single gene changes.
2. Chromosome mutations (or aberrations) visible with cytogenetic techniques. They involve changes of large section of the chromosome and the addition or loss of the whole chromosome.
3. Karyotypic mutations, i.e. mutations that result from the combination of the asymmetrical, symmetrical, complete or incomplete interactions of lesions of unduplicated chromatids.

Asymmetrical exchanges always give rise to one or more eccentric fragments that are left behind anaphase and not incorporated into daughter nuclei. In all types of exchange aberrations the process may be “complete”, i.e. non-free broken ends, or “incomplete” in which there are some chromosome parts that do not form new configurations.

It is well-known that mutations occurring in the course of evolution have produced the individuality of different species of plants and animals. Spontaneous or natural mutations are the prime movers of the evolution process. The cause of such mutations is not understood, although the chemicals, including the sex hormones, ultra-violet and ionizing radiation, and high temperature can increase the mutation rate in plants and animals. Mutations may arise in germ (generative mutations) as well as in somatic cells (somatic mutations) under irradiation. Independently on the site where alterations occur, the radiation-induced mutations may cause changes of any property of an organism. Although the most mutations are considered to be harmful for an organism, the beneficial changes occur as well.

The genetic effects of radiation are the result of gene mutations and chromosome aberrations. Mutations may appear as a result of direct physical destruction of chromosome segments under ionizing radiation or functional inactivation of vitally important cell structures under the effect of radiolysis products.

The mutagenic effect is dose dependent. Both experiments with animals and data from irradiated patients showed that aberration yield (y) (after the cell exposure to low LET radiation) best corresponds to the mathematical function $y = \alpha D + \beta D^2$, where D is the dose, and α and β are constants. This equation is consistent with the hypothesis that some aberrations are the result of a single ionizing track (single hit) so that the yield is proportional to dose (αD), while other aberrations are produced by two separate tracks when the yield is proportional to the square of the dose (βD^2). The 1-hit aberration increases in liner dependence with a dose (Fig. 37), while the more complex aberrations increase in a curvilinear manner.

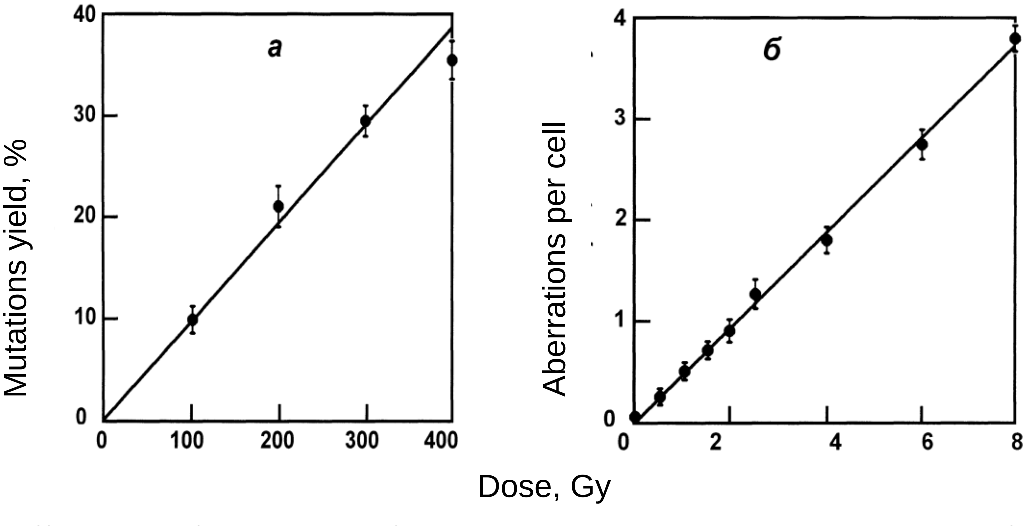

Fig. 37. Dose-effect curves for mutations of *Chlorella* cells (a; V. Shevchenko, 1979) and for chromosome aberrations in meristem cells of horse beans (b; I. Gudkov, 1984).

The yield of 1-hit aberrations seems to be unaffected by a dose rate and evidences that the degree of genetic damage is proportional to a dose. There are also no evidences about threshold action of ionizing radiation, because any low dose may cause radiation damage to the chromosome and, thus, induce mutations. Appearing of more complex aberrations requires two lesions, which in turn may be provoked by one or two ionizing track. Therefore the actual shape of the dose response curve for 2-hit aberrations depends on the rate and the LET of the radiation.

Thus, depending on a dose, types of radiation, an organism and other factors, mutations yield that follows cell damage may form the parabolic curve. The character of such curve greatly depends on the effectiveness of the repair mechanisms, especially at low doses.

The increase of irradiation dose is followed by an increase of mutations and a decrease of an organism survival. At relatively high doses, the number of mutations reaches maximum (stabilized) or even decreases. Under γ- and X-rays irradiation mutations yield may reach 50% of all individuals survived at a plateau of 1–2% of survival.

The measure of genetic action of ionizing radiation is a dose, which reduplicates the mutation yield. However, it is difficult to estimate this dose. For mammals as well as some radiosensitive species of plants this dose varies widely from 0.1 to 1 Gy.

Elevated radiation background, contaminated soil, plants, fodder and foodstuff increases the probability of the mutation appearance.

Mutations influence germ cells of the body more than somatic cells. A mutation in a somatic cell may result in the malfunctioning or even the death of that cell or any of its descendants. Since there are millions of cells in any organ, the effect of one or two mutant cells will be insignificant. However, somatic mutations are considered to be the basis for cancer and for the phenomenon of ageing.

In contrast, mutations occurring in the germ cells may have disastrous effects on the offspring. Thus, mutations occurring at any development stage of ovum and sperm or of fertilized ovum (zygote) are very likely to lead to the progeny death or, at least, may produce seriously defective offspring.

5.2. Deterministic (early) and stochastic (late) radiobiological effects

Depending on the reveal time after irradiation deterministic (early) and stochastic (late or delayed) radiobiological effects are distinguished (Fig. 38).

The deterministic effect (a loss of organ function) occurs when enough cells in an organ or tissue are killed or prevented from reproducing and functioning normally. The loss of function becomes more serious when a number of affected cells increase. There is a continuous process of a loss and replacement of cells in many organs and tissues. An increase of the loss rate may be compensated by an increase of the replacement rate. Net reduction in the number of cells that are available to maintain the functions of the organ or tissue may be a transient, and sometimes permanent. Many organs and tissues are unaffected by small reductions in the number of available cells, but if the decrease is large enough, pathological conditions are clinically observable, i.e. the loss of tissue functions, or consequential reactions if an organism tries to repair the damage. If the tissue is vital and damaged sufficiently, the end result is death. Deterministic effects can be observed within a few hours after irradiation; stochastic radiobiological effects are revealed in later periods.

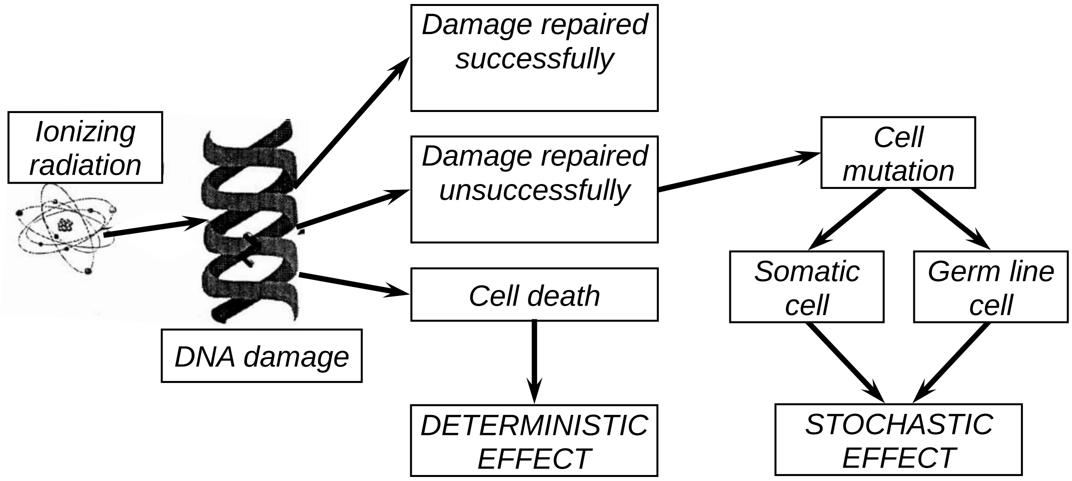

Fig. 38. Deterministic (early) and stochastic (late or delayed) radiobiological effects.

More exact time may be determined only concerning specific organism in connection with the duration of ontogenesis period, which varies considerably for different organisms from a few days to tens of years. Deterministic effects of annual agricultural plants reveal during first hours, days, one or two weeks followed by a single irradiation. Stochastic radiobiological effects reveal, as a rule, at the end of ontogenesis in following generations, i.e. within months and years.

Deterministic radiobiological effects are: radiation stimulation that reveals immediately after irradiation; most of the morphological changes in tissues and some organs that appear during the first days or weeks after irradiation; acute radiation sickness of all degrees of heaviness that develops in plants during first weeks, and in animals-mammals appears during 1–1.5 month; death, when high doses are applied. Generally, the acute effects of radiation occur in rapidly dividing cell population within days or weeks. On the contrary, slowly proliferating or non-proliferating tissues are examples of a diversity of later radiation damage.

A modified somatic cell may retain its reproductive capacity and may give rise to a clone of modified cells that may eventually result in malignant formations. A modified germ cell may transmit incorrect hereditary information and may cause severe harm to descendants. These somatic and hereditary effects that may start from a single modified cell are called stochastic effects.

The response of the organism to the clone development of modified somatic cells is complex. The initial stages of clone development may be inhibited unless some additional agent promotes its development and any surviving clone is likely to be eliminated or isolated by the organism’s defense. Otherwise, after a prolonged and variable delay called the latency period it may result in the development of a malignant condition in which the proliferation of modified cells is uncontrolled. Such conditions are commonly grouped together and called malignant formations. Such radiation-induced formations are not distinguished among those caused by other conditions.

Stochastic radiobiological effects are ageing speeding up and lifespan shortening that are clearly observed during the late periods of ontogenesis. Stochastic radiobiological effects in mammals are morphological changes that result in the appearance of malignant formation (leukemia and tumors). Radiation-induced cataract is a typical stochastic radiobiological effect that is morphological by nature. Radiation-induced nephrosclerosis is the next sickness that is due to morphological degeneration of tissues and vessels of kidney resulted by radiation-induced damage of radioactive substances, incorporated inside the organism. As a rule, such effects reveal themselves some years later after irradiation.

There are two approaches in studying the cause (pathogenesis) of these later effects. One hypothesis suggests that later damage, i.e. month, years, or even decades after the radiation, is primary due to vascular damage. This approach is based on the idea that the damage of small blood vessels eventually leads to a degeneration of the tissue cells and to a generalized later fibrosis of its associated connective tissues. According to another hypothesis it suggests that the wide diversity of later effects occurred in different tissues is due to the difference in the time of their appearance and the rate of development. The later is best explained in terms of cell kinetics. This hypothesis suggests that acute radiation effects occur early in rapidly dividing tissues, so later effects occur later in slowly- or non-proliferating tissues. The effects are "later" because the result of damage at mitosis has to wait for the slow appearance of such division.

We've already mentioned that the genetic action of radiation attributes to latest effects of irradiation. Moreover, parents may have no signs of radiation damage, but various abnormalities may appear in next generations. Experiments *in vivo* (plants, laboratory animals, insects and other organisms) showed that the first generation might have about half of the mutations; other mutations may appear during next 15–20 generations.

Regarding risk assessment of genetic effects of irradiation it is very important to know if mutations are dominant, i.e. caused by one allele that determines such sign, or recessive, i.e. caused by two different alleles of one gene. The character of inherits finally determines the specificity of damage distribution in next generations after the irradiation. If mutation is dominant it will occur in next generations. In the case of recessively inhered signs appearance of genetic damage may be prolonged or even not shown up at all.

Most of the radiobiological effects appear only when altered gene is associated with a gene, bearing analogous damage. It depends on the frequency of mutation appearance that in turn, (as well as the total number of mutations) depends on the dose of irradiation.

The hypothesis of stochastic effects is considered to be a probability theory. It means that later radiobiological effects cannot be determined for one particular organism in advance, in comparison with most of the early radiobiological effects. Epidemiological studies also cannot provide the reliable information. These studies provide only statistical associations. Such associations give reliable information if they are clearly dose-related and supported by corresponding experimental data. For instance, when 1 000 pea's plants are irradiated with a dose of 0.5 Gy, all or almost all of them show signs of radiation stimulation; at dose of 8 Gy all of them show various radiation-induced morphological changes; and at dose of 15 Gy all plants die. If, e.g., one sheep or sheep are irradiated by a dose of 2 Gy all of them show signs of radiation sickness of the first or the second or even the third degree (depending on the individual sensibility to radiation). However, it is impossible to predict the appearance of any later radiobiological effects. The probability of such effects may be only determined by using statistical analysis of changes revealed in irradiated population and estimated as a percentage of damaged individuals in irradiated population or as a number of damaged persons per thousand or million.

5.3. Radiomimetic induced biological effects

Radiomimetics, or radiomimetic substances are chemical substances that affect cells, tissues, organs and organism as a whole similar to ionizing radiation. First of all they are alkylating compounds, i.e. highly chemically reactive compounds, that attach hydrocarbon group (such as methyl (CH_3), ethyl (C_2H_5) and others) that form covalent bounds with organic compounds, including cell biopolymers with the following induction of damages, similar to ionizing radiation-induced ones. Such poisonous substance as yperite (mustard gas), which is known since World War I, is a typical representative of radiomimetics, along with such less known chemical substances as ethylenimine, diethylsulphonate, methylsulphonate etc.

Some researches consider various peroxides as a radiomimetics. Peroxides comprise alkylating compounds and therefore may act similarly to action of ionizing radiation. There are evidences that damages of the organism depend upon increased oxygen content and are similar to radiation-induced symptoms.

Radiomimetics, similar to ionizing irradiation may inhibit DNA synthesis, induce chromosome aberration, cease cell division the growth and the development of an organism, and cause malignant formations and finally death of cells and entire organism.

Similar reactions do not always mean similar action mechanism. P. Koller found similarities of some final reactions of chromosome damages in onion rootlet cells induced by yperite and ionizing radiation in 1954. However, some radiobiologists suggest that similarities of the final reactions cannot have the same mechanisms with the action of yperite and ionizing radiation on the organism. In spite of this many researches consider the same damaging mechanisms in both cases. Such opinion is based on the fact, that ionizing radiation and mentioned radiomimetics, especially those comprising alkylating compounds, induce deep changes of chemical and physical properties of DNA, i.e. a “target” of radiation damage. Apart of this, radiosensitive organisms reveal also resistance to radiomimetics when radioprotectors are applied.

There is no need to continue discussion about such particular specific problem, however, it has to be mentioned that radiomimetics is widely used as a factor causing mutations in plant and other organisms (chemical mutagenesis). A number of new species of agricultural plants with practically useful signs was obtained. Some of the methods, used in chemotherapy of malignant formations are based on the ability of radiomimetics to inhibit cell division.

Summarizing mentioned above it has to be emphasized that the dose of irradiation of the organism is the major factor that determines the reveal of one or another radiobiological effect. When relatively low doses result in radiation stimulation of irradiated organism, the higher dose may cause various morphological changes, radiation sickness of different degrees, ageing speeding up and lifespan shortening. Very high doses result in organism death. The degree of genetic damage is also determined by a dose. However, due to the different radiosensibility the same radiation dose may cause radiation stimulation of an organism, and induce radiation sickness or even death. Thus, radiosensibility is the factor that mainly determines outcome of irradiation.

Control points to chapter 5:

1. The major types of somatic radiobiological effects.
2. Somatic and genetic radiobiological effects.
3. Genetic radiobiological effects.
4. Radiation-induced stimulation of plants.
5. Radiation-induced stimulation of animals.
6. Radiation-induced morphological changes of plants.
7. Radiation sickness of plants.
8. Radiation sickness of animals.
9. Ageing speeding up of plants and animals.
10. Radiation-induced lifespan shortening.
11. Deterministic and stochastic radiobiological effects.

6. RADIOSENSITIVITY OF ORGANISMS

6.1. Radiosensitivity and radioresistance. 6.2. Comparative radiosensitivity of organisms. 6.2.1. Radiosensitivity of plants. 6.2.2. Radiosensitivity of animals. 6.2.3. Radiosensitivity of bacteria and viruses. 6.2.4. Radiosensitivity of phytocenosis. 6.3. The reasons of wide variability of organism radiosensitivity. 6.4. Comparative radiosensitivity of cells on different stages of their development. 6.5. Critical organs. 6.6. Effects of low doses of radiation on living organisms.

Radiobiological effects depend on the dose received by a living organism. Radiation stimulation is the first somatic effect that can be observed at minimum doses. The morphological changes and radiation-induced deceases reveal at much higher doses. Higher doses may cause organism death.

However, radiobiological effects depend on many other factors. Thus, stimulating doses for plants of *Brassicaceae* family (cabbage, rape, garden radish) may be lethal for beans and pea. Doses that are harmless for insects are lethal for all mammals. All radiobiological effects are determined by the sensitiveness of organisms to ionizing radiation, or their radiosensitivity.

6.1. Radiosensitivity and radioresistance

Two terms that characterize the response of an organism to ionizing radiation in radiobiology are radiosensitivity and radioresistance. It is generally accepted that these terms are stand for the same phenomenon, i.e. if an organism has high radiosensitivity; it is characterized by low radioresistance, and vice versa. However, these two concepts have to be distinguished.

Radiosensitivity of an organism is its ability to react on the minimum radiation doses and to catch insignificant irradiation by different cells and molecule systems. Radioresistance is an ability of an organism to withstand high doses of irradiation.

It means that the lower dose that causes unlethal radiobiological effects is the higher radiosensitivity of an organism. And the higher dose that results in death of an organism is the higher its radioresistance. An organism can be subjected to two levels of doses: lower level stands for radiosensitivity and higher level stands for radioresistance. An interval between these doses is the range of radiobiological or biologically effective doses.

The concept of effective dose is used to estimate the radiosensitivity or radioresistance, i.e. the degree of radiation effect. An effective dose is a dose that causes a certain radiobiological effect, e.g. radiation stimulation or some type of morphological changes. Usually, the term LD$_{50}$ for semi-lethal and LD$_{100}$ for lethal doses are used to define the level of organisms' radiosensitivity and radioresistance. LD$_{50}$ and LD$_{100}$ are doses that kill, accordingly, on average 50 or 100 per cent of the population within, e.g. 30 days of the irradiation (LD$_{50/30}$).

Effective doses are determined by *dose-effect curves*. The *dose-effect curve* is a curve that shows an influence of a dose and a dose rate of radiobiological effect induction. The graphical presentation of the fraction of the surviving population against the dose of radiation received is known as a *survival curve*.

The survival curve is plotted by using experimental data about different doses irradiation of identical groups of plants or animals. Later, when the result of an experiment is obvious, the amount of individuals died and survived is estimated and a curve is plotted (Fig. 39). Usually, such curve has S-like or similar to that shape. What does it mean? First of all, it means that survival response versus to a genetic effect has a (plateau) threshold. All irradiated individuals survive at a certain dose level and the survival curve on this area goes parallel to abscissa axis. As the dose increases the proportion of individuals killed increases and the survival curve goes down. On this area the dependence of survival on a dose has, as a rule, a linear or similar to a linear character. At this point, LD$_{50}$ of irradiated population may be estimated rather accurately. Further increase of dose leads the curve to the plateau again evidencing that all doses that are above a certain level are lethal for all individuals of irradiated population.

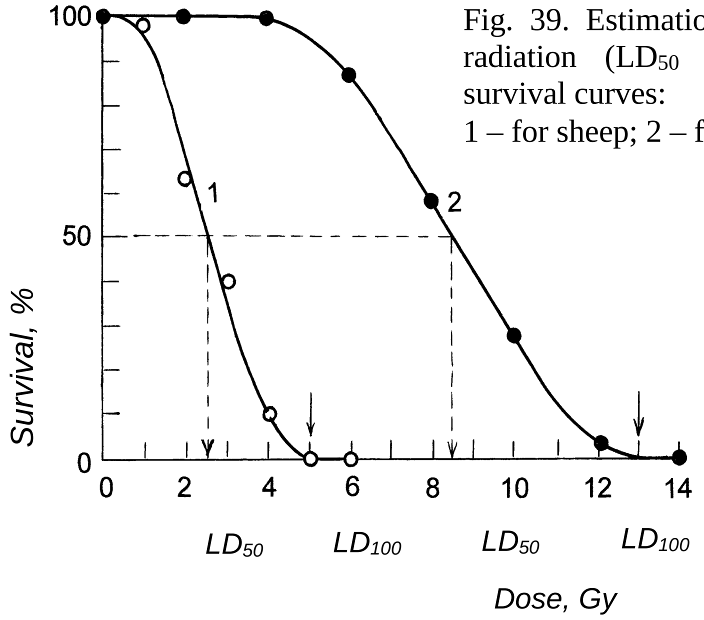

Fig. 39. Estimation of effective doses γ-radiation (LD$_{50}$ and LD$_{100}$) by using survival curves:
1 – for sheep; 2 – for pea plants.

Thus, the radioresistance of an organism may be estimated by a dose, causing death of some part of irradiated population within a certain time after irradiation, e.g. $LD_{50/30}$. The estimation of radiosensitivity of an irradiated organism is more difficult. To some extent, the level of radiosensitivity can be characterized by a dose causing stimulation, cytological, and cytogenetical damages or some biochemical distortions.

6.2. Comparative radiosensitivity of organisms

Radiosensitivity of living organisms of different taxonomic groups varies widely. Thus, semi-lethal dose does not exceed a few Gy for the most radiosensitive species, e.g. some types of higher plants and mammals; it reaches the value of a few thousands Gy (a few kGy) for the most radioresistant species, e.g. lower plants, bacteria, viruses.

Why do we study the radiosensitivity and radioresistance of organisms?

Firstly, the study of comparative radiosensitivity of organisms of various taxonomic groups is of theoretical importance. Such studies allow understanding the reasons of low radiosensitivity of some species. Such knowledge is of primary importance because it gives an opportunity of the artificial increase of radioresistance of sensitive organisms, including a man.

Secondly, the knowledge of radiosensitivity of different of living organisms is of practical importance due to the wide application of radiation biotechnologies such as irradiation of seeds and growing plants to increase yield; irradiation of seeds and plants to obtain new varieties; pest sterilization by ionizing radiation; sterilization of insects that are the spreaders of agricultural animal’s sickness; biotechnology of fodder preservation, disinfection and the improvement of its quality, etc.

6.2.1. Radiosensitivity of plants

Nowadays data about radiosensitivity of more than 3 000 plants belonging to different families, genera, sorts and varieties are available. However, most of these data concerns seeds, e.g. stage of plant ontogenesis, when a plant is in a state of a deep organic or forced rest and, therefore, is highly resistant both to the ionizing radiation and other factors. Very often it means an impression that plants are highly radioresistant to ionizing radiation. But it is not always true.

When seeds placed in the moist environment, metabolic processes begin within a short period of time and seeds germinate. At a shoot stage radiosensitivity of a seed increases by a factor of 15–30 (Fig. 40) and remains at this level up to the end of vegetation. It has to be mentioned that data about radiosensitivity of plants at vegetative stage are much limited in comparison with seeds. Seed's radiosensitivity of 50 plant species is shown in Table 19.

It is generally accepted that some of lily species are considered to be the most radiosensitive plants among other plants or even living organisms. Ground lily (*Trillium cernuum* L. – a plant of liliaceous family) has similar affinity at the vegetative state. That's why a lily, as an exception, is included in this table. The plants grown from the lily seed and irradiated by a dose of 20 Gy die at the spring stage. And they die at shoots stage only at a lethal dose of 2 Gy. The coniferous plants (pine and spruce) are considered to be very radiosensitive. The lethal dose for some of these seeds is 20 Gy. Many forest and decorative leafy arboreal species, including vine, fruit-trees, and shrub plants have a high index of radiosensitivity.

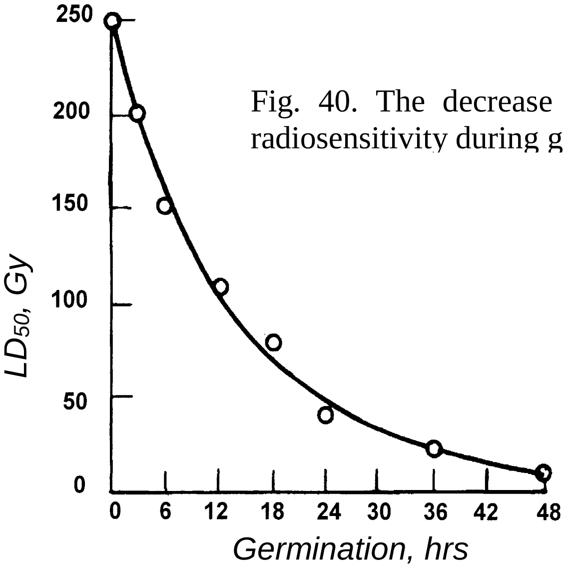

Fig. 40. The decrease of pea seeds radiosensitivity during germination.

The highest radiosensitivity is typical for seeds of leguminous family plants. Among them are beans that are represented in flora by only one species, e.g. a horse bean. High radioresistance is typical for cereals, some vegetables, as well as industrial crops. The highest radioresistance is peculiar to the cruciferous family.

Growing plants, as a rule, have higher factor of radiosensitivity (15–30 (Table 20). in comparison with seeds. Generally, relationship exists between radiosensitivity of seed and growing plants. As for plants, as well as for seeds, the highest index of radiosensitivity is typical for liliaceous, pine and legunous and the lowest one is for cruciferous family.

Table 19. Radiosensitivity of seeds of some higher plant species to X- or γ-radiation

Species	LD_{50}, Gy	LD_{100}, Gy
Lily	10	20
Pine-tree	10	120
Vine	10–90	–
Fir-tree	20–60	50
Apple-tree	20–70	70–150
Pear	30–40	70
Currant	30–40	70
Plum	40–100	80–200
Cherry	50	100
Bean	50–100	75–125
Birch	50–100	100–150
Pea	50–250	150–500
Maple	100–150	160–600
Corn	100–150	250
Onion	100–150	250
Lettuce	100–150	250
Rye	100–180	150–250
Buckwheat	100–200	200–400
Kidney bean	100–250	250–500
Aubergine	150	250
Soy	150–170	250–500
Wheat	150–250	250–450
Barley	150–250	250–500
Ash	150–300	300–600
Pepper	190–360	–
Cotton plant	200–360	–
Tomato	200–400	400–750
Oat	250	500
Dill	250	500
Poppy	250–300	450–500
Lupine	250–300	750–800
Linden-tree	300	600
Hemps	300–350	500

Beet	350–400	700–750
Potato	350–500	500–1000
Pumpkin	500	–
Cucumber	500	1000
Water-melon	500–700	–
Carrot	500–1000	1000
Esparcet	500–1000	1250
Alfalfa	500–1500	1500
Clover	500–1500	1500–2000
Cabbage	700—800	1500
Melilot	700–1000	2000
Rape	750–1000	2000
Mustard	800–1500	1600–2000
Flax	1000	2000
Radish	1000–1500	2000
Garden radish	2000	3000

Table 20. Radiosensitivity (X- or γ-radiation) of growing plants of some species

Species	$LD_{50/10*}$, Gy	Genera	$LD_{50/10*}$, Gy
Lily	0.5–1	Wheat	13–18
Pine-tree	1–3	Tomato	15–18
Fir-tree	3–5	Lupine	15–20
Bean	3–5	Corn	18–22
Pea	7–9	Cucumber	20–24
Kidney bean	10–13	Alfalfa	20–25
Soy	12–15	Clover	25–30
Barley	13–17	Garden radish	50

* „10” stands for a day, when the survival test of the meristem death of the main root was conducted after the irradiation.

Data of Table 19 and 20 show effective dose ranges for some plant species. However, it may vary significantly within sorts. No wonder that different sorts have different resistance to various factors such as high and low temperature, sickness, chemical agents, etc. Thus, effective doses for cereal seeds of different sorts can differ by a factor 2–3, and seeds of pea differ by a factor 5.

Radiosensitivity varies also during the growth period of a plant. It occurs because any stage of ontogenesis is characterized by a certain complex of physiological and biochemical features that affect the radiosensitivity of plants. Therefore, when plant radiosensitivity is examined, the signs of a specific plant at any stage of the development have to be taken into account. It allows revealing of reasons for high or low plant radiosensitivity and making a correct comparison of plants radiosensitivity of a different phylogenetic origin.

Fig. 41 shows generalized data of plant radiosensitivity at some stages of ontogenesis, i.e. from a seed that is formed up to the beginning of gametogenesis, i.e. the formation of a new seed. It’s obvious that the milk stage of seed ripeness is the most sensitive to radiation. The radioresistance increases when plants grow and get maximum values, i.e. plants reach a complete ripeness. The beginning of seed germination is characterized by the increase of radiosensitivity that slightly decreases when vegetative organs and axis of inflorescence are formed. The generative stage of plant is the formation of sexual organs that is characterized by the increase of radiosensitivity. Radioresistance of a plant slightly increases and decreases when the process of sporogenesis and gametogenesis begins and elements of flower are formed.

There are several stages of plant development that are characterized by high radiosensitivity: the germination of a seed and the stage of shoots, the transfer from the vegetative to generative stage and gametogenesis. The irradiation of plants at these stages can result in noticeable damage.

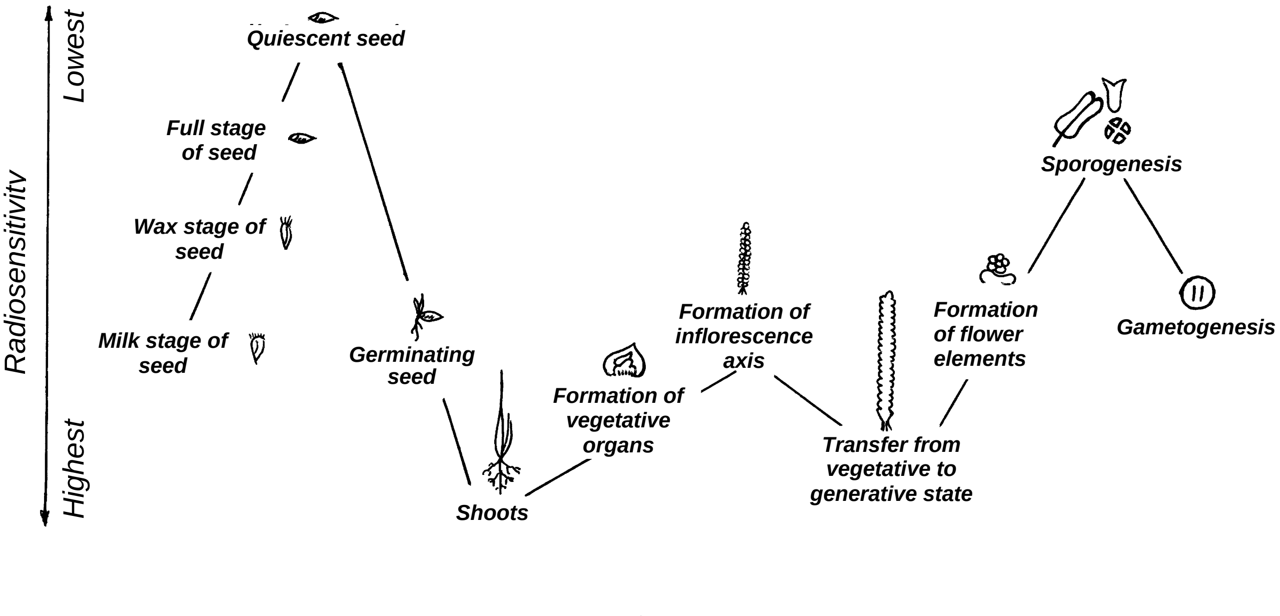

Fig. 41. Radiosensitivity variation of plants during ontogenesis.

Radiosensitivity of lower plants is observed in organisms that are widely spread, and many of them are considered to be an important component of soil microflora. The example of high radiosensitivity of living organisms is a well-known mutagenous form of micrococcus family bacterium revealed in the USA in the channel of nuclear reactor, where the dose rate was about 0.12 Gy s^{-1}, and a dose of irradiation per day was accordingly more than thirty thousands Gy. There, bacterium not only survived but also propagated oneself. For this reason bacterium was named *Micrococcus radiodurans* (radioresistant).

M. Kraus, the American researcher, revealed even higher radioresistance of blue-green algae. For some species LD_{50} was found to be equal to 12 000–15 000 Gy (acute irradiation – dose rate exceeded 0.12 Gy s^{-1}).

Low radiosensitivity is typical for mosses and ferns. Semi-lethal doses are from 200 to 700 Gy. LD_{50} varies from 100 to 1 000 Gy for fungi. Lichens have high radioresistance. Semi-lethal doses for lichens are mainly determined by radiosensitivity of fungus that is a component of lichen.

Studies show a wide range of radiosensitivity among plants. The knowledge of reasons of such variability and especially high radioresistance is of primary importance for radiation protection purposes as well as for development of radioprotective pharmacological agents.

6.2.2. Radiosensitivity of animals

The radiosensitivity of mammals, perhaps, is of primary interest among other animals. Some representatives of this class are well studied. However, the most reliable data are obtained from small laboratory animals such as mice, rats, ground squirrel, rabbits, dogs. Much less is known about radiosensitivity of large animals such as horse, cow, and camel. No data are available about radiosensitivity of wild animals, especially of large size. The only rough data are available about radiosensitivity of a man mainly due to difficulties related to the dose measurement in the case of nuclear accident.

Table 21 shows generalized data available in literature about animal’s sensitivity to γ-radiation. It follows that values of semi-lethal and lethal doses of γ-radiation for animals vary widely. Such variation is hard to explain using only the race or the line of animals. It depends on experiment conditions, irradiation conditions, age of animals etc. Nevertheless, the semi-lethal and lethal doses for most of mammals vary from 4–5 to 8–9 Gy respectively. The most radiosensitive domestic animal is a sheep. The minimum LD_{50} value for it is only 1.5 Gy. Rabbits are animals with the highest radioresistance (LD_{50} value varies from 8 to 10 Gy).

In 1960s the scientists from M.V. Lomonosov Moscow University found out that rodents (*Mongolian squirrels*) that are widely spread in the region close to the Baikal Lake (Fig. 42) have an extremely high index of radioresistance. Semi-lethal and lethal doses were found to be 13 and 15–18 Gy respectively. It is also found that other animals (mice, hamsters, marmots etc.) living in that region has high radioresistance. However, natural resistance of animals decreased when they were placed in the laboratory and fed by a fodder that differed from natural diet of animals.

Table 21. Radiosensitivity of mammals (X- or γ-radiation)

Species	$LD_{50/10}$, Gy	LD_{100}, Gy
Guinea-pig	1.5–3	4–6
Sheep	1.5–4	5.5–7.5
lambs up to 3 months	1.5–3	6
Cattle	1.6–5.5	6.5
calves up to 5 months	1.5–2.5	3
Goats	2–5.5	7.5
Donkeys	2–5.5	8
Camels	2.5	–
Humans	2.5–4	6
Marmoset	2.5–5.5	4–6
Pig	2.5–6	8
piglets up to 2 months	2.8–3	4.5
Horse	2.5–6	–
Dog	3.5–4	5–6.5
puppies up to 3 months	2–3.5	4–5
Mouse	4.5–7	8–10.5
Rat	4.5–7.5	7–10
Cat	5–7	8–9.5
kittens up to 2 months	3.5–4	6.5–7
Mouse bat	5–7.5	–
Hamster	5–8	9–10
Ground squirrel	6–9	11
Marmot	6–9.5	–
Rabbit	8–10	12–14
Mongolian squirrel	10–13	15–18

This phenomenon is known as “vivarium effect”. There is an opinion that some plants that compose a diet of those rodents in nature have radioprotective affinities.

Young animals seem to be more radiosensitive in comparison with adults. This observation corresponds to the law of Bergonie and Tribondeau, i.e. cells are sensitive if they are mitotically active, normally undergo many divisions and are morphologically and functionally undifferentiated. Differentiated cells are considered to be mature, i.e. specialized cells that are unlikely to undergo a division. So, the radiosensitivity of a tissue is directly proportional to its mitotic activity and inverse to the degree of cell differentiation.

Fig. 42. Record holder with radioresistance among mammals Mongolian gerbil (*Meriones unguiculatus*).

Among vertebrates birds are characterized by higher radiosensitivity in comparison with mammals. Semi-lethal doses of X- or γ-radiation for most bird families, including poultry are 8–25 Gy. These doses vary from 10 to 15 Gy for chickens, 12 to 16 Gy for ducks, 12 to 18 Gy for geese. Semi-lethal doses are in the range 5–20 Gy for fishes, 25–30 Gy for amphibians. Reptiles show even higher variation: 15–20 Gy for tortoises and 80–200 Gy for serpents. Although according to the Japanese researchers for Japanese salamanders semi-lethal doses make only 7–8 Gy (Fig. 43).

Fig. 43. The Japanese giant salamander (*Andrias japonicas*) is the most radiosensitive among amphibians species.

Invertebrate animals are highly radioresistant. Semi-lethal doses for most of the insects are in a range of 50–300 Gy, and lethal doses vary from 100 to 500 Gy, although the index for some insects is 1 000 Gy. Radiosensitivity of insects greatly depends on the stage of their development. Adult insects appear to be radioresistant organisms. For example, the semi-lethal dose for 3-hours old eggs of Drosophila fruit flies is 2 Gy, for 4-hours old is 5 Gy, for 7.5-hours old is 8 Gy, for the stage of pupa is 20–65 Gy, and for grown up individuals is 95 Gy. Menhinick and Crossley (1969) irradiated a group of 12 insect species (< 10 to 5 000 Gy) and compared life expectancy. Although differences in sensitivities were found, life expectancy was significantly reduced for all species at doses equal or greater than 80 Gy.

Protozoans also appeared to be relatively radioresistant. On of the most resistant appears to be the ciliate protozoan, *Paramecium aurelia*, which is reported to have a LD_{50} in excess of 1000 Gy (Z. Bacq, P. Alexander, 1961). Also relatively radioresistant are sponges, hydroids, and annelids.

Semi-lethal doses are in a range of 20–200 Gy for shellfishes, from 100 to 1 000 Gy for arthropoda, from 50 to 2 500 Gy for coelenterata, from 1 000 to 3 000 Gy for protozoa (amoeba and infusorians).

6.2.3. Radiosensitivity of bacteria and viruses

Bacteria and viruses are considered to be the most radiosensitive organisms. We have already mentioned blue-green algae that are not real algae. They belong to a group of bacteria called cyanobacteria. We've also discussed radiosensitivity of *Micrococcus radiodurans*, the semi-lethal dose for this bacterium is about 4 000 Gy (a range of 1 000–7 000 Gy). However, different bacteria strains differ in their ability to survive under irradiation. Thus, the semi-lethal dose for *M. sodensis* is 300 Gy, but LD_{50} for intestinal bacilli *Escherichia coil* is 30–60 Gy. Nevertheless, LD_{50} for most of the bacteria vary from 300 to 2 000 Gy. Spores of bacteria are even more resistant to radiation.

LD_{50} for viruses are still higher, even if they are in the reproduction stage, it varies from 4 000 to 7000 Gy. At other stages their resistance is much higher. Obviously, lethal doses for bacteria and viruses as well as for their spores are considered to be much higher. Based on the lethal doses for bacteria and viruses the doses for pasteurization, disinfection as well as sterilization are estimated. In some cases these doses may be as high as 20 000–25 000 Gy. More detailed information will be given in chapter 13.

6.2.4. Radiosensitivity of phytocenosis

When a plant community is subjected to ionizing radiation even at relatively low doses (much lower of semi-lethal doses for the most radiosensitive components of cenosis), the substantial changes can be observed in phytocenosis structure. Even negligible inhibition of the growth and the development of one or two plant species can result in the violation of cenosis relations that in its turn provide better conditions for the growth and the development of other plant species.

Prolonged irradiation of phytocenosis can make more harm in comparison with an acute one. Plant species affected for many years by prolonged irradiation promote the accumulation of various deviations in the plant development. Phytocenosis subjected to acute irradiation during relatively short time undergoes rehabilitation.

The first studies of contaminated phytocenosis were conducted in the areas with high natural radiation background or near the nuclear weapon test places.

The gradual disappearing of some radiosensitive moss species from their natural ecological population after irradiation by γ-radiation at a dose rate of 0.76–0.91 mR h^{-1} was observed by Polish investigators I. Sarosiek and H. Wozakowska-Natkoniec (1968). Meanwhile, some marshancia mosses species, which are more radioresistant, continued to grow.

Various changes in the phytocenosis structure in the middle-taiga area of Komy Republic on the local radium areas appeared over 50 years ago as a result of the exposure on the earth surface of radioactive waters due to a human activity has been observed by A. Taskajev et al. (1996). The dose rate at this experimental zone was 2 mR h^{-1}, while dose rate at neighbouring zone (control) located in the same area was 10–15 mcR h^{-1} for decades. The morphological changes of plants (especially in coniferous species), the elevated mutagenity in most of the plants, the substantial changes in floristic composition of phytocenosis; the violation of the microbe cenosis structure of soil, the decrease of population of some animals (particularly mice like rodents) were observed at the experimental zone.

V. Shevchenko et al. (2001) studied biocenosis changes in the zone of East-Ural radioactive track and in the 30-km restricted zone of Chernobyl NPP. They observed various biochemical mutations, chromosome aberrations, visible mutations, changes of genetic structure of the population, the decrease of plant species radiosensitivity and the disappearance of species and, finally, the degradation of biocenosis. The authors believe that genetic effects of ionizing radiation are main reasons of ecological changes in plant and animal communities and of primary importance. They found out that single genetic effects are observed at a dose rate of 10^{-6}–10^{-4} Gy day^{-1}; steady genetic effects in coniferous species are at a dose rate of 2×10^{-5} Gy day^{-1}; steady genetic effects in most of the species are at a dose rate of 0.1 Gy day^{-1}; the decrease of plant species radiosensitivity begins at a dose rate of 10^{-2} Gy day^{-1}.

Special studies of phytocenosis are performed in gamma-fields, equipped with a source of artificial ionizing radiation (Fig. 44). The American radiobiologist A. Sparrow about 50 years ago proved that pine-trees are the most radiosensitive species among other components of forest phytocenosis, namely in the gamma-field of Brookhaven National Laboratory in USA. Similar situation was observed near Chernobyl (Red forest), where irradiation was so high that killed the trees that had to be destroyed as radioactive waste.

Obviously, the radiobiological reactions of most radiosensitive plants are the main factors causing violation of cenosis relations. In spite of the fact that dose levels that are considered to be safe for phytocenosis may differ significantly from those causing noticeable deviations of plant growing or other reactions. The comparative study of radiosensitivity of phytocenosis components is important for radiation safety. It is known that inhibiting as well as stimulating doses of ionizing radiation may cause the changes in cenosis. Thus, growth stimulation and the development of certain species of cenosis make them enable to compete for resources and in turn to provide worse conditions for other species that can fall out from the cenosis. Since changes of phytocenosis are mainly affected by prolonged irradiation, the dose rate is more important characteristic than a total received dose. The safety for phytocenosis is such a dose which does not cause any changes of its structure at any time of exposure. It is suggested that this dose rate should be slightly above the natural radiation background.

In the case of elevated natural radiation background levels (e.g. mentioned in chapter 4 areas of India, Brazil and Iran) the phytocenosis being stable to the existing dose rates were formed by natural selection during many thousands years. Transfer of such phytocenosis to the areas with normal radiation background may result in the gradual changes of cenosis structure.

Any changes in phytocenosis structure cause corresponding changes in cenosis as a whole. It influences the microbe and zoological components as well as various regulatory relationships between them. Such changes, in turn, lead to the change of biocenosis of specific region or even ecosystem.

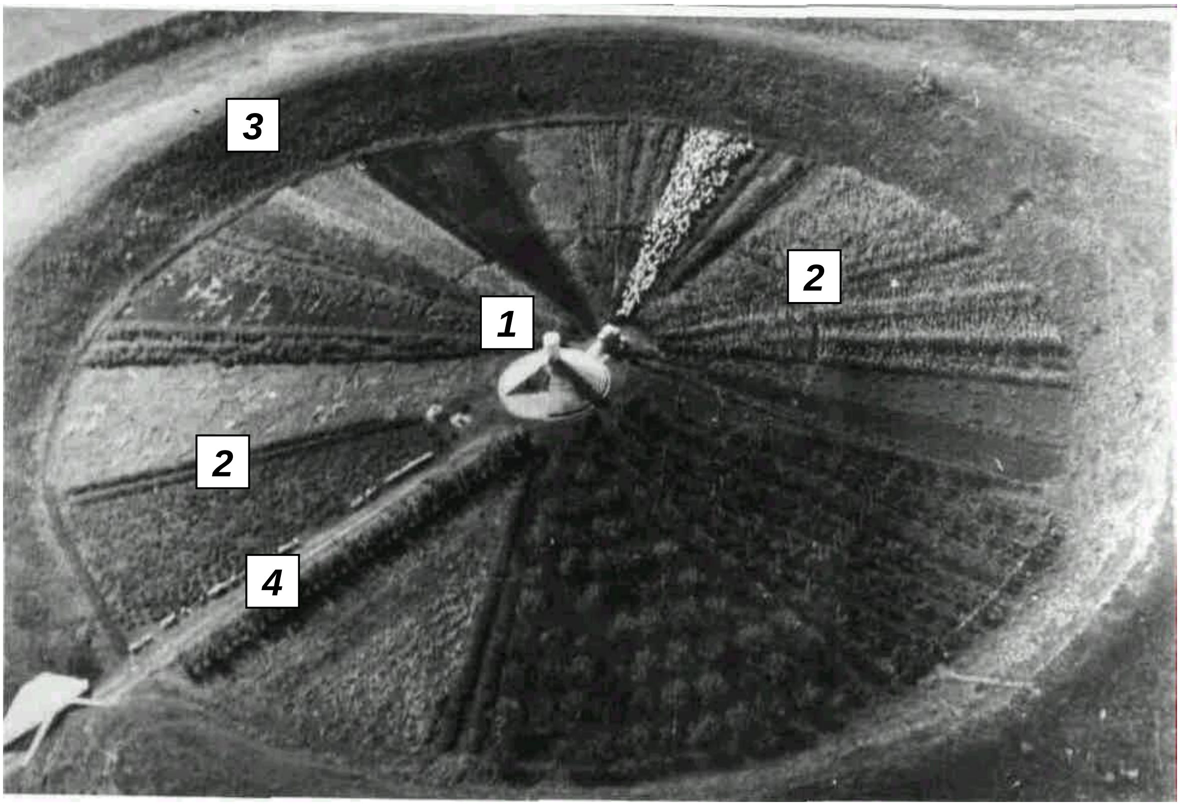

Fig. 44. General view of experimental “Gamma-field” of Moldova Agrarian University: 1 – γ-source (^{60}Co) installation, 2 – experimental field plots with plants (radius 50 m), 3 – protective earthen bank (5.6 m height) and 4 – access road.

Human activity causes the replacement of natural biocenosis by agrobiocenosis and phytocenosis by agrophytocenosis or agrocenosis. If phytocenosis historically is composed by variety of plant species, the agrocenosis created by man is very often composed by only one species or even by one cultivated sort. The radiosensitivity of such agrocenosis will be determined mainly by the radiosensitivity of cultivated crop. However, it is not always true. For example, weeds often show higher radioresistance in comparison with agricultural crops. Even insignificant inhibition of a crop growth that can be observed only in an experiment enhances the growth and the development of weeds that further inhibit cultural plant. Thus, the behavior of cultivated crops in agrocenosis and its productivity may alter with time in the case of insufficient increase of radiation background. It requires new approaches to estimate the effects of low doses radiation.

It is rather difficult to estimate the contribution of one or other factor on the biological effects, including changes in biocenosis. Or vice versa, the complete stoppage of any human activity in evacuation zone around Cehrnobyl NPP resulted in rather deep changes in phytocenosis as well as former agrocenosis during relatively short time. It is very important therefore to estimate direct influence of radiobiological effects on the succession phenomena in such conditions.

6.3. The reasons of wide variability of organism radiosensitivity

As we mentioned already, living organisms of different kingdoms, classes, families, genera, species and even sorts differ significantly in their ability to withstand radiation. So, they have different radiosensitivity. It is well known that basic metabolism processes at a cellular level such as synthesis of nucleic acids and proteins, anaerobic and aerobic glycolysis, tricarboxylic acid cycle (also called the Krebs cycle), oxidative phosphorylation and others are common not only for animals and plants, but also for bacteria. Moreover, the main components of living cells of any organism are responsible for the radiation damage (nucleic acids, proteins-enzymes, ATP) and show *in vitro* approximately the same sensitivity to ionizing radiation. Thus, the reasons of different radiosensitivity of organisms depend on the level of the organization and properties of structure comprising components, on metabolic state of cells, etc.

Physical, chemical and biological factors can modify the radiation-induced damage. All these factors can be divided into two major groups: the structural and functional factors. The structural factors are the volume of nuclei and chromosomes, the number of chromosomes and ploidy. The functional factors are the functional state of cell structures, the physiologycal state of genome, the stage of ontogenesis, the content of various natural compounds (antioxidants, macroergs, sulphydryl compounds, physiologically active substances etc.), the ability to undergo postradiation reparation and biological rhythms.

The attempts to find correlations between some of these factors and radiosensitivity for different organisms were undertaken. In spite of the fact that such attempts failed it was shown that radiosensitivity is a complex phenomenon.

The most interesting attempt to find correlation between radiosensitivity and size of nuclei and chromosomes, i.e. the structural signs which are considered to be one of the most stable genetic characteristics of the species was undertaken by a group of American researchers together with A. Sparrow. They studied plants, since it was known, that size of nuclei and chromosomes in different plant species varies by several orders of magnitude.

The correlation between the average volume of meristem cells nuclei in an interphase and a dose rate of daily irradiation to inhibit plant growth was found. Plants species having smaller nuclei size were found to be more radioresistant. However, this regularity was not confirmed as a general tendency. The possible reason was that the volume of nuclei depends largely on the physiological state of a cell and can vary by a factor of 1.5–2.

More close correlation was found between plant radiosensitivity and the volume of their chromosomes (Fig. 45).

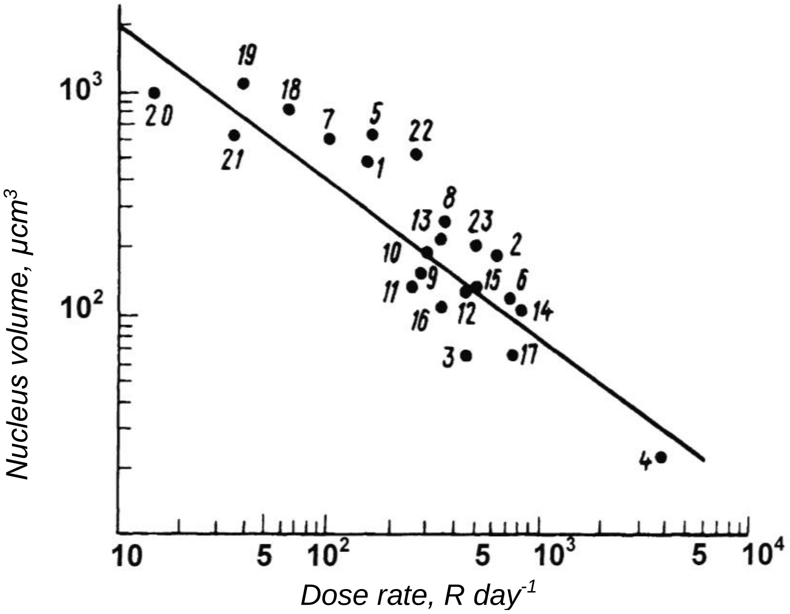

Fig. 45. Relations between the nuclei volume and a dose rate of γ-radiation, provided the same degree of growth inhibition (A. Sparrow, 1966): 1 – onion, 2 – dill, 3 – snapdragon, 4 – mouse-ear cress, 5 – brodinea, 6 – graptopetalum, 7 – havortia, 8 – sunflower, 9 – garden balsam, 10 – wood rush, 11 – tobacco, 12 – lady’s clover, 13 – pea, 14 – garden radish, 15 – castor oil plant, 16 – violet, 17 – live-forever, 18 – wandering jew, 19 – trinity trillium, 20 – trillium, 21 – thulbagia, 22 – beans, 23 – corn.

Fig. 46. Microphotographs of chromosomes of different plant species illustrating their size variation (magnification of 1850 times; A. Sparrow, 1966): 1 – trillium, 2 – devil's apple, 3 – narrow-leaf hawk's beard (*Crepis tectorum* L.) and 4 – lady's clover.

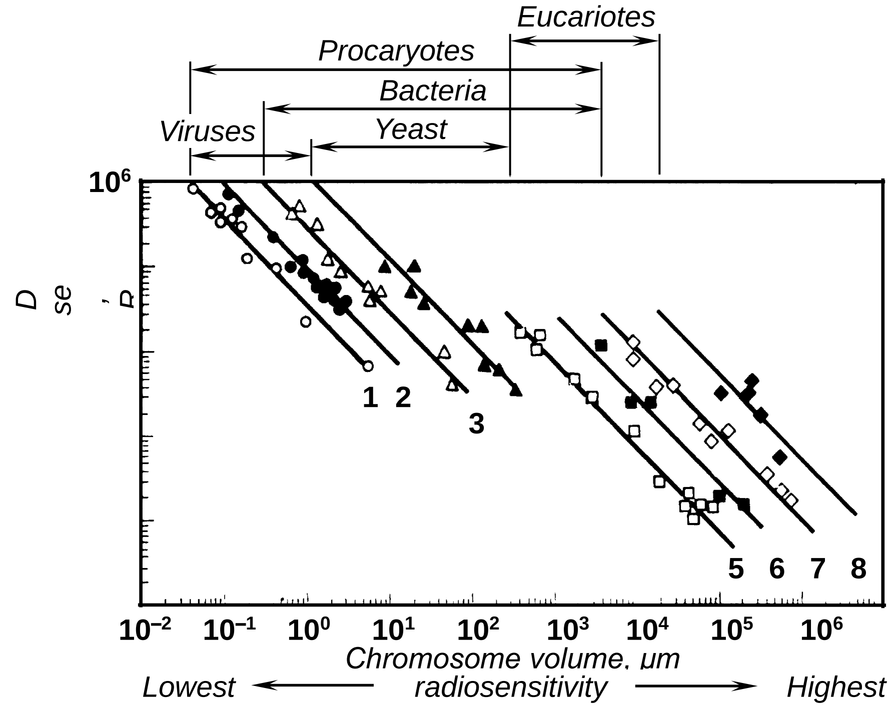

Fig. 47. Relations between chromosome size and a dose rate for 8 radiotaxones (A. Sparrow et al., 1968): 1 – RNA-viruses, 2 – DNA-viruses, 3 – DNA-viruses, 4 – viruses, 5 – yeast, bacteria, mammals, 6 – bacteria, algae, amphibian, 7 – bacteria, plants, 8 – algae, fern.

The size of chromosomes of different plant species differs by order of tens and hundreds times. For example, picture (Fig. 46) shows the large chromosomes of trillium (liliaceous family) having the greatest radiosensitivity, and only just visible chromosomes of lady's clover have high radioresistance. A. Sparrow found a rough value of chromosome volume by dividing the nuclei volume in interphase with the number of chromosomes. Obtained in such a way values were found to be in good correlation with radiosensitivity (the smaller chromosomes volume the lower radiosensitivity of plants).

Such correlation was found for higher plants only. Many other organisms were studied: some mammals, bacteria, yeast and viruses. The correlation between chromosome volume and radiosensitivity was found. By plotting the dependence curve on a logarithmic scale the curve can be transformed into a straight line. Generalizing results, obtained by A. Sparrow, divided organisms according to their radiosensitivity in certain groups named radiotaxones (Fig. 47).

There were attempts to correlate radiosensitivity of the organisms with ploidy. The data show that the damaging action of ionizing radiation decreases with the increase of a chromosome

There were attempts to correlate radiosensitivity of the organisms with ploidy. The data show that the damaging action of ionizing radiation decreases with the increase of a chromosome number in a cell (polyploidy). An increased amount of chromosomes (chromosome shoulders) is a phenomenon that is not associated with polyploidy and affects greatly radiosensitivity. Among two plant species that have the same nuclei size but different number of chromosomes, those having greater number of chromosomes, as a rule, are more radioresistant.

In spite of the fact that structural characteristics of a cell are very important for species radiosensitivity estimation, they are not sole parameters responsible for it. Early works on radiobiological effects evidenced an importance of the physiological state of cells and of entire organism. They are the functional state of genetic structures and the presence in the organism of endogenous substances that have radiomodifying affinities. Some studies indicate the correlation of radiosensitivity with the fat content (in seeds and plants) and unsaturated fatty acids, ascorbic acid, carotin, various biologically active substances, salts of some of the metals, sulphhydryl compuonds and other metabolites, including those which can provide negative effect on an organism and enhance radiation-induced damage. Radiosensitivity also depends on the ability of an organism to undergo postradiation reparation.

Thus, radiosensitivity of living organisms is determined by many factors (Fig. 48). Therefore more experimental data are required to mark out the factors that allow finding better correlation between radiosensitivity of different species and a complex of their certain biological affinities.

6.4. Comparative radiosensitivity of cells on different stages of their development

Within the cycle of nuclear division (from mitosis to mitosis) a cell passes several stages that are accompanied by different biochemical processes and changes in chromosome and nuclear substances. *The cell division cycle or life cycle of a cell is a period of time between the identical state of maternal and daughter's cells, i.e. the existence of a cell between previous and following divisions.*

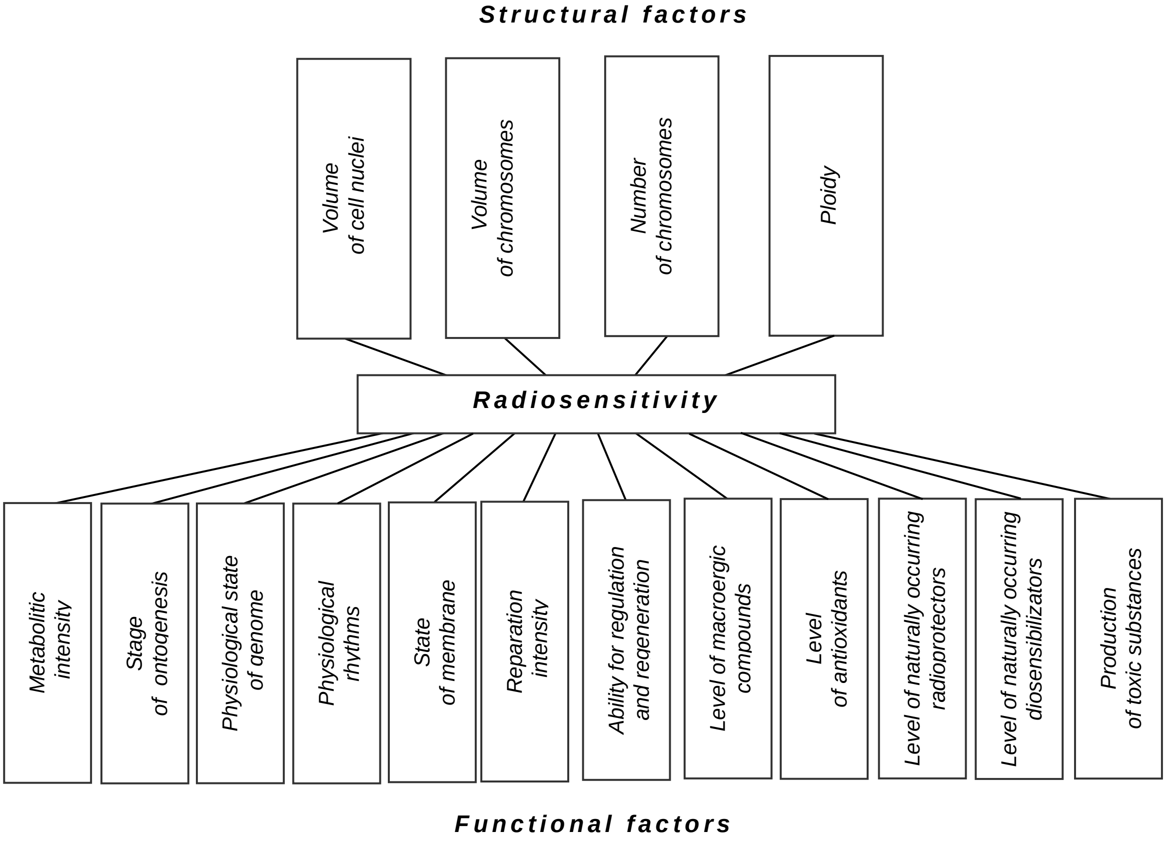

Fig. 48. Factors that determine the radiosensitivity of organisms (I. Gudkov, 2003).

Cell division cycle is divided into two phases: interphase, which is the processes of DNA precursory accumulation, DNA doubling and formation of a complex molecular apparatus, which provides mitosis; mitosis itself, when the transmission of the identical genetic information to two daughter cells occurs. The interphase comprises three successive phases: pre-synthesis phase (G_1), synthetic phase (S) (when the process of DNA synthesis occurs) and post-synthetic phase (G_2) followed by mitosis phase (M). Mitosis phase consists of prophase, metaphase, anaphase and telophase.

The phenomenon of cell division delay under irradiation estimated by reduction of mitotic cells in meristems, by propagation rate of single-celled organisms and by other signs is well known. However, later studies evidenced that cell division delay is caused by its blocking mainly on the phase of DNA preparation for synthesis. Therefore prolongation of cell division cycle under irradiation is mainly due to the cease of G_1 and G_2 phases at relative stability of M (mitosis) and S phase (Fig. 49).

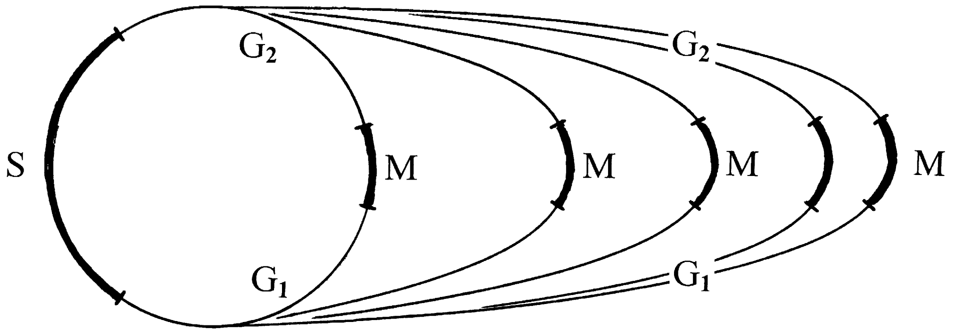

Fig. 49. Schematic view of cell division cycle prolongation at irradiation due to ceasing of G_1 and G_2 phases.

Since the character of biochemical processes greatly depends on the phase of cell division cycle the differences in cell radiosensitivity may be expected when irradiated at different phases of a cell cycle. Such studies require the cell population to be in a certain phase of a cell cycle. The cell cultures dividing more or less synchronically were obtained. They are called synchronous unlike to cells of natural origin that undergo asynchronous division.

Studies of cell radiosensitivity at different phases of a cell cycle in plants require the application of chemical methods with the aim of synchronization of cell division in meristems. Chemical synchronizers are usually mitotic toxins that block a cell division cycle at a certain phase. The most effective synchronizer for many types of cells, including plant cells, is hydroxiurea, i.e. the specific inhibitor of DNA synthesis that blocks a transfer of a cell from G_1 to S-phase. The radiosensitivity of irradiated by γ-rays plant cells passing different phases of a cell cycle can be estimated.

Fig. 50 shows the radiosensitivity of root meristem cells in pea and corn at different phases of cell division. The absolute values of semi-lethal doses differ by a factor of 2.2–2.5 and vary from 5.8 to 12.8 Gy for pea and from 13 to 28 Gy for corn. According to their radiosensitivity cells may be ranked in the following increasing order: pea – early G_1-phase, the middle S, late S, early S-phase, late G_1, M and G_2-phase; corn – the middle S-phase, late S, early G_2, early S, G_1, M and late G_2-phase.

The cells at G_2-phase and mitosis were found to be the most radiosensitive for both studied species. Mitosis is characterized by high radioresistance of cells in the beginning of a phase (prophase). Metaphase and anaphase are more radiosensitive.

Cell passage through the division cycle in constantly renewal cells population (meristem) is a complex continuous process, where the previous division determines each following one. However, such sequence of a cell cycle can be disturbed in some cases, e.g. under the action of external factors or internal regulatory mechanisms. As a result cell goes out of the division cycle and passes to the rest state – G_0-phase.

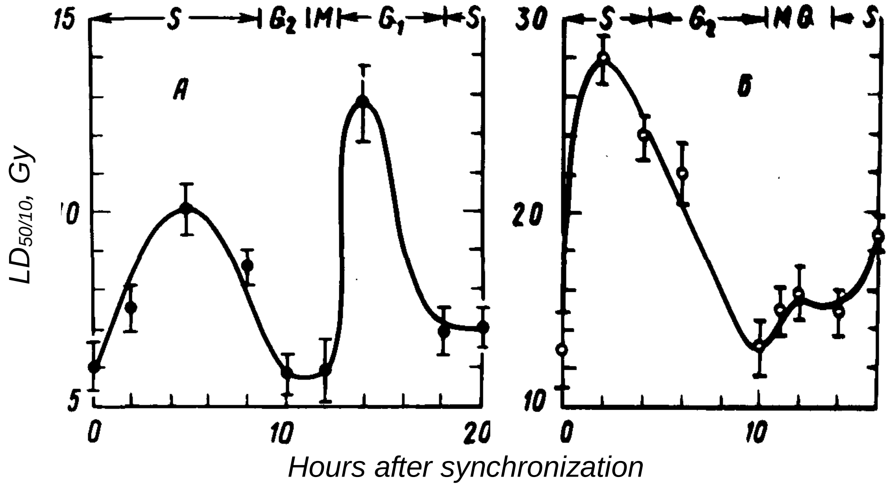

Fig. 50. Variation of root meristem cell radiosensitivity in pea (a) and corn (b) depending on a phase of cell division (I. Gudkov, 1985).

Two types of cells in a rest state are distinguished among plants: cells that are diffusely distributed within actively dividing meristem cells, and cells of tissues in a rest state. The rest cells of the second type are known to be more resistant to damaging factors in comparison with actively dividing ones. Cells in G_0-phase show higher radioresistance in comparison with actively dividing cells in any phase of the cell cycle.

Cell radiosensitivity depends on a phase and a period of a cell cycle and varies rather widely. However, due to asynchronous mode of cell division in nature any tissue at any time comprise both radiosensitive and radioresistant cells. It predetermines the stability of organs to different damaging agents including ionizing radiation. It also includes the appearance of periods when cells enter the sensible phases that make them be especially vulnerable to the damage.

Cells in a rest state having high resistance to damaging factors is assumed to be a kind of a reserve that may be used for postradiation repair.

All mentioned above, i.e. radiosensitivity of some processes and functions, concern not only plants but also animals. Similar to plants the damage of DNA molecule of animals is considered to be the main cause of radiobiological effects. Synthesis of RNA molecules and proteins as well as other metabolic processes are considered to be less radiosensitive in both organisms. Radiosensitivity of both types of organisms depends on the phase of a cell division cycle. More attention is paid to plants, because the present book is intended for students of agricultural departments.

6.5. Critical organs

Variations of cell radiosensitivity that depend on the phase of a cell division cycle concern, first of all, actively dividing cells. According to the law of Bergonie and Tribondeau cells of such tissues must be highly radiosensitive. Although, these cells are about one percent of the total mass of differentiated and specialized tissues and organs, they determine organism radiosensitivity. They are called critical organs. *Critical organs are vitally important structures, tissues and organs the radiation-induced damage of which causes significant distortions of their functions or even death.*

We’ve already mentioned that the law of Bergonie and Tribondeau generalizes the idea that actively dividing tissues are radiosensitive and non-dividing tissues are radioresistant. The liver, kidneys, muscles, brain, bones, cartilage and connective tissues of mammals are often classified as radioresistant tissues because all these tissues of adults present little- or non-active cell division and are composed of mature, specialized cells. On the contrary, the cells of bone marrow, the germinal cells of the ovary and testis, the epithelium of the intestine and the skin are all considered to be radiosensitive tissues. It must be stressed, that it is not the cell types which are either intrinsically radiosensitive or radioresistant. The process of cell division determines radiosensitivity. There is one exception: the oocytes and the small lymphocytes those are not divided, but are nevertheless radiosensitive. The reason for it is unknown.

In higher plants the meristem tissues that present high dividing activity for a long time are radiosensitive. Their radiosensitivity is tens and hundreds times higher in comparison with differentiated and specialized tissues. The radiation damage of meristem leads to the damage and radiation sickness of all plants. The death of these tissues, in turn, leads to the death of a plant. That’s why plant meristem is named the critical organs of higher plants. From this point, the radiosensitivity of plants means radiosensitivity of their meristem, which, in turn, is determined by the ability to keep constant cellular composition and to support normal propagation rates of cells irradiated by a certain dose rate of ionizing radiation.

The generative organs of mammals and other animals as well as the generative organs of higher plants are also considered to be the critical organs due to their high radiosensitivity.

6.6. Effects of low dose radiation on living organisms

At the beginning of this chapter we defined the concept of „radiosensitivity” as a respond of an organism to the minimum dose of radiation. What does the minimum dose mean? In the case of stimulant effect for pea seeds it is a dose of 3–5 Gy; it is a dose of 10 Gy for corn and tomato seeds. The stimulant dose of pea shoots is more than an order of magnitude lower in comparison with their seeds and is about of 0.35–0.5 Gy. The stimulant dose for bean shoots is about of 0.15–0.2 Gy. Thus, the concept of “low dose” that causes a certain radiobiological effect is relative and depends on organism radiosensitivity.

Experiments with animals showed that similar doses (0.01–0.3 Gy) do not cause any visible damages but activate many organism functions: increase hatchability; enhance postembryonic development and the growth of chickens. Moreover, there are data that low doses increase animal lifespan.

Indeed, it is generally acknowledged, that all living organisms on the Earth developed at the elevated natural radiation background and radiation is considered to be one of the prime movers of the evolutionary process that generated such great variety of living organisms. However, is it correct to say that so-called "low doses" that slightly exceed the natural radiation background affect living organisms positively? Facts contradict each other.

Thus, even low doses of gamma-radiation applied to seeds that provide stimulating effects on plants increase greatly the yield of chromosome aberrations in meristem cells (Fig. 51). The number of mutations in generative organs of plants must increase as well. The number of such mutations doesn't have any significance, when agricultural plants and agricultural animals are subjected to irradiation increasing their productivity. Moreover, existent system of updated seed material and pure-strain cattle practically eliminates the distribution of the induced mutants.

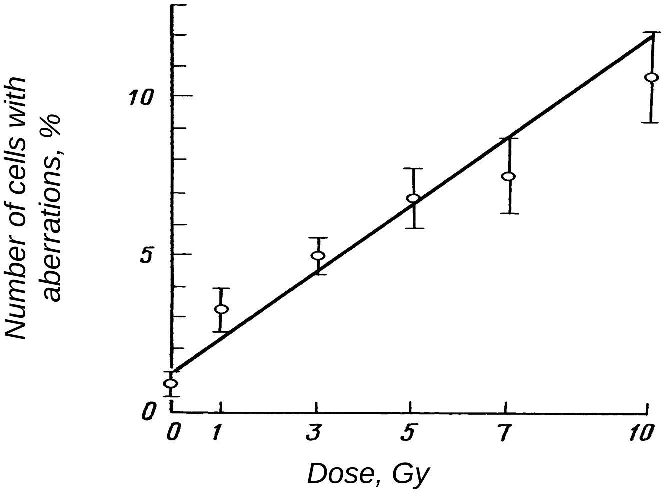

Fig. 51. Effects of γ-radiation low doses on pea seeds, including stimulating dose (3 Gy) on the yield of chromosome aberrations in the cells of root meristem.

On the contrary, mutations occurring in the germ cells may have disastrous effect on the offspring. Mutations occurring at any stage of the ovum and sperm development or of the fertilized ovum (zygote) lead to death of the progeny or at least produce seriously defective offspring. *"No threshold concept of ionizing radiation" means that there is no harmless dose, i.e. any low dose causes inherited changes.*

H. Starl (1982) suggested that the existence of "very low doses" causes the decrease of mutations yield in comparison with the initial (background) level. For mammal cells such dose is 0.02 Gy. The dose of 0.05 Gy increases the yield of chromosome aberrations in blood lymphocytes. According to the data of Ju. Mitrofanov (1987), the dose that reduces the yield of chromosome aberrations in plants of *Crepis tectorum* L. is about 0.05–0.1 Gy.

Authors suggest that "very low doses" mentioned above trigger reparation processes of DNA. It is the main argument of researches, which argue with representatives of the "no threshold" concept of ionizing radiation. The probable character of both radiation damage and postradiation repair is unlikely correspond to such point of view. However, most radiobiologists deny the existence of "very low doses".

The organisms, including plants, subjected to low as well as high doses of ionizing radiation are prone to various infection diseases. Such immunity decline is one of the possible reasons of low stimulation effect for irradiated seeds of agricultural crops before sowing.

The estimation of biological effects of low doses is important for chronic exposure application. There are regions and provinces on the Earth with high natural radiation background. However, there are no reliable data of their harmful influence on living organisms, including humans. Special experiments performed to eliminate the effect of natural background in the chambers and mines placed deeply in the earth crust showed the decrease of protozoan reproduction rate as well as the development rate of laboratory animals (larvae and insects). However, the subjection of experimental organisms to the natural radiation background level brought the growth and the development processes to the normal rate.

It means that normal growth and development of all living organisms on the Earth have to be "supported" by certain level of radiation, i.e. the natural radiation background level. Nevertheless, the experiments mentioned above are still limited. They are performed by different methodological approaches, therefore they are not perfect and difficulties arise when one tries to reproduce or to explain the results of such experiments. For this reason many radiobiologists deny the results of such studies because they do not correspond to the generally accepted concepts. However, the results of such studies cannot be ignored.

Unfortunately, there is a gap of knowledge about possible effects of elevated or reduced background level of radiation on some organism reactions, particularly on the genetic effects and the frequency of the inherited sickness. Any negative scientific experience requires careful interpretation, especially concerning humans. Some of researchers argue about harmless or even usefulness of ionizing radiation sometimes comparing it with toxins. Some of them consider ionizing radiation as innocuous or even useful, when low doses are applied. However, the majority of radiobiologists agree that we have too little evidences to take an enormous responsibility before the humanity to give any recommendation concerning absolute harmless levels of ionizing radiation.

Therefore, so called "concept of biological risk of ionizing radiation effects", which is based on the approaches concerning the estimation of risks of ionizing radiation effects is adopted in radiobiology. When possible effects of ionizing radiation are estimated not only the risk but also the biological significance of radiation-induced damage accounting for the probability of damage caused by other factors are to be taken into consideration. The problem might be solved by the estimation of proper correlation of known danger of a certain factor effect and advantages of its use.

People and their health are subjected to everyday risk. The probability of such risk, as a rule, increases with the development of human civilization. Most of the risks are related to traffic accidents, fires, various toxines, e.g. CO, toxic evaporations, pesticides and other chemical substances. Though, there is a probability to die from cancer, cardiovascular sickness, vascular injury of the central nervous system that are also connected with the scientific and technical progress.

Thus, about 4 thousands of people sink in water every year in Ukraine, it accounts for 78 cases per 1 million of population per year. Approximately the same number of people dies in fire. Traffic accidents take 9000 of people, which account 176 cases per 1 million per year. Even the number of traffic accidents is higher in Australia (220) and in Germany (233). However, any country does not raise a question to close the beaches or reduce freightage.

Spontaneous frequency of malignant tumours in the different regions of the world equals 1000–2000 morbid events per 1 million of population per year. A half of those people finally die. Unfortunately, 70000-80000 people per 1 million of population die every year in Ukraine due to malignant tumours.

The frequency of the haemopoiesis system sickness (leukemia), which is one of the characteristic radiation-induced diseases caused by a dose of 0.01 Gy, equals 1–2 cases per year. "Ordinary" frequency of this sickness is 50 cases per 1 million of population per year. The total risk of all types of tumour at this dose equals 3–6 cases per year. If natural radiation background is elevated by a factor 20–50, the dose rate of 0.01 Gy per year can be achievable. The first months after the accident on Chernobyl NPP similar radiation background existed in some regions of Ukraine and Byelorussia. At present, such dose rates exist only in some places of restricted area around Chernobyl.

All mentioned above gives some ideas about the importance and complexity of the problem of low doses effects. It requires special attention.

Thus, the problem of radiosensitivity of an organism is the main in a radiobiology. It is important from the academic point of view to get more information about radiosensitivity of organisms belonging to the different systematic groups. Understanding of the phenomenon of high radiosensitivity of some species is a key to solve the main problem of radiobiology, i.e. to control radiobiological reactions by means of their modification and, first of all, the ways of radiation protection and postradiation rehabilitation. These questions, results and achievements will be examined in the next chapter.

Control points to chapter 6:

1. Differences between the concepts of radiosensitivity and radioresistance.
2. The concept of effective dose. The semi-lethal and lethal doses of ionizing radiation.
3. The most radiosensitive and the most radioresistant types of plants.
4. Radiosensitivity of m ain agricultural crops.
5. Comparative radiosensitivity of seeds and vegetative plants.
6. Comparative radiosensitivity of different types of animals.
7. Specific action of ionizing radiation on phytocenosis.
8. The reasons of wide variability of radiosensitivity of species.
9. Comparative radiosensitivity of metabolic processes.
10. Effects of ionizing radiation on nucleic acids.
11. Comparative radiosensitivity of cells on different phases of cell division cycle.
12. Critical organs of plants and animals.
13. The effects of low doses of ionizing radiation on living organisms.
14. “No threshold” and “threshold” concepts of ionizing radiation: two points of view in radiobiology.
15. The essence of the conception of biological action risk of ionizing radiation.

7. MODIFICATIONS OF RADIATION DAMAGES OF AN ORGANISM

As was mentioned in chapter 1 *the main task of radiobiology is the study of interaction of ionizing radiation and living matter in order to be able to control the radiation-induced reactions of the organism and to investigate the possibilities of radiation modifications*.

The modification of radiation damage is the degree alteration of radiobiological effect by means of physical, chemical and biological factors that can modify the amount of radiation-induced damage. Radioprotective and radiosensibilizing agents, applied before or during the irradiation, are called prophylaxis. Such agents influence postradiation recovery of an organism.

The restoration at the molecular level (that is the restoration of the original structure and functions of radiation-damaged intracellular formations) is termed repair. The restoration of the cellular structure of organs and tissues by reproduction and dissemination of cells (repopulation) is called regeneration.

7.1. Biological radiation protection and sensibilization

Biological radiation protection is considered to be a mitigation of the ionizing radiation action on an organism in the result of physical or chemical agent application before or during the irradiation.

Radiosensibilization (radiosensitization, radiosensibility) is an intensified ionizing radiation action by means of physical or chemical agents.

7.1.1. Physical radioprotective and radiosensitizing agents

There are several physical factors that determine the state of an organism during irradiation. Among them are gas-environment, temperature and humidity.

Gas-environment. Alteration of the gas-environment influences an organism radiosensibility. In 1921–23 German physiologists E. Petry found out that irradiation of wheat shoots enriched by CO_2 environment increases its radioresistance. English scientists C. Henshaw, D. Francis and D. Mottram showed in the experiments with plants that radiation-induced damage may be mitigated by any inert gas, replacing oxygen. This phenomenon, called “oxygen effect”, is known as the famous discovery in radiobiology.

First studies of oxygen effect were performed by English radiobiologist L. Gray in 1930. The unit of absorbed dose is named after him. In the experiment with horse beans it was shown that maximum oxygen effect is achieved in the atmosphere at oxygen concentration about 20% (the content of oxygen near earth surface is about 20.9%). Later, such results were confirmed by other studies performed with various objects (Fig. 52).

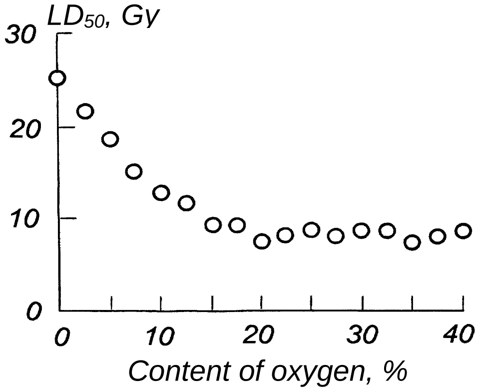

Fig. 52. A half-lethal dose of γ-radiation for pea seedlings depending on the oxygen content in the environment.

There are two definitions of oxygen effect. The first definition characterizes oxygen effect as an enhancement of radiation-induced damage at higher concentration of oxygen in the environment in comparison with irradiation in anaerobic environment. The second definition of oxygen effect is the mitigation of radiation-induced damage of an organism at decreased concentration of oxygen in the environment. Both definitions do not contradict each other but consider the same phenomenon from different points of view.

Oxygen effect is universal and one of the most fundamental phenomena in radiobiology, since it reveals almost all biological systems so far tested. Oxygen modifies the quantitative amount of radiation damage, but does not alter its quality; it merely reduces the dose of radiation required to give a certain radiobiological effect.

The oxygen sensitization is considered to occur via a fixation process, i.e. oxygen combines with free radicals formed in the target molecule producing peroxy–radicals such as $O^{\bullet}$, $OH^{\bullet}$, $HO_2^{\bullet}$ and H_2O_2. An alternative hypothesis (electron transfer model) suggests that the radiosensibilizing properties of oxygen and other radiosensibilizers are related to their electron-affinity properties. Electron-affinity agents, including oxygen, may react with free electrons that are produced due to direct actions of ionizing radiation on molecules (see chapter 4). Such electron-affinity agents prevent recombination, thus, allow more damage to occur. Recent developments of rapid mixing of oxygen with cell suspensions showed that not merely the partial pressure of oxygen in the environment but the oxygen tension inside the cells or tissues under irradiation alter their radiosensitivity. Thus, when intracellular oxygen concentration is approximately equal to the extracellular oxygen concentration, the equilibrium is reached. The range of oxygen tensions of most vascular tissues in mammals lies between 40 to 70 mm Hg, so the tissues *in vivo* are maximally sensitive to radiation as far as the oxygen effect is concerned. It means that they are two and three times more sensitive in comparison with the tissues without oxygen. The factor 2–3 is known as the oxygen enhancement ratio (OER).

Oxygen enhancement ratio is used to estimate oxygen effect that is defined as a ratio between effective dose (usually LD_{50}*) applied to hypoxia and a dose providing similar effect when irradiation occurs in the air.*

To estimate effectiveness of radiation protective and radiosensibilizing agents the *factor of a dose change (FDC)* is sometimes used. FDC *is defined as a ratio between effective dose with modifying agent and a dose providing similar effect without modifying agent (control).*

FDC (dose–effect curve) is illustrated in the Fig. 53. The method of dose–effect curve is described in previous chapter. Thus, FDC of any physical or chemical agents may be found for experimental and control curve by using LD_{50}.

FDC for radiation protective and radiosensibilizing agents is > 1 and < 1 respectively.

Practically, oxygen effect cannot be observed in dry systems (seeds, spores, pollen). However, if a seed is in an active state (*e.g.* germination), oxygen effect increases and reaches the maximum in actively metabolizing shoots and plants that are supplied by water.

The discovery of oxygen effect about modifications of radiation-induced damage was revolutionary and opened possibilities to control the radiation-induced reactions.

Humidity. Oxygen effect as well as radiobiological reactions depends on the humidity of biological system. There are many studies, indicating the influence of humidity on radiosensitivity first of all plants and seeds. It has been shown that the highest radioresistance is related to the conditions, when the water content in seeds is a little bit higher than in air-dry seeds. Higher as well as lower water content results in the decrease of radioresistance (Fig. 54).

Such complicated dependence is explained by Swedish radiochemist L. Ehrenberg. He suggests that a certain dose produces the same amount of free radicals at any level of the seed humidity. At humidity of 3–5% free radicals do not show recombination for long time, *e.g.* some months. Higher humidity promotes increasing the amount of free radicals with time as well. The increase of humidity mitigates the damage, while biological damage is directly related to the concentration of free radicals.

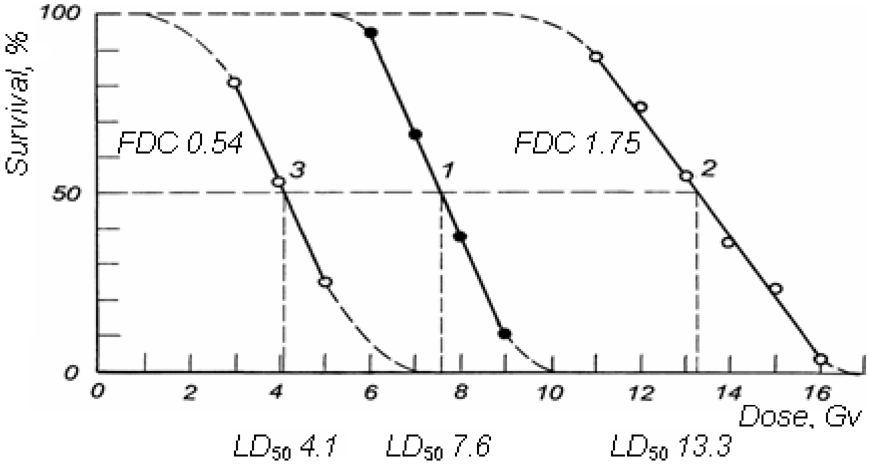

Fig. 53. The determination of FDC for radioprotective (2) and radiosensitizing agents (3); 1 – control.

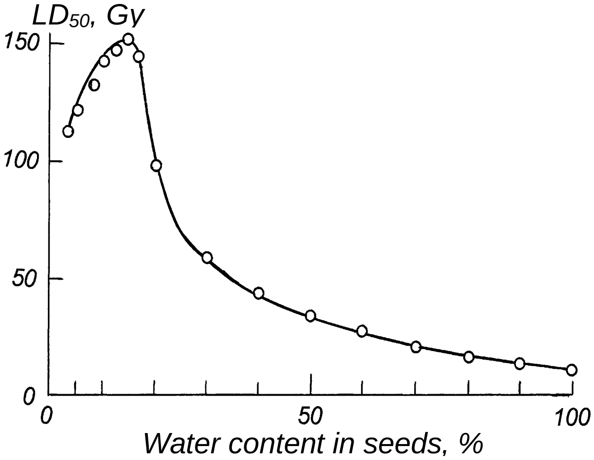

Fig. 54. Radiosensitivity of pea seeds and their humidity (experiments performed at 1–2°C to avoid an effect of physiological processes).

Irradiation of seeds at 15% humidity is accompanied by reactions connected with the alteration of their physiological state with the following germination. Such reactions lead to the increase of radiosensitivity.

The role of humidity in radiosensitivity of vegetative plants is ill-investigated. However, it is assumed that the formation of some tissue xeromorphy that leads to the loss of water and the decrease of metabolic activity increases radioresistance.

Temperature. There are many experimental data about an effect of temperature on plant radioresistance. Such data also concern mainly seeds since their physiological state allows evaluating a wide range of temperatures without essential distortions of their functions. It is found out that low temperatures at the moment of irradiation, *e.g.* the temperature of dry ice (–78°C) or liquid nitrogen (–190°C), result in considerable radiation protection effect. It is considered that the protection action of low temperatures occurs via unfavourable conditions for the transfer of energy and its absorption by matter. The mobility of free radicals and their interaction with matter becomes complicated at low temperatures.

It is also known that high temperatures (35–80°C) at the moment of irradiation mitigate radiation damages and decrease oxygen solubility (the mitigation of oxygen effect).

Temperature also influences radiosensitivity of vegetative plants. The radiation protective effect is observed at low temperatures of 5–10°C. When high temperature is about 30 °C or higher, as a rule, radiosensitivity of plants enhances.

Irradiation by non-ionizing types of radiation. Irradiation of an organism by non-ionizing radiation before irradiation by ionizing radiation may directly influence radiosensitivity of an organism by inducing regeneration processes in cells or influence indirectly, affecting the intensity of metabolic processes.

It is known that the previous irradiation of plants, animal cells culture by ultra-violet radiation mitigates damaging effects of γ-radiation. It is proved that such irradiation induces reparation processes in irradiated cells that lead to the increase of radioresistance. However, in some cases, the previous irradiation by ultra-violet rays may result in more damage, which is determined by a dose, wave length, time interval between the previous and the main irradiation as well as other factors. There is not enough information about the effectiveness of infrared rays. Previous irradiation by infrared rays with wave length 750–1900 μm with maximum 1 000 μm may cause a cell division delay in the meristem of shoots and increase their resistance to the following irradiation by ionizing radiation.

Plant radiosensitivity may be changed by their previous illumination or growing under different ray regimes. Depending on the intensity and the spectral composition of visible ray, many reduced compounds such as free aminoacids may occur in plant cells during photosynthesis that promotes higher radioresistance.

Growing interest to the action of magnetic and electric fields as well as microwaves on living organisms made scientists pay attention to the joint action of ionizing radiation and mentioned above types of non-ionizing radiation on biological objects. There are data showing that previous or joint treatment of seeds and shoots by the magnetic field and γ-radiation leads to the mitigation of γ-radiation damage.

Possible reasons of radiation protection action of these factors might be the following: the alteration of the state and the permeability of cell membranes under the influence of magnetic and electric fields and microwaves; the redistribution of anions and cations between different tissues and even the production of radioresistant complex compounds as a result of binding of proteins with magnetic sensible microelements, etc. Unfortunately, all of them are not well understood and have to be considered as hypotheses.

Generally, it has to be emphasized that mentioned above possibilities of radiation modification by using various physical factors provide the basis for solving the problem to control radiobiological reactions. They are still far from the final decision, especially concerning the radiation protection for humans. Though this problem was not formulated correctly till 1945 in scientific and social aspects, it became the problem number one in the radiobiology after tragic events in Japan (August 1945), when many people died after the radiation exposure. It is the task for nowadays science to produce such substances that will be able to protect an organism against ionizing radiation.

7.1.2. Chemical radioprotective and radiosensitizing agents

In 1949 radiobilogists Z. Bacq and A. Herve (Belgium) and H. Patt with his colleagues (USA) practically simultaneously announced about two chemical compounds injected in laboratory animals before γ-irradiation. Experimental group of animals showed higher ability to survive in comparison with the control group of animals. The first compound was a strong poison – cyanic sodium, 5 mg kg^{-1}injection of which was made to mice before irradiation. It decreased the degree of radiation damage. The second compound was aminoacid cysteine, 1 000 mg kg^{-1} injection of which increased the survival of mice at a lethal dose of irradiation.

Two years later Z. Bacq with his colleagues found out that decarboxyled cysteine named cysteamine and its disulphide cystamine have much more expressed ability to mitigate radiation damage as in the case of injection as well as in the case of entering animal body with food. When mice were injected (in comparison to cysteine) by 150 mg kg^{-1} of cysteamine, FDC was 1.8–2 (for cyanic sodium and cysteine FDC does not exceed 1.4). It means that the application of cysteamine before irradiation allows increasing the dose rate by factor 2 and shows the same result as it is without using cysteamine.

Later, effectiveness of all three mentioned above compounds and their analogues were confirmed in the experiments with animals, plants, insects and microorganisms, i.e. the universality of its radioprotective affinities were demonstrated.

Thus, the doctrine of biological radiation protection and radiation protective agents, i.e. radioprotectors, arose in the beginning of 1950s. *Radioprotectors are substances the application of which before of irradiation or under irradiation, reduce the effectiveness of radiation.* Ideal radioprotector has to meet the following criteria: high radiation protection effectiveness, which is the main trait; to be stable, i.e. to keep its protective affinities for a certain period of time; do not show the toxicity penetrating an organism.

7.1.3. Classification of radioprotective agents and mechanisms of their action

There are two major types of radioprotective agents. The first type is general action compounds able to show radiation protective affinities when any living organisms are irradiated. The mechanism of radioprotection is that mentioned compounds intrude into a way of radiation damage at the initial stages of its development. They are called true radioprotectors.

Others are agents that provide unspecific effects on the organism systems by increasing radioresistance against radiation and not only against it. But it often gets other factors. Normally, such radioprotectors are only effective for a certain systematic group of living organisms (animals or plants).

Sulphhydryl compounds. Sulphhydryl compounds belong to the first group of protective agents. The sulphhydryl compound group includes mentioned above sulphur–containing cysteine, cysteamine as well as S-

(aminoethyl) isothiuronium bromide hydrobromide (AET), glutathione (GSH), cytaphos, thiourea, and other compounds. The sulphhydryl compounds are considered to be the most effective group of radioprotectors.

Table 22 shows the most effective radioprotective agents for mammals, and Table 23 shows such agents for plants. Thus, using chemical radioprotective agents reduces the effectiveness of ionizing radiation by a FDC from 1.5 to 2.0.

However, it should be emphasized that only some radioprotective agents showed in these tables reduce the effectiveness of radiation by a factor >1.5. The majority of listed above compounds have the reduction factors varying from 1.2 to 1.4.

The protective action of sulphhydryl compounds as well as other radioprotective agents in plants is observed, when such compounds are added to the growing medium, when plants are in the solution contained protective agents some hours earlier before irradiation, when plants are sprayed by the solution with protective agents.

There are many theories that try to explain the molecular mechanism of radioprotection of sulphhydryl compounds. However, the most acceptable hypothesis that explains the mechanism of radioprotection is that H atoms are transferred from the sulphhydryl compounds (M–SH) to the biological free radical ($R^\bullet$). The $R^\bullet$ is repaired and converted to RH:

$$\text{M–SH} + \text{R}^\bullet \rightarrow \text{RH} + \text{MS}^\bullet \text{ (repair).}$$

Table 22. The most effective radioprotective agents for mammals at acute X- or γ-irradiation

Radioprotector	Animal	Protective dose, mg kg^{-1}; mode of entering	FDC
Cysteamine	mouse, monkey	75–250 ^{1}	1.8–2.0
		200–500 ^{2}	1.6–1.8
	rat, cat	50–100 ^{3}	1.5–1.7
	dog	75–100 ^{4}	1.7–2.0
Aminoethylisothiuronium (AET)	mouse, monkey	250–480 ^{1}	1.8–2.0
	rat	1500 ^{2}	1.6–1.8
Cysteine	mouse	950–1200 ^{1}	1.4–1.6
	sheep	1000–1500 ^{3}	1.4–1.6
Serotonin	rabbit	95 ^{1}	1.5–1.8
Histamine	rat	100 ^{1}	1.4–1.5
Cyanic potassium	mouse	0.1–0.2 ^{1}	1.3–1.5
Cystamine	rabbit	200–400 ^{1}	1.4–1.5

Cytaphos	sheep, monkey	100 [1]	1.6–1.8
Sodium dithiocarbomate	cat	500–600 [1]	1.4–1.6
Selenium	rat, mouse	4.3–4.6 [1]	1.4–1.5
WR 638[5]	mouse	200–500 [1]	1.4–2.2
WR 2721[5]	mouse, monkey	300–500 [1]	1.5–2.5

[1] intraperitoneal, [2] oral, [3] underskin, [4] intravenous,

[5] aminophosphorusthioates – complex compounds that are still under study.

In 1964 Z. Bacq and P. Alexander together with colleagues suggested a quite original theory of radioprotection mechanism of sulphhydryl compounds called “biochemical shock” or “metabolic protection”. The essence of this theory lies in deep biochemical alterations of an organism at protective concentrations of sulphhydryl compounds followed by changes of normal metabolic activity. Such distortions reveal through the inhibition of DNA, RNA, proteins and carbohydrates syntheses, disconnection of oxidative phosphorylation, the inhibition of anaerobic and aerobic glycolysis. Such temporal “shock” followed by breaking of metabolism and morphological changes are the main causes of radiation protection.

Some radiobiologists suggest similar mechanism when other radioprotectors are used, since reactions peculiar to “biochemical shock” may be caused by many radioprotective agents entering an organism.

Other antioxidizers. Sulphhydryl compounds as well as many other chemical compounds showing reduction affinities are effective radioprotectors. American radiobiologist H. Riley showed that plants being contained in 4×10^{-4} – 4×10^{-3} *M* solution of hyposulphite, metabisulphite, sodium sulphhydrate (30–min) decreases the radiation damage to 27–55%.

Ascorbic acid (vitamin C) has the property of a radioprotective agent. It is shown that shoots growth inhibition decreases from 50 to 20%, when seeds are soaked in 0.06–1 *M* solution of ascorbic acid before the γ- and neutron irradiation for 1 hour.

Table 23. Effectiveness of some radioprotective agents for plants at acute X- or γ-irradiation

Radioprotector	Protective dose, *M*	FDC		
		Bean	Pea	Maize
Cysteamine	10^{-3}	1.5–2.0	1.4–2.2	1.4
AET	5×10^{-4}	1.5–2.1	1.4–2.0	1.4
Cysteine	10^{-3}	1.4–1.8	1.4–1.8	1.4-1.5
Sodium metabisulphite	2×10^{-2}	1.3	1.2	–
Ascorbic acid	3×10^{-2}	–	1.4	–

Ethyl alcohol	1	1.2–1.3	–	–
Iron chloride	2×10^{-4}	1.5	1.3–1.7	1.3
Manganese chloride	2×10^{-4}	1.5	1.2–1.5	1.4
Zinc chloride	2×10^{-4}	1.7	1.3–1.7	–
Cobalt chloride	2×10^{-4}	1.4	1.4	–
Hydroxyurea	10^{-3}	–	1.4	1.3
Chloramphenicol	2×10^{-4}	–	1.3	–
Hydroxyl amine	10^{-3}	–	1.2–1.5	–
Sodium azide	10^{-4}	–	1.3	–
DNA hydrolyzate	2×10^{-4}	–	1.3	–
Abscisic acid	2×10^{-5}	–	1.4	–
Ethylene	3×10^{-3}	–	2.0	–
Adenosyntriphosphate	10^{-4}	–	1.5	–
Cyclic adenosynmonophosphate	10^{-3}	–	1.5–1.7	–

The antioxidizing affinities of spirits are well known. Soaking of bean shoots for 10 min before or after γ-irradiation in 1.6 *M* solution of methyl spirit, 0.2 *M* solution of propil spirit or 0.7 *M* solution of ethylic spirit mitigates radiation-induced growth inhibition by FDC 1.5.

The ethylic spirit is an effective radiation protective agent for animals. However, radiation protective effect of spirits is often overestimated. According to many studies only relatively low radioprotective effect of ethylic spirit (FDC – 1.2) may be reached at the concentration of 10–15 ml of 25–40% alcohol per kg body mass.

Mentioned above substances together with sulphhydryl compounds belong to radioprotective agents having a universal action, however, their radioprotective effectiveness is relatively low and does not exceed 1.4. But they are more stable and less toxic, in comparison with, for example, cysteamine.

Ions of metals. According to many studies some salts of metals show radiation protective affinities. Soaking of seeds or shoots in 0.05–4 *M* salt solution of sodium, calcium, magnesium or potassium decreases radiation-induced damage of X-rays or γ-radiation. Higher effect is observed in solution of salts of metals belonging to heavy metals. Soaking of seeds, germination of shoots being contained in 10^{-5}–10^{-3} *M* salt solution of iron, zinc, manganese, cobalt, nickel and even cadmium during a short period of time, spraying vegetative plants by solution containing these metals decrease radiation-induced damage by FDC 1.3–1.7 (Fig. 55). Some of the metals increase radioresistance of animals when entered a body.

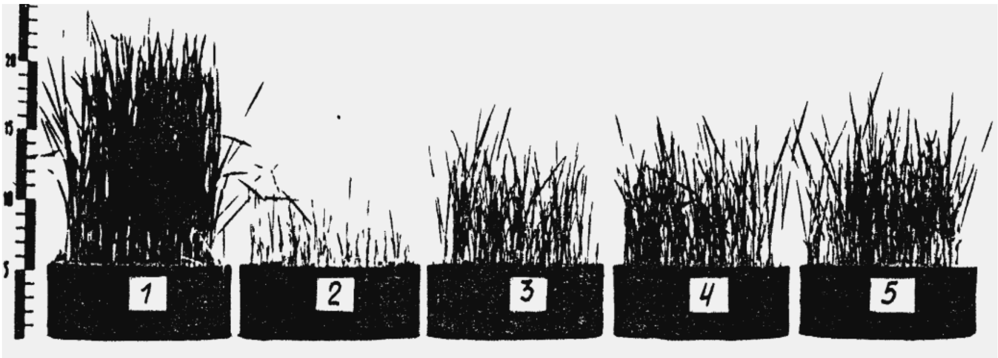

Fig. 55. Radioprotective action of metals. The wheat seeds were soaked for 18 hours in 10^{-3} M solution of metal salts before γ-irradiation: 1 – control, 2 – irradiation at a dose of 300 Gy, 3 – seeds soaked in solution of manganese chloride before irradiation, 4 – seeds soaked in solution of zinc chloride, 5 – seeds soaked in solution of ferrum chloride.

There are many preparations that are made on the basis of mentioned above metals. As a rule, they are rather complex chemical compounds having one or more metals. Radioprotectors that include cobalt cobamide, cobadex, cobaline and others that include nickel (nickavite and nickamidon) are known. Some radioprotectors include iron, zinc, manganese, selenium and complexes with two or three metals.

Mentioned above radioprotective agents are considered to be rather effective, but many of them belong to heavy metals and are toxic. Although radioprotectors, as a rule are used in low amounts, their toxicity has to be taken into account. It is also known that salts of metals and their solutions are stable and may keep their chemical properties for a long time.

Since many listed metals are essential for living matter, several mechanisms may be involved in its radiation protection process. One of the hypotheses to explain the mechanism of radioprotection is connected with enzymes containing metals such as iron, zinc, manganese and others.

G. Eichhorn proposed quite fruitful hypothesis according to which the radioprotective effect of metals occurs due to the stabilization of hydrogen bounds in some cells of biopolymers under the effect of positively charged ions of metals. As a result some sections of DNA and proteins including enzymes are able to withstand radiation-induced break of sensitive hydrogen bounds promoting regeneration of their secondary structure.

Growth–regulating substances and hormones. Growth–regulating substances such as phytohormones, auxins, gibberellins, cytokinins, abscisic acid, ethylene and some other substances, being entered an organism in concentrations that induce growth-regulation (growth–promotion or growth–

inhibition) or in higher concentrations, may mitigate radiation-induced damage. The mechanism of growth-regulating substances action is rather simple. As we mentioned above (see chapter 5) radiation damage in plants may be observed through growth inhibition caused by distortion of balance between growth–promotion and growth–inhibition. Entering the plants growth–regulating substances are able to restore mentioned above balance, mitigating effectiveness of radiation. Radioprotective action of phytohormones-inhibitors (such as abscisic acid and ethylene) is achieved through the blockage of cell division and the induction of the plant state similar to resting.

Phytohormones as well as other growth–promoting substances are effective radiation protectors only for plants.

Hormones of animal origin show radiation protection affinities for mammals. The most effective hormones are biogenous amines (such as serotonin, tryptamine, histamine, rhezepin), some steroid (sexual) hormones androgens and esterogenes, hormones of adrenal gland (adrenaline and noradrenaline), hormones of pancreas insulin, hormone of thyroid gland thyroxin.

Mentioned above biologically active substances reduce the effectiveness of radiation by a FDC from 1.3 to 1.4. However, effectiveness of some of phytohormones, *e.g.* ethylene, is higher and they are more or less stable and less toxic.

Metabolism inhibitors. This group of radioprotectors includes variety of biosynthesis inhibitors that break consequence chain of various substances transformation and induce *e.g.* blockage of cell division or cause another changes providing conditions close to “biochemical shock”. Biosynthetic inhibiting substances may act as radiation protective agents when entered a plant or an animal organism in concentrations inversely inhibiting functions of metabolism systems. Such affinities are shown by inhibitors of DNA synthesis (hydroxyurea), inhibitors of protein synthesis (hydroxylamine, chloramphenicol), inhibitor of respiration (sodium azide, amital), etc. Usually, metabolism inhibitors inhibit synthesis and activity of the enzymes, responsible for the processes on biochemical level. Therefore such radioprotective agents are nonspecific for plants and animals and have to be considered as those having universal action protectors. Some of them are rather effective and may reduce the effectiveness of radiation damage by factor 1.5, being relatively stable and toxic.

Natural metabolites. Most effective radioprotectors are considered to be more or less toxic for all living organisms. Moreover, many of them being in toxic concentrations show radioprotective effect, i.e. their radioprotective affinities are caused by their toxicity. For this reason, scientists find it natural for organism metabolites to be used as radioprotectors. Among them (apart of hormones marked here as a separate group) are nucleic acids, amino acids, carbohydrates, enzymes, co-factors and vitamins.

It is shown that preparations of DNA have radiation protective affinities. Independently of their origin the entering of exogenous DNA in plants reduces the effectiveness of radiation. Radiation protective affinities are not shown only by native double helix DNA but also by their hydrolyzates as well as some nucleotides of DNA and RNA. Moreover, such preparations show the effectiveness of modifying agents not only for low LET γ- and X-radiation but also for high LET radiation (such as fast neutrons), where many radioprotectors are not effective at all.

Nucleotide ATP (adenosine triphosphate) that is a carrier and the main accumulator of chemical energy in living cells and cyclic nucleotide AMP (adenosine monophosphate), which is the universal regulator of metabolism inside the cell, have high effectiveness to reduce radiation-induced damage. It is suggested that radiation protection action of hexose sugars used as a substrate for respiration and of some other carbohydrates entered exogenously is stipulated by means of ATP synthesis.

The possibility to use vitamins for radiation protection and treatment of radiation disease of a man are of great interest among radiobiologist. For example, the vitamins–antioxidants such as C, A, E, U, B_1 as well as B_6, B_{12}, P, K and their combinations clearly show the radiation protective effect.

Mentioned above substances belong to radiation protective agents of universal action which are effective for irradiated plants and animals. They have a moderate radiation protective effectiveness, rather stable with relatively low toxicity even at high concentrations, and are suitable for multiple, almost regular use. Due to the listed above affinities, especially the last one some of them are considered to be radiation protective agents in future.

Essential elements. By providing an organism with essential nutrients and affecting the size and intensity of metabolic processes, synthesis and accumulation of some substances, certain so called endogenous background of radioresistance are formed. The background formed by a great number of various organic and inorganic substances makes difficult to explain the decrease or increase of plants radiosensibility when one or another essential element is added. Nutrient elements are likely to affect the repair processes in postradiation period. Many studies indicate that effectiveness of radiation depends upon nutrients supply of plants and animals before and after the irradiation.

So, the application of optimal doses of phosphorus, potassium and magnesium fertilizers to soil reduces the effectiveness of γ- and β-radiation on plants as well as the increase of seeds radioresistance. Fertile soils increase the survival of γ–irradiated plants. Rich in protein forage increases animal radioresistance.

There are other known radiation protective agents: cyanides, nitriles, oxidants, antimutagens, various complex compounds etc. (see Tables 22 and 23).

It is worth underlining that in practice of radiation protection usually not one but a mixture of radioprotectors are used to combine their positive affinities: high effectiveness, *e.g.* sulphydryl compounds; low toxicity, *e.g.* natural metabolites; stability, *e.g.* salts of metals. Such combinations allow reducing the effectiveness of radiation at low concentrations of radioprotectors and decreasing their negative effect on an organism. The action of mentioned above protective agents WR-638 and WR-2721 (Table 22) is based on such principles.

However, effects of radioprotectors, their FDC for plants and for animals listed in the Tables above are relevant to single acute γ-, β- or X-irradiation. Nowadays, in post–Chernobyl period it is important to find the radioprotectors of prolonged action, which could be effective in the case of chronic exposure.

7.1.4. Radioprotective agents with prolonged action

Obviously, at chronic irradiation only those radioprotective agents are effective that have prolonged action, *i.e.* stable ones.

Rather high stability is an affinity of metal salts. However, they are considered to be stable only in comparison with mentioned above unstable compounds. Many metals undergo oxidation and are involved in metabolism with following excretion from an organism. It requires additional entering of radioprotectors. The last may be toxic for an organism.

Relatively effective radiation protective agents of prolonged action are radioprotectors of natural metabolites and nutrition elements. The use of complex preparations (hormones, vitamins and other biologically active compounds as well as such macro- and micro-elements as calcium, potassium, iron, zinc, cobalt, manganese, copper) promotes the stabilization of hormonal and immune state of an organism, enhances its unspecific resistance to various unfavourable factors, including ionizing radiation. Generally, this problem is not well studied yet.

7.1.5. Radioblockators and radiodecorporants

Nowadays many people live on the territories contaminated by radionuclides. About 90–95% of the received dose is due to the internal irradiation. To minimize the uptake of radionuclides with food and water into an organism is the only way to reduce the dose obtained. It may be achieved through the application of *radioblockators, i.e. substances that reduce the uptake of the radionuclides by an organism.*

The protection against ^{90}Sr and ^{137}Cs, therefore, is based on the increase of substances absorption by an organism, i.e. their chemical analogues – calcium and potassium, that interact antagonistically with radionuclides and decrease their uptake by an organism. Substances called enterosorbents and complexonates, being taken up, bind the radionuclides, preventing its involving in metabolism.

Radiodecorporants are substances that speed up the excretion of the radionuclides from an organism. An excretion is considered to be a therapeutic method, although its effectiveness is lower in comparison with prophylaxis methods, where radioblockating and radiodecorporating agents belong to.

At the same time natural and synthetic preparations that may provide selective binding of radionuclides and speeding up of their excretion together with metabolic products from the organism are known. They are called complexones, i.e. naturally occurring and synthetic preparations that may react with strontium and caesium and form stable but well soluble compounds. Being involved into metabolism such complexones speed up the excretion of radionuclides.

Finally, there is the forth group of the radioactive protective agents, so-called "growing factors". This is a great group of various unspecific substances, stimulating metabolism, speeding up cell division and repair processes, promoting decontamination of toxic products and speeding up of their excretion from an organism.

All mentioned substances are generalized on the Fig. 56, and will be discussed in chapter 10.

7.1.6. Radiosensibilizators

If radiosensibilization is a process of artificial increase of radiosensitivity leading to the increase of radiation damage, radiosensibilizators are *chemical substances that enter an organism before or at the moment of irradiation and increase radiation damage.*

Data about radiosensibilizators are very limited. Oxygen is considered to be unique radiosensitizer able to enhance the effectiveness of a radiation dose. It is known as “the oxygen effect”. All biological systems are more sensitive to X- and γ-radiation in the presence of oxygen than when they are irradiated at very low levels of oxygen or in the absence of the oxygen.

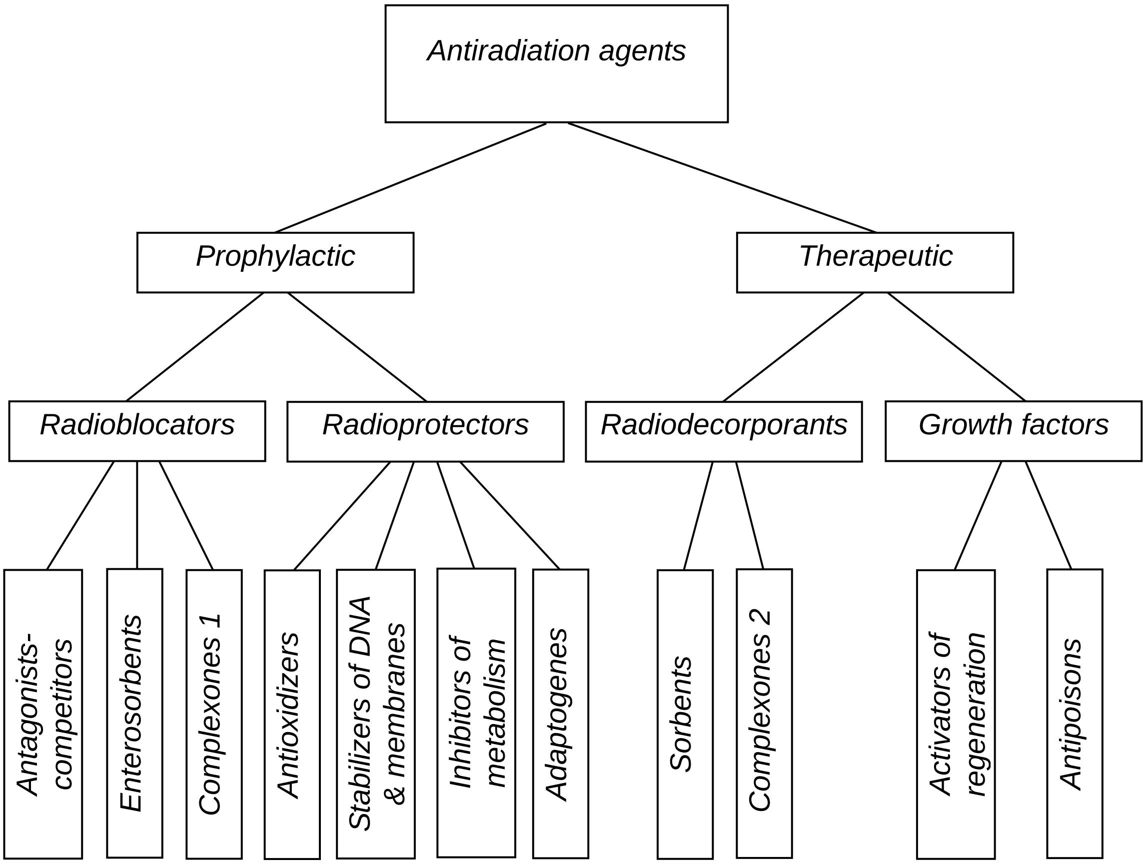

Fig. 56. Antiradiation agents.

Recently the affinities of radiosensitizing compounds based on the oxygen effect have been intensively investigated. Being similar to oxygen, *i.e.* having similar electron–acceptor affinities, such compounds significantly influence (enhance) the effects of radiation damage. The derivatives of very strong oxidizer (nitroimidazol – metronidazol) and mizonidazol have similar affinities.

The sensitization of ionizing radiation action by the specific compound of iodineacetamide is of special interest. It may form free iodine radicals that bind sulphhydryl groups of proteins and mitigate radioprotective effectiveness of endogenous sulphhydryl compounds. The presence of plants in 2×10^{-4}–10^{-3} *M* solution of iodineacetamide enhances the radiation damage by two times (FDC – 0.5).

Copper has similar affinities. Soaking of seeds and presence of plants in 10^{-4} *M* solution of chlorides or copper sulfate enhance the effectiveness of γ-radiation by FDC 0.7–0.75. There are two reasons of such phenomenon. Copper has a unique affinity to destabilize the structures of higher orders of cell biopolymers providing in such a way radiosensitizing effect on the contrary to ions of other metals. By stabilizing such structures some ions are considered to enhance radioprotective affinities. Copper is a specific poison of amino acids, especially of those containing SH–groups. It catalazes joining of the oxygen to sulphur providing its following oxydation that, in its turn, reduces the radioresistance, determined by native content of sulphhydryl compounds.

The need of radiation protection development is obvious. It is clear that radiosensitizing agents have a little importance in practical use and are mainly used when there is a special need to enhance radiation-induced damage. Radiosensitizing agents are used in medicine especially in radiation therapy. They enter directly a zone of irradiation when there is a need to protect healthy tissues.

The radiosensitization is applied in many biological technologies including agricultural sector when there is a need of high doses of radiation, *e.g.* radiation treatment (sterilization) of agricultural products, forage etc. The use of radiosensitizing agents allows reducing exposure dose, time of exposure and energy.

There is a perspective to use radiosensitizing agents in radiation mutagenesis of plants and to raise new species of plants.

The biological radiation protection and radiosensitization are connected with the problem of postradiation reparation and regeneration. In fact, it is rather difficult to distinguish among these two phenomena. That’s why it will be discussed in next chapters.

7.2. Postradiation recovery of an organism

Postradiation recovery is recuperation or restoration of the cell functions of its critical organs that, in turn, provide normalization of its functional activity and recovering of an integral system after radiation-induced damage. Such definition of the term “recovery” reflects the essence of the processes leading to the normalization of functions of a multicellular organism damaged by ionizing radiation.

However, the phenomenon of postradiation recovery and regeneration of an organism is a multilevel process. Therefore “recovery” usually reflects the functioning of complicated reparation systems, working on the different organization levels.

According to the scheme (Fig. 57), the general “recovery” of an organism includes the following postradiation recovery: reparation, repopulation, regeneration and reconstruction.

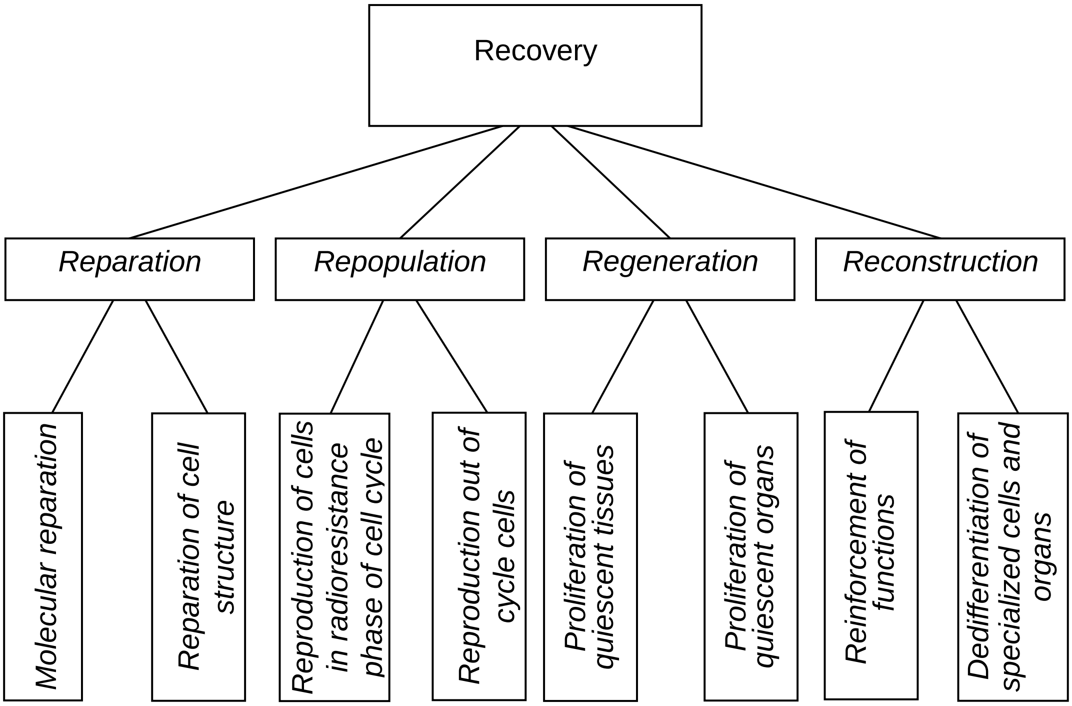

Fig. 57. The ways of postradiation recovery of an organism.

Reparation means the recovery of such macromolecules as DNA and such subcellular structures as chromosomes, membranes, etc. Repopulation means reparation by reproduction of cells that at the moment of irradiation are in radioresistant state and therefore save their ability to undergo division. Regeneration is the result of proliferation of tissues and organs in the rest state. In contrast to other organisms, regeneration is important for higher plants. Finally, reconstruction, or compensatory regeneration takes place, when functions of damaged cells (tissues, organs) are carried out by undamaged cells (tissues, organs), partly due to the dedifferentiation of specialized cells and tissues into proliferating.

7.2.1. Reparation

There are two types of radiation-induced damages: potentially lethal and sublethal. *Potentially lethal radiation-induced damage may result in cell death; however, in certain cases they also might be repaired. Sublethal damages do not lead to cell death itself, but they may become lethal after additional irradiation.*

Correspondingly, there are two types of reparation: reparation of potentially lethal and sublethal damages. The possibility to repair sublethal damages may be proved by an experiment with the use of fractionated irradiation. The hypothesis considers that radiation damage has irreversible character. If it is so, the effect, caused by fractionated irradiation at a certain dose rate should be similar to the radiation-induced effect at a single dose. But many studies indicate that radiation-induced damage at fractionated irradiation is insignificant and it proportionally decreases with the time between fractions and their number (Fig. 58).

In dry system (seeds, spores, pollen) and under the limited access of oxygen the fractionation effect and a dose rate do not reveal at all or is insignificant. It seems to be the best explanation of such phenomenon to recognize the existence of cell regeneration that require active cell metabolism.

However, it is not possible to reveal the nature of such regeneration by using dose fractionation and, therefore, it requires special investigations by using modern methods of molecular biology.

Molecular reparation. Damage of DNA molecules is the main radiation-induced damage. Radiation-induced single and double strands breaks (SSBs and DSBs) of DNA are considered to be the main damages of DNA polynucleotide chain. The repair of SSBs and DSBs that plays the main role in cell death was shown first in the experiments with bacteria. It allows obtaining strains having defects of some enzymes controlling stages of repair. Fig. 59 shows a general model of the main stages of SSBs repair.

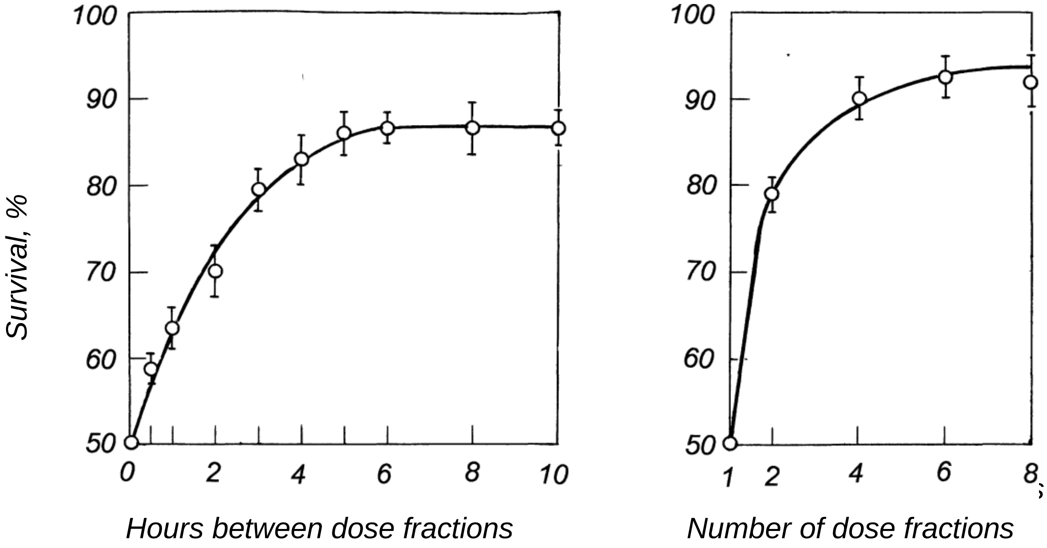

Fig. 58. Survival curves of pea shoots at fractionated dose of 8 Gy of γ-irradiation: a – double irradiation (4+4 Gy) with different time intervals between separate dose fractions, b – different number of dose fractions at the same time of irradiation (3 hours).

The repair of SSBs in, for example, mammals is very rapid and efficient. It probably occurs by the mechanism called “excision repair”. This involves the excision of the length of nucleotide strand containing the defective piece of DNA and uses the complementary (undamaged) single-strand as the template for the resynthesis of a new length of DNA. The process is enzyme controlled and is temperature dependent with no repairing occurring at 0°C. The first step is the recognition of the site of the distortion or disruption when an inclusion is made by endonulease enzymes. The inclusion is followed by the complete excision of the lesion and sometimes of a wide area around it. This process involves endonucleases. The produced gap is filled with a new nucleotide bases by the action of DNA polymerases using the opposite and undamaged strands as the guide. When this “repair replication” is complete, the new section of DNA is linked to the intact DNA by enzymes called ligases.

The other types of DNA repair synthesis are known. Generally, most of them follow by a scheme the essence of which is determined by the principle of “*excision repair*”.

The repair of DSBs is difficult to imagine and it requires the presence of an active system of recombination and of undamaged DNA strands, homologous to those having double-strand breaks.

The molecular repair of RNA, some proteins, i.e. nuclear protein chromatin, some bases of DNA also exists. The repair mechanism is thought to be similar to that of DNA and DNA repair is the main mechanism of molecular reparation.

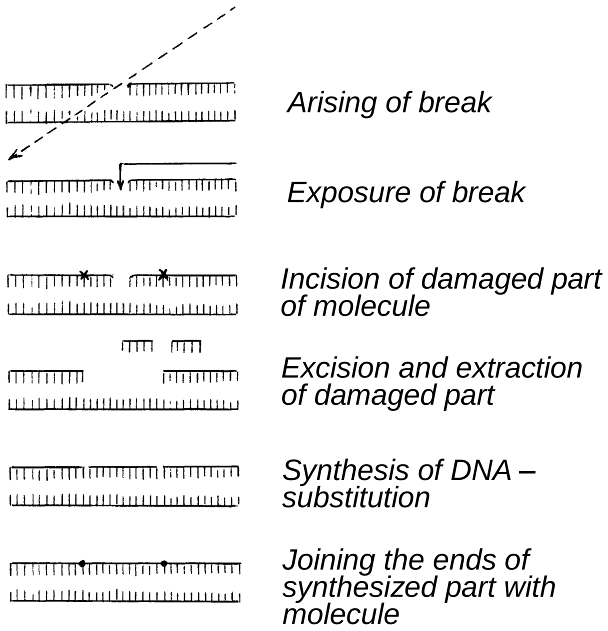

Fig. 59. A general model for radiation-induced damage of DNA.

Reparation of cell structures. In 1950s the hypothesis about the possibility of radiation-induced damage reparation on the chromosome level was proposed. It was based on the experimental data that the number of chromosome aberrations per cell depends on the time interval between the dose fractions. It was found out that at small time intervals (minutes, hours) the number of chromosome aberrations decreases between doses. At increased time intervals two alternatives were observed: the number of chromosome aberrations decreases to a certain level or the number of chromosome aberrations first decreases and then increases again. Data obtained in the experiment with plants and animals illustrate the same pattern: curve 1 or curve 2 (Fig. 60), named by Lane who described such relationships.

It is known that chromosomes undergo repair in postradiation period, thus, a decrease of radiation-induced distortions. However, the mechanism of such repair is much more complicated in comparison with that in DNA and is not clear yet. Structural organization of eukaryote chromosomes is complex. Apart of DNA it also consists of some amounts of RNA, various proteins that have strong binds with nuclei acids. It is difficult to imagine that an electron can damage such complicate structure and even much more difficult to imagine the reparation mechanism.

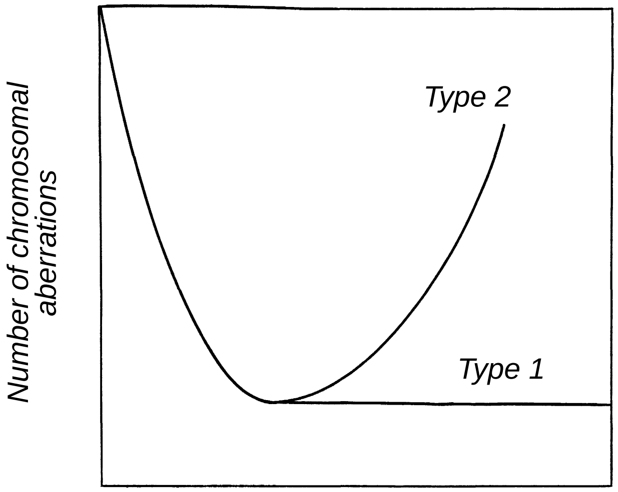

Fig. 60. The generalized scheme of two curves, showing the dependence of the number of radiation-induced chromosome damage and time interval.

There are data about repair of the radiation-induced damages in cell membranes. The structure of the membrane and its permeability may be repaired with time. However, molecular mechanisms of such repair are not well understood.

The role of cell repair in general recovering of a multicellular organism is not clear. There is no clear correlation between radioresistance of higher organisms and their ability to undergo repair. There are only some studies indicating possibilities for such relationships.

Undoubtedly, repair processes play an important role in saving proliferating cells. I[illegible]zation of the ability of critical organs to perform their functions requires, as a minimum, several cycles of cell division, *i.e.* some days but not hours. Therefore, postradiation repair of any multicellular system is not only the function of repair of some cells but propagation of cells which save their ability to division (repopulation).

7.2.2. Repopulation

Cells reproduction originates from cell population that at the moment of irradiation is in radioresistant state and, therefore, saves their ability to undergo division or is in the rest state (“out of cycle”).

Propagation of cells that at the moment of irradiation are in the radioresistant state. Radioresistance of cells may differ by factor 2–3 depending on the phase and the period of a cell division. There are always cells in population that are at the different stage of the division due to the asynchronization of cell division, which actually is the mechanism of the tissue stability to damaging factors. Such cell population is rather mixed, since there are three major groups of cells depending on their radioresistance (Fig. 61): cells that lose their ability to undergo division (they are at the radiosensitive stage of a cell division at the moment of irradiation); practically undamaged cells (they are at the most radioresistant stages), and cells with potentially lethal damages that may pass to class 1 or 2, depending on the circumstances and situation (they are between radioresistance and radiosensitive stages of a cell division cycle).

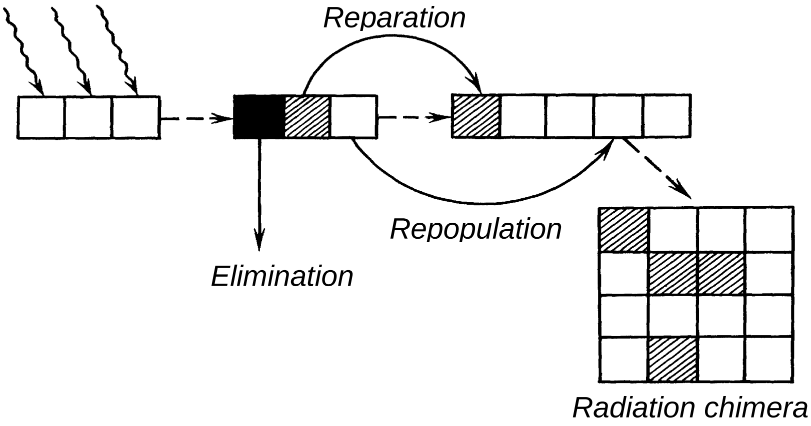

Fig. 61. Scheme of cell reproduction of an irradiated organism.

The cells that save their ability to divide continue to propagate. Moreover, to compensate the cell elimination in the meristem cell division rate is usually higher in comparison with a normal situation. It is shown that the duration of cell division cycle in root meristem shortens from 17 to 13 hours (Fig. 62). Thus, the meristem compensates its initial cell volume and the cell reproduction is completed after irradiation (several cycles of cell division) (Fig. 63).

Propagation of cells that at the moment of irradiation are "out of cycle". The reserves of cell propagation in the rest state are those that are "out of cycle". There are two possible ways for such cells after termination action of the factor: to return on the way of cell division or to the differentiation. The choice is mainly determined by the interactions between cells.

Cells being in the rest state are more radioresistant in comparison with those that undergo division. When dividing cells are irradiated at doses causing a loss of their reproductive ability, the “out of cycle” cells are ready to undergo cell division. The critical situation for tissue is cell devastation. That is why turning of the cells to the rest state is considered to be a way to create tissue reserves, i.e. the basis of cell reproduction.

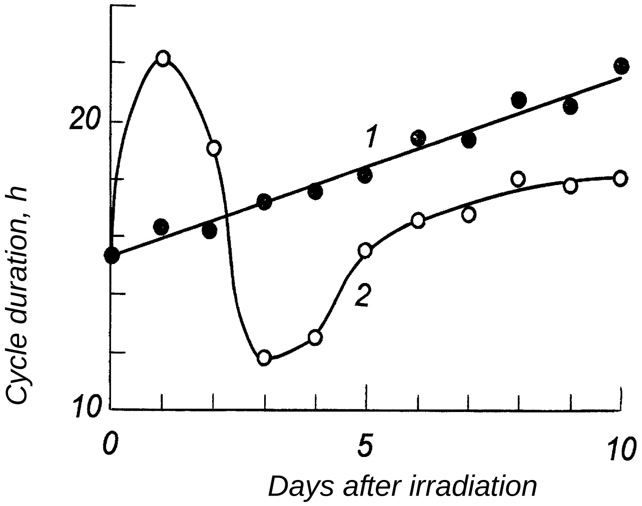

Fig. 62. The duration of the cell division cycle in the root meristem of pea normally (1), with time after γ-irradiation at a dose of 4 Gy (2).

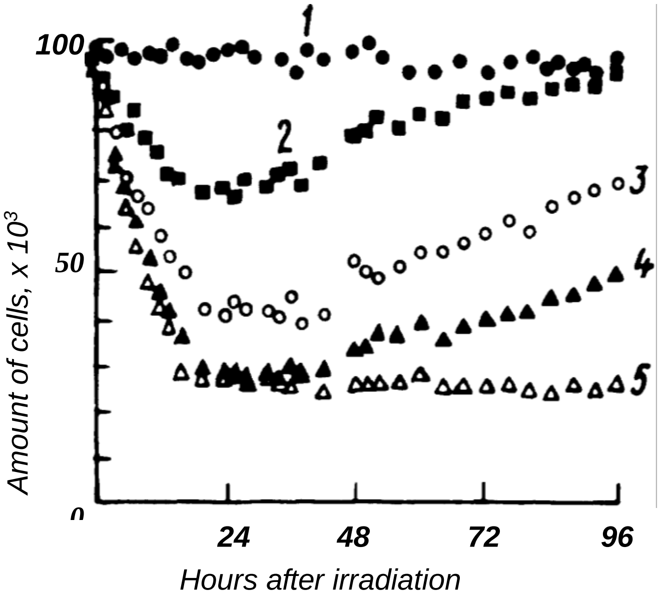

Fig. 63. The cell amount in the root meristem of pea normally (1), 2 Gy (2), 4 Gy (3), 8 Gy (4), 12 Gy (5).

The possibility and the rate of cell reproduction depend on the pool size of cells, able to undergo division. If a dose increases the pool decreases and the probability for cell reproduction in this way decreases. Theoretically, cell reproduction in the way described above is possible if only one cell in cell population is able to divide. In experiments with mammals it was shown that among rapidly dividing crypt cells of intestine epithelium only one dividing cell may replace the epithelial cell loss.

Transplantation of bone marrow cells from a healthy to a sick person, i.e. the cell reproduction, is the most effective for today medical treatment of radiation disease for humans. This method is used at high doses of radiation, when bone marrow cells lose their ability to self-reproduction completely.

7.2.3. Regeneration

If reparation and repopulation are typical mechanisms of postradiation recovery for all multicellular organisms (plants and animals), the regeneration recovery is an affinity mainly of plants. The evolution determines the most of the plants species to be attached to a certain permanent place. It means that plants cannot avoid unfavourable environmental conditions. That is why evolution endowed plants with such protective features as seeds. It is a very resistant stage of ontogenesis. By powerful system of regeneration, it makes plants regenerate some organs or even all the plant due to the presence of special tissues and organs that have cells in the rest state and, therefore, are very resistant to any harmful factors.

Here we examine two main types of regeneration of higher plants: tissue regeneration and organs regenartion that are in the rest state.

Tissues regeneration that are in the rest state. On the very tip root on the border with root case there is a special group of cells forming semi-sphere or convexo-convex lens (Fig. 64). This formation contains about 1 000–2 000 seldom (once per 200–500 h) dividing cells while surrounding cells undergo division every 12–24 h. English plant physiologist F. Clowes first studied this root section in 1954 and named it as a “quiescent centre”.

The functions of quiescent centre are not well understood. Some botanists did not discover the existence of the rest center, using ordinary painting methods on anatomical preparations. However, some scientists consider rest centre as a centre of the meristem, which produces all types of root cells. When meristem is damaged and loses the ability to divide, the cells of rest centre begin to divide and restore the initial cell volume.

There is a certain critic level of meristem damage, which induces the division of cells in the rest centre. However, cells in the quiescent center may be involved in a reparation process only when the certain number of cells loses their ability to divide. It occurs due to the intercellular interactions between cells subpopulations that are in the rest state and undergo division. When the number of cells reaches the normal level and complete meristem reparation, a new quiescent centre appears.

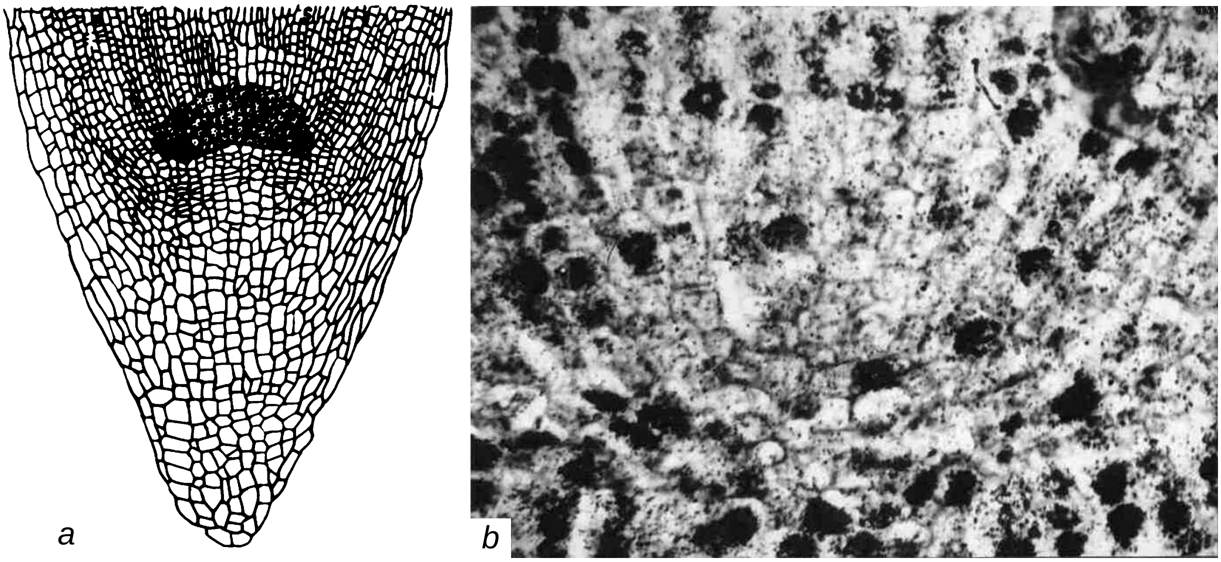

Fig. 64. Quiescent centre in the root tip: a – schematic image (F. Clowes, 1956), b – radioautography of root tip section of pea after the presence of shoots in the environment with ^{3}H-thymidine for 24 h. A zone with lighter not dividing cells is clearly seen (I. Gudkov, 1979).

Organs regeneration that are in the rest state. The apex meristem of higher plant shoots normally inhibits the cells division in meristem of lateral buds. This phenomenon is called apical dominance. It is a strong intercellular interaction on the level of the whole organism. Removal of the apex leads to the elimination of apical dominance and the enhancement of tissue proliferation that is in the rest state, and wakens up of lateral buds. All these phenomena are considered to be repaired by means of regeneration.

The apical domination is mainly determined by a hormonal effect on the growth point. Many studies indicate that growth activating substances such as kinetin and heteroauxin may alter the apical domination, when an apex meristem is removed.

It is quite natural that irradiation of plants causes damage of actively growing and dividing apex meristem cells. It is known that radiation-induced damage of the certain number of cells will stimulate regeneration of highly radioresistant organs of a plant that are in the rest state at the moment of irradiation. The intensive branching (dichotomy, fasciations) formation of the additional lateral roots as well as intensive bushing out of irradiated plants and other anomalies are examples of apex meristem removal and the following regeneration of radioresistant organs.

The phenomenon of the apical domination is well studied in leguminous plants that are considered to be the best object for its demonstration. The lateral buds of leguminous are located in the axils of leaves and, therefore, named axile. They are usually in the rest state during the ontogenesis. However, if the apical bud is removed, e.g. mechanically, it begins to grow and develop in the shoot that resembles the main shoot and forms a new plant.

Similar phenomenon arises at the damage of an apical bud caused by the radiation and the chemical agents, drying up, freezing and other factors. There is a certain threshold of ionizing radiation causing the removal of the apical domination that depends on species and a dose rate. The radiation inhibits cell division, phytohormone synthesis and axile bud growth (Fig. 65) resulting in proliferation of axile buds.

Regeneration seems to be the most powerful recovery system of plants endowed by evolution, since higher plants avoid another possibility to protect it. It is based on the unspecific adaptive reactions widening the growth condition borders of plants and mechanism of regeneration that is considered to be the most effective against any damaging agent.

7.2.4. Reconstruction

Reconstruction, or compensatory regeneration is not well understood, but radiation-induced compensatory enhancement of different functions of an organism may be often observed. Among them there are two main types of reactions. The first type of reactions is that undamaged cells, tissues or organs perform unusual functions. The second is that undamaged cells, tissues or organs enhance their own functions to compensate functions of those that lost their ability.

Differentiation of specialized cells and tissues. In the course of an organism development the specialized cells, tissues and organs are formed. This is a result of differences between homogeneous cells and tissues appearing during morphogenesis are called differentiation. Thus, meristem cell undergoes tension after some (five-seven) cycles resulting in alteration of the shape and the increase of size with following differentiation. Differentiation of cells stimulates different affinities providing different types of tissues with the following specialization that is characterized by different levels of metabolic activities and the degree of the structural organization of cells and tissues.

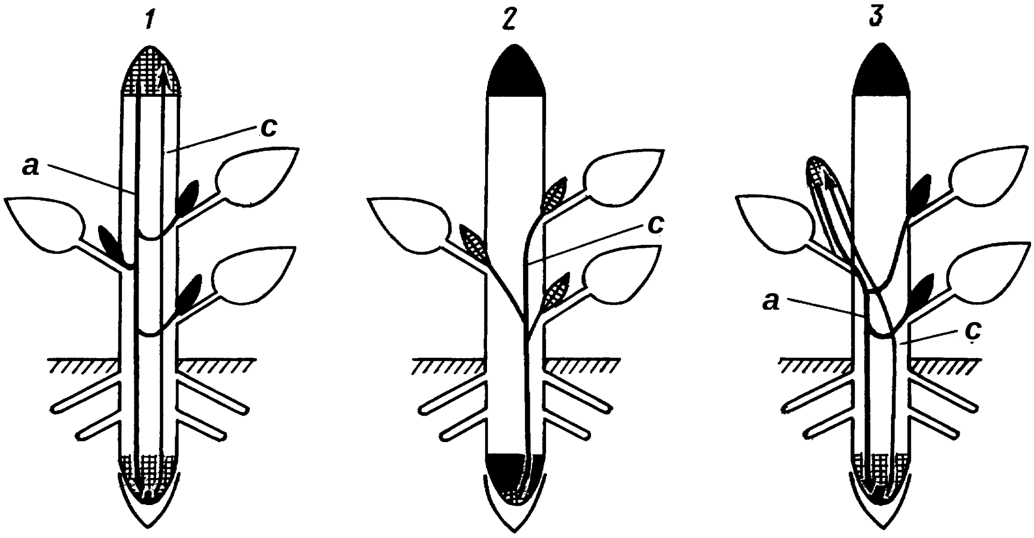

Fig. 65. The interaction of the phytohormones in the plant under normal conditions and at the radiation-induced removal of the apical domination: 1 – the plant in the natural state: cytokinins (c) synthesized in the root and transported to the apical bud of a shoot cause division of its cells; synthesized in apical bud of a shoot auxins (a), moving down to the stem and inhibit division of the lateral bud cells and the cells of the rest center of a root by means of induced production of ethylene and abscisic acid; 2 – at radiation-induced removal of the apical domination; the inhibition of the auxins synthesis and directed movement of cytokinins to the lateral buds and the rest center with the cells at the beginning of division cycle; 3 – the renewal of a new apical organ of the root meristem.

Of course, differentiation is irreversible. However, in the case of tissue damage, malignant growth and other cases causing the change of physiologically active balance, the natural way of cell passage through the life cycle is disturbed. The last may cause differentiation in opposite direction, i.e. dedifferentiation. Such process may occur in the case of plants irradiation that causes alteration of phytohormone balance with following loss of the ability to meristem cell division. In such case differentiated cells begin to divide and become a source of meristem regeneration or a source of new forming tissues.

Dedifferentiation is one of the most striking examples of compensatory regeneration, when irradiated cells acquire unusual functions.

The enhancement of functions of undamaged cells, tissues or organs in order to compensate functions of those that have lost their ability, is also considered to be the way of postradiation compensatory regeneration.

Thus, if bushy cereals are irradiated, the number of shoots decreases, but, as a rule, the survived shoots show better growth and they are stronger in comparison with the control group of shoots. When reproductive organs are damaged and the number of ovaries decreases, the formed ears, pods and fruits are more productive in comparison with the controlled ones. The radiation-induced decrease of amount of grains in inflorescence results in higher absolute mass of saved grains in comparison with the controlled ones.

Such facts may be explained by redistribution of the nutrients coming from the root system. The nutrients intended for a certain number of fruits may be obtained by less number of fruits. The data obtained on the level of cells and tissues are less illustrative but may be treated in the same way. As we mentioned above the division of γ-irradiated plants at doses causing the increase of meristem cells by factor 2–3 slows down quickly. Undamaged cells restore the initial volume by means of active division. The cell division rate increases significantly and results in shortening of a cell cycle after a short time of inhibition. Later, when meristem reaches the normal state, it begins to increase in size and, finally, reaches the initial level (Fig. 63).

Thus, the enhancement of cell division is a specific reaction of the compensatory phenomenon on the level of cell population.

The increased yield of synthesized nucleic acids, proteins, phytohormones, enzymes and other substances caused by damaging doses is another example of compensatory regeneration. The outcome of mentioned above processes is the cell division enhancement that is considered to be an integral index.

Generally, the term “reparation” means the whole complex of processes providing survival of an irradiated organism as a system. This system that provides the number of functions is to be well-studied in order to be able to manage and control such processes.

7.2.5. Regulation of postradiation recovery processes

Till 1960s, it was supposed that outcomes of radiation-induced damage may not be modified in postradiation period. The observed alterations of irradiated plant and animal reactions during postradiation period are supposed to be mainly related to the environmental factors and do not directly relate to the processes of radiobiological effects formation.

There are number of data showing that many chemical substances that have reduction potential, i.e. salts of various metals and nutrient elements, hormones, enzymes and other physiologically active substances, may affect the development of radiation-induced damage entering nutrient medium in postradiation period.

The mechanism of most modifying agents of radiation damage of physical and chemical nature is usually related to the action at later stages of radiation damage not at initial ones. Thus, the effect of increased temperature, humidity, gas environment, chemical reductants is explained by the increase of free radicals recombination speed, i.e. damaging factor that occurs in near postradiation period. The effect of low temperatures and ultra-violet radiation is often attributed to the reparation of the DNA molecules and chromosomes.

The effect of some modifying agents of chemical nature applied before irradiation may proceed during postradiation period affecting reduction processes. It is assumed that post-radiation reduction processes are directly related to the radiation protection action of DNA preparations, some nucleotides, enzymes, hormones, etc.

Radiosensitizing action of some chemical substances is related to processes of reparation inhibition. Such properties show some specific inhibitors of DNA reparation such as caffeine, acriflavin.

The effectiveness of repopulation and regeneration renewal is mainly determined by the rate of cell division that saves their ability for division after irradiation. Therefore, the rate of postradiation reparation may be affected by changing the cell division rate. Thus, providing optimal conditions for plant growth (temperature and gas regime, light, mineral nutrients, growth activating phytohormones), it is possible to promote postradiation renewal processes. It may provide limited possibilities for altering the outcomes of radiation-induced damages. That is why, it is important to study and generalize the knowledge about the effect of modifying agents on the reparation processes and outcomes of radiation-induced damages on the different levels of life organization.

The special strategy has to be worked out concerning plants in postradiation period. As we’ve already mentioned, in the emergency case, i.e. nuclear accident with the following acute irradiation and prolonged radioactive contamination of the earth surface, not only a limited number of plants but the whole biocenosis may be subjected to radioactive contamination and irradiation. Regarding measures that speed up the postradiation renewal of damaged phytocenosis, there are two main approaches: to provide optimal conditions for plant growth and the development in postradiation period (1) and the application of physiologically active substances in order to speed up processes of postradiation renewal, mainly those that promote cell division and proliferation of tissues and organs (2).

Such approaches may considerably reduce the outcomes of radiation-induced damages of phytocenosis including forest vegetation. These questions will be examined in the following chapter.

Control points to chapter 7:

1. The notion of modification of radiation-induced damage of an organism.
2. The essence of biological protection and sensitization of radiation-induced damage.
3. Physical radiosensitizing agents.
4. The mechanism of the oxygen effect in cell and oxygen enhancement ratio (OER).
5. The factor dose change (FDC) and its values for radioprotective and radiosensitizing factors.
6. Chemical radioprotective agents.
7. The definition of radioprotectors and their classification.
8. Comparable effectiveness of radioprotectors within different classes.
9. The practical application of radioprotectors and radiosensitizers.
10. Radioblockators and radiodecorporators.
I1. The definition of postradiation recovery.
12. The classification of postradiation recovery types.
13. Types of repopulation recovery.
14. The mechanism of excision DNA repair.
15. The role of asynchronous cell division in repopulation.
16. The role of cells and tissues that are in the rest state, in postradiation renewal.
17. The role of apical domination in regeneration.
I8. Reconstruction.
19. The postradiation repair processes and the possibility for its managing.

8. BIOLOGICAL EFFECTS OF INCORPORATED RADIONUCLIDES

8.1. Biological effects of incorporated radionuclides on plants. 8.2. Biological effects of incorporated radionuclides on animals. 8.3. Radiation-induced damage of “hot particles” incorporation. 8.4. Dosimetry principles of ionizing radiation of incorporated radionuclides. 8.5. Prognostication of radionuclide uptake by agricultural products. 8.5.1. Prognostication of radionuclide uptake by plants. 8.5.2. Prognostication of radionuclide absorption by animals. 8.6. Norm setting of radionuclide content in agricultural products.

The studies of radionuclides behaviour in the environment and especially radionuclides of artificial origin, examined in previous chapter, have a practical application. First of all, it concerns a possible penetration of radioactive substances in foodstuffs. The crucial point in general scheme of studies connected with the pathways of radionuclides migration in the biosphere is the transfer of radionuclides through the biological and food chains. Agricultural plants and animals play the important role in radionuclide transfer to a man. The internal dose of irradiation is mainly formed due to the consumption of contaminated foodstuffs. Normally, the contribution of external irradiation does not exceed 20–25% of the total dose. For this reason the studies of biological effects of radionuclides incorporated into cells of plants, animals and humans are the important objects of radiobiology.

Depending on their physical and chemical properties, quantity, localization within the body and biological half-time radionuclides incorporated into an organism provide various radiobiological effects: radiation stimulation, morphological changes, radiation sickness, aging speeding up and lifespan shortening, death and genetic effects. During 1950–60s due to the limited sources of external irradiation for research and practice in agriculture, the induction of radiation stimulation effect in plants and animals, and obtaining mutants in the process of selection solutions of different radioactive isotopes were used.

When plants are growing in the medium with short-lived radionuclides producing hard ionizing radiation, e.g. ^{32}P, the symptoms similar to typical sickness caused by radiation may be observed: metabolism distortion, morphological changes, etc.

Radioactive substances incorporated into an organism may be dangerous due to several reasons. First and foremost it is the ability of some radionuclides for selective accumulation in some tissues and organs. In the case of external irradiation all living tissues are evenly exposed to the irradiation. Incorporated radionuclides may provide high local doses to specific organ or tissue depending on the chemical properties of radionuclide, the specificity of metabolic activity of an organ or tissue and biological specificity of an organism as a whole.

The second reason is that damaging effect of incorporated α- and β-emitters may increase with time. Due to their low penetration ability in the matter such radionuclides are relatively safe for internal organs and tissues. Being incorporated into an organism they become very dangerous sources of irradiation for internal organs and tissues. Such α-emitters as plutonium, americium, curium, radium, uranium and other radionuclides that have high relative biological effectiveness (RBE) are especially dangerous.

The third reason is that incorporated radionuclides cause long-term irradiation of an organism. Data in Table 56 show that half-life ($T_{1/2}$) and biological half-life (T_{biol}) of many radionuclides including ^{90}Sr and ^{239}Pu are rather long. It means that an organism undergoes exposure during the whole life.

Important thing is that radioprotective agents effective at external irradiation are practically useless for internal irradiation. The possibilities for speeding up of radioactive substances removal from an organism that are examined in the following chapters are too limited.

Mentioned above features of irradiation by incorporated radionuclides mainly concern an animal organism and especially humans. However, a plant is an intermediate and first link in the long chain of radionuclide transfer starting in soil.

8.1. Biological effects of incorporated radionuclides on plants

Plant radiosensitivity caused by accumulation of radioactive substances in tissues is not well studied in comparison with external irradiation. It is mainly because most plant types have higher radiosensitivity in comparison with animals. Even high radionuclide concentration in plant tissue has a little radiobiological effect. However, many plants with relatively high radiosensitivity may have severe damage induced by incorporated radionuclides.

It was mentioned above that some agricultural plant species, e.g. belonging to leguminous family (beans, pea, kidney beans, soy), are highly radiosensitive (LD_{50} is about 3–15 Gy only). All leguminous are calciphiles and accumulate strontium together with its chemical analogue calcium, providing intensive internal irradiation of plant tissues and organs.

Accumulation of radionuclides is a plant dependent process leading to a different degree of radionuclide accumulation in various organs and tissues that, in turn, provides different irradiation doses.

Such pattern of radionuclides behavior may be seen on the plant radioautographs, i.e. a picture obtained after the injection of radioisotopes into a plant. Radioisotopes mainly deposited on their pathways within plant-conducting tissues as well as in tissues and organs are characterized by high metabolic and mitotic activity. They are mainly meristem and generative plant organs that are also highly radiosensitive. For this reason radiobiological effects may be observed, first of all, in mentioned above tissues at external and internal irradiation. Such effects on meristem tissue are chromosome aberrations and slowing down of cell division that, in turn, results in various morphological changes of leaves and other organs as well as retardation of plant growth. All mentioned symptoms evidence disease caused by radiation in plants.

Pine tree is characterized by high radiosensitivity among the plants and among all living organisms. After the Chernobyl accident pine trees accumulated many different radionuclides, mainly, by over ground organs. In highly contaminated forest ecosystems the most severe radiation-induced damages were found in meristem. Such lesions lead to their mass death, the proliferation of lateral buds and newly formed shoots with distorted orientation, the formation of shortened or enormous big curved needles. Such types of distortions are shown in Fig. 30.

Certainly, it is not only due to internal irradiation of plants. Plants were irradiated by high doses of external irradiation, especially during the first days or weeks after the accident. Later external irradiation of plants was caused by fall-outs deposited on the earth surface as well as by radioactive particles located directly on the plant’s surface.

That is why, some years later, when a radiation background decreased by several orders of magnitude, the number of such anomalies decreased as well. However, 3–4 years later an intensive root uptake of radionuclides not only by annual but also perennial plants occurred. Radionuclide accumulation by over ground parts of a plant followed by radiobiological effect was caused mainly by internal irradiation. And even today young pine trees growing on the places, where residues of „Red forest” were buried, have various morphological distortions (Fig. 32).

The studies of radioactive substances injection into plants through the root system are well known. Though, external irradiation is hardly possible to deny, its contribution is negligible. Thus, the experiments to inject α-emitters or compounds containing low energy β-emitter (e.g. radioactive isotope of hydrogen – tritium) are demonstrative. These isotopes are characterized by a short pathway (some microns) in plant tissue. Injection of such isotopes into plant tissue excludes external irradiation. Well known experiments with radioactive tritium tracer on thymidine (^{3}H-thyimidine) are especially bright example. ^{3}H-thymidine is a specific predecessor of the DNA synthesis. Being injected into a plant or other living object, it is concentrated in dividing cells and enters in such a way in DNA molecule. Thus, it provides polynucleotide chains break, which, in turn, results in the distortion of synthesis of DNA and RNA, proteins, and other chains of metabolism. It is the mechanism of radiobiological effect induction.

Potassium is an element, which is actively involved in cell division and its growth. Stable cesium as well as radioactive ^{137}Cs (both are chemical analogues of potassium) are concentrated mainly in actively dividing and growing cells, providing in such a way their irradiation. ^{137}Cs was mainly concentrated in a root meristem – division zone (Fig 66), i.e. a dose to meristem cells was several times higher in comparison with the rest root tissue.

That is why observed radiobiological effects on plants growing on the contaminated territories often correspond to about one order of magnitude higher doses of external irradiation in comparison with that one estimated by means of ordinary dosimetry.

Calcium functions in plants, unlike animals, are rather limited. Ca is mainly involved in formation and strengthening of cell membrane both differentiated and specialized cells. It is also found in conducting cell area of root, which are several orders of magnitude more radioresistant in comparison with dividing cells. Being a chemical analogue of calcium strontium behaves in a similar way. Therefore, ^{90}Sr usually causes less damage than ^{137}Cs.

The behaviour and following radiobiological efficiency of incorporated into a plant radioactive substances depend on chemical and biochemical properties of associated with radionuclides compounds. Some compounds can be actively involved in metabolism quickly transported within the plant and accumulated in the most radiosensitive places. Other compounds, having the same radionuclides of different form, can be accumulated in the beginning of its pathway (e.g. in root) or may be transferred quickly through the plant and eliminated. We've already mentioned that tritium being included in thymidine compound is involved in DNA and causes various radiobiological effects. Being a constituent of water molecule, it is involved in a water cycle and is eliminated from a plant making no severe damage.

^{90}Sr that is taken up by a plant as, for example, strontium nitrate or strontium phosphate may be bound to DNA and chromatin proteins localizing in such a way in the nucleus of dividing cells.

^{137}Cs that is taken up by a plant as, for example, caesium chloride is more or less evenly distributed within a plant cell. Thus, radioactive strontium may cause more damage to cells in comparison with radioactive caesium, when equal amounts of radioisotopes are applied.

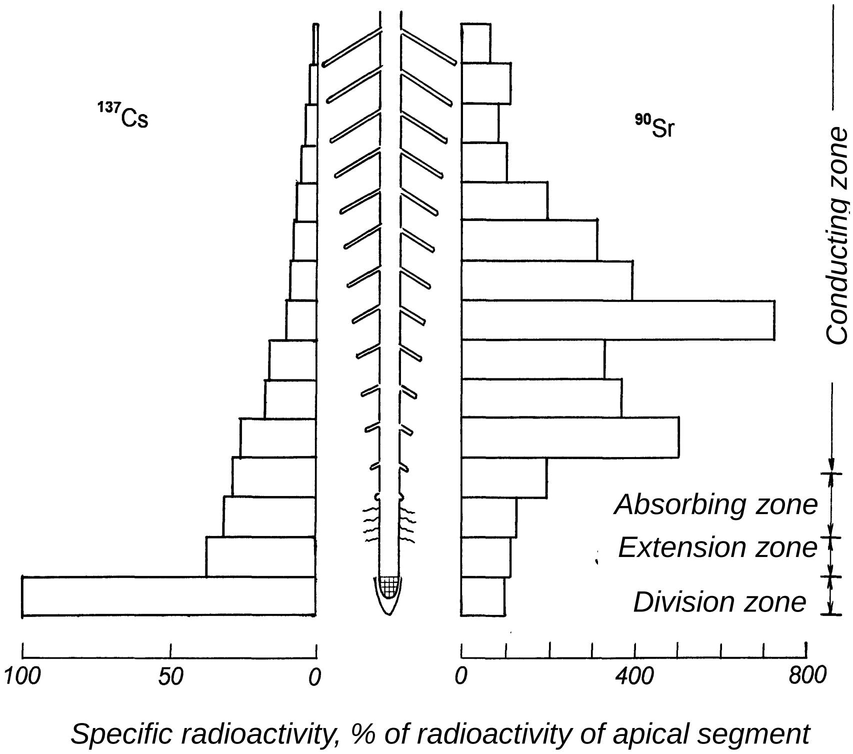

Fig. 66. ^{137}Cs and ^{90}Sr activity of 5-mm segments of a main root of pea shoots, growing in 30-km area of Chernobyl NPP (A. Mikhyeyev, 1999).

There are several studies indicating that coniferous plants are very radiosensitive to internal irradiation. Thus, after the nuclear accident on South Ural in 1957, when easily assimilated radioactive hydrosols by over ground plant organs were deposited on the pine and spruce trees, the doses due to radionuclides accumulation in needles and buds meristem reached 5–30 Gy. The mass anatomic distortions, slowing down of buds opening, the formation of shortened and distorted shoots, the alteration of needles colour from green to yellowish, reddish and brownish (similar to those facts observed in “Red forest” at external and mixed irradiation), drying of shoots were observed. Trees perish at a dose of 50 Gy and higher.

A. Tikhomirov (1982) designed and carried out the experiments where the solution with radioactive strontium was sprinkled into crowns of pine trees, simulating background level of (3–60)$\times 10^7$ Bq m^{-2}. Thus, doses accumulated by meristem tissues during the period of vegetation varied from 2 to 20 Gy. Even minimum doses caused the reduction of shoot increase, the change of their shape, length and orientations. At maximum doses a tree crown perished and drying of trees were observed.

As a rule, mentioned above somatic radiobiological effects are shown in most radioresistant plant types at the level of radionuclide accumulation and following internal irradiation dose of one or two orders of magnitude higher. However, it does not mean that low doses are harmless for them. Chromosome aberrations in somatic and sexual cells as well as other distortions may be found very often in a remote period or in the next generations in quite healthy by appearance radioresistant plant. Representatives of liliaceous, pine trees and leguminous families show clear signs of inhibition at similar doses. Increased accessibility of disease to plants evidences their low immunity.

Incorporated radionuclides show also different relative biological effectiveness. The α-emitters and especially transuranium elements that accumulate mainly in so-called “on the entrance” (in roots) have the highest RBE values. However, even such radionuclides may provide root meristems with significant doses, causing various radiation-induced damages and growth inhibition. Gamma-radiation of ^{131}I and ^{137}Cs is more penetrable and, accordingly, causes more damage in contrast to relatively soft β-radiation of ^{90}Sr.

All mentioned above features of incorporated radionuclides predetermine various radiobiological effects in plants. Thus, more early flowering and ripening of some plants (radiation stimulation), changes of leaves shape and their gigantism (morphological changes), inhibition of growth and development (radiation sickness), increased number of specific mutations in pollen, acquisition of new signs at daughter's plants (genetic action) were observed on the territories contaminated by radionuclides.

However, the main danger of incorporated radionuclides is not for plants themselves, but it is due to their link between soil and more radiosensitive species, i.e. agricultural animals and humans.

8.2. Biological effects of incorporated radionuclides on animals

The specific character of radiobiological effects of incorporated radioactive substances in an animal organism is mainly determined by their affinities to accumulate in certain places of an organism, creating in such a way centres of strong irradiation. It was found out that from 30 to 50% of ^{131}I can be accumulated in the thyroid gland that makes only 0.02–0.05% of the body mass. ^{90}Sr accumulates almost in bones. It is due to the specific structure of animal organs, physiological and chemical role of some elements and their chemical analogues in implementation of certain functions.

Thus, the thyroid gland is a specialized endocrine organ of vertebrates producing hormones thyroxin and triiodinethyronine that take part in energy and substances metabolism in an organism. Iodine is required for normal functioning of this organ. Such basic processes as growth, development, tissues differentiation and specialization require relatively large quantities of iodine. It penetrates an organism with foodstuffs, water and air in the form of the stable isotope of ^{127}I. However, some soil types of non-black, steppe, deserted and mountain biogeochemical areas contain insufficient or unbalanced with some other elements (Co, Mn, Cu) amounts of iodine. In Ukraine it is Polyssia region that is also the most contaminated by radionuclides after Chernobyl accident. Iodine isotopes such as ^{131}I, ^{133}I and others were among the radionuclides, injected into the environment after the accident. Having the same chemical properties as stable iodine such isotopes may enter an organism of animals and a man, and accumulate in a thyroid, creating additional irradiation by hard γ-radiation. It is especially important pathway in area of iodine deficit. The same situation happened on the great territories of Ukraine, Byelorussia and Russia during first weeks (half-life of the longest-lived iodine isotope ^{131}I is 8 days) after the beginning of the accident.

The highest concentration of ^{131}I in the thyroid gland of mammals after the prolonged absorption is observed in two weeks. Accumulation factor (AF) of ^{131}I by the thyroid gland tissues is several orders of magnitude higher than in other tissues. Assuming the concentration of iodine in blood, muscular tissue, spleen and pancreas equals 1; in kidneys, liver and ovaries – 2–3; in salivary glands and urine – 3–5; in faecal mass and milk – 5–15; and the thyroid gland equals 8000–10000.

However, the main part of a dose caused by ^{131}I (to 80%) is formed during the first 4 days. Since some other iodine isotopes with short life-time, e.g. ^{133}I (20.8 h), ^{135}I (6.6 h) may provide a dose higher than that of ^{131}I. The doses of local irradiation of the thyroid gland may reach tenth and hundredth of Gy. It results in the distortion of structure and functions of this important organ, size reduction and complete destruction. Even relatively low doses may cause local necroses, fibrosis, spreading out of paunch tissue, hypofunction of the thyroid gland, immunity decrease, reproductive function decline, lactation period shortening in cows and negative consequences in offsprings.

Radionuclides from blood may be selectively deposited in bones and, as a rule, stay there for a long time. As a result bone tissues, red marrow and other tissues located on bone surface are irradiated by charged particles or γ-radiation. Such radionuclides are named osteotropous. These are, first of all, ^{45}Ca and chemical analogues of calcium (e.g. artificial ^{90}Sr and its daughter product short-lived pure β-emitter ^{90}Y; and natural ^{226}Ra), actinides (artificial ^{239}Pu, ^{241}Am, natural ^{232}Th, ^{238}U). Radionuclide-analogues of calcium, as well as calcium itself are distributed more or less uniformly within bone volume. From the beginning actinides are mainly deposited on internal and external bone surfaces and later are redistributed within the whole bone volume.

The concentration of osteotropous radionuclides in an animal skeleton, as a rule, hundreds times higher in comparison with soft tissues, creating in such a way strong irradiation field for marrow, i.e. the most radiosensitive organ. The cells of the bone marrow play a major role in the haemopoietic system. Haemopoiesis is the process by which the different cell types of blood are produced. Death or disappearance of any cell element of peripheral blood or of another area of an organism is compensated by the formation of new cells in bone marrow. However, death or damage of one marrow cell may result in the disappearance or the appearance of the whole group of blood cells. It is so-called pathological cellular line. The degeneration or breakdown of the architecture and the vascular structure of the bone marrow occur at the mass irradiation. The number of nucleated bone marrow is reduced. The reduction in cell numbers is primarily due to the fact that the cells are being inhibited from dividing or killed if they attempt mitosis, so that no new cells are being produced. It is known as bone marrow syndrome. Damage of bone marrow cells is lethal since it is the renewal system of the circulating blood cells.

The lethal dose of ^{90}Sr for most mammals is 10–40 MBq per kg^{-1} the body mass. Lower doses may cause in animals such types of blood disease as anaemia, leukemia and others. Syndromes of such disease are sleepiness, fever, appetite loss, haemorrhage of mucus membrane. Generally, animal reactions on absorption of great amounts of ^{90}Sr are similar to external irradiation. It is typical for different stages of radiation sickness. This is natural, since in both cases the bone marrow syndrome develops.

The rate and the quantity of plutonium, americium and other actinides isotopes entering from blood to bone tissue is less. However, their α-particles (nuclei of helium atoms) are more harmful to bone marrow in comparison with

β-emitters (electrons) of ^{90}Sr. Besides, relatively large quantities of plutonium may be accumulated in animal ovaries and testis, resulting in irradiation of ovumes and spermatogenous cells. A biological effect of radionuclides is mass reduction of testis, and sperm production, the decrease of woman's sexual hormone production and oocytes number, that, in turn, negatively affect offspring producing. Undoubtedly, the irradiation of animals' sexual cells increases the possibility for radiobiological effects in next generations.

Appreciable amounts of some other radionuclides such as ^{45}Ca, ^{131}I and ^{137}Cs may accumulate in actively dividing sexual cells inducing gene and chromosome mutations as well as other distortions.

Radioactive isotope ^{137}Cs is the most dangerous isotope for an animal organism among other cesium isotopes. Being incorporated into an organism it is distributed more or less uniformly mainly within soft tissues. Relatively high amounts of ^{137}Cs accumulate in actively metabolizing muscles tissues, including heart tissues. High energy γ-radiation of ^{137}Cs affects negatively not only the soft tissues but also other organs, including critical ones. That is why incorporated into an animal organism ^{137}Cs causes morphological changes of marrow and blood structure. The same danger occur by incorporation of ^{90}Sr, ^{239}Pu as well as by general external irradiation.

^{137}Cs easily penetrates from a mother organism into fetus during the pregnancy period in animals. The concentration of ^{137}Cs in mother organism and fetus equilibrates rather quickly in the case of chronic radionuclide incoming. Radionuclides transfer through the milk to young animals is also rather quick. It concerns not only ^{137}Cs but also ^{90}Sr and ^{131}I.

8.3. Radiation-induced damage of "hot particles" incorporation

Radionuclides are especially dangerous when enter an organism in the form of so-called "hot particles". The "hot particles" are aerosols of microns and submicron size, which radioactivity is several orders of magnitude higher in comparison with similar size particles. Usually, these are particles of reactor fuel that contains fission products of uranium (Fig. 67) or highly radioactive particles produced at nuclear explosions.

Radioactivity of "hot particles" is very high. The particle of few micrometers size may provide a dose of few tens of Grays in living tissue in the radius of 50 μm. Such dose causes death of hundreds and damages thousands of cells.

When “hot particle” deposited and “fixed” on the “sticky” and edged with fur (Fig. 68) it may literally “burn out” cells resulting in various morphological changes of an organ. So called flower uptake of radionuclides (see previous chapter) is especially important in this case, since large particles may enter the flower with following plugging of garden-stuff ovaries.

Being involved in fodder, such particles enter an organism of agricultural animals and humans. However, the most important and therefore dangerous pathway of “hot particles” to an organism is absorption by inhalation.

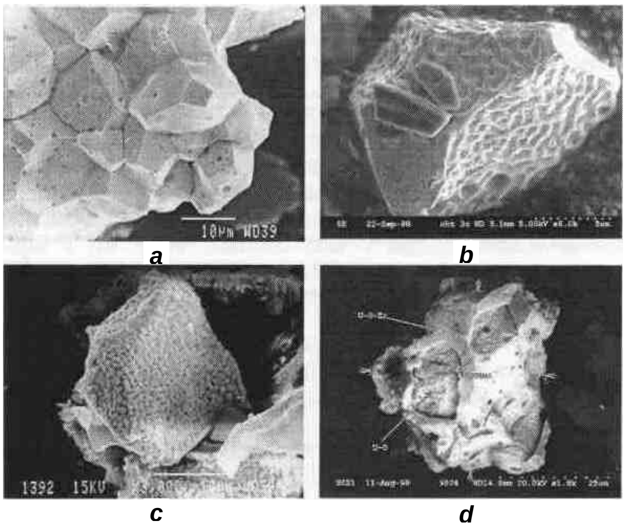

Fig. 67. Typical original appearance of “hot particles” of Chernobyl origin: a and b – slightly, c and d – strongly transformed “hot particles” due to the interaction of nuclear fuel pieces with the construction material of a reactor at a high temperature. Size of particles is about 10 micrometers (V. Kashparov, 2000).

Such pathway is considerable not only during the fall-out period but also due to the secondary wind lifting of radionuclides from the earth surface. Most of the “hot particles” entering an organism with fodder are eliminated through the digestive tract. However, penetrating the lung most of them are “fixed” in the alveoles and very slowly eliminated due to its low solubility. Penetrating the lung and digestive tract, hot particles create “zones” of very intensive irradiation of tissues, including local death of large enough groups of cells causing their damage, various transformations, including malignant ones.

Fig. 68. Radioautography of ordinary radioactive particles and “hot particles” of Chernobyl origin on the pine-needle of pine-tree (A. Bulakh, 1986).

It is suggested that the number of “hot particles” in the environment, particularly, in the atmosphere, is extraordinarily small (one per tens and even thousands m^3 of air). However, the amount of “hot particles” may be significantly higher due to nuclear explosions in the atmosphere, and some types of radioactive substances release at accidents on nuclear plants. In such case it may be spread out over large territories. Thus, fuel particles of Chernobyl origin were detected in many countries of Europe: Sweden, Norway, Germany, Greece, Austria, Switzerland, Poland, Bulgaria, Romania and others.

8.4. Dosimetry principles of ionizing radiation of incorporated radionuclides

Generally, the dosimetry of internal irradiation of plants and animals is rather complicated. Since, incorporated into an organism radioactive substances are nonuniformly distributed within various tissues and organs. The dose formed by incorporated into organism radionuclides depends on many factors that are difficult to control: types of radionuclides, types of compounds with associated radionuclides; types of pathways into an organism, their transfer rate within an organism, localization, life-time; their elimination rate, etc. As a rule, special approaches and methods based on complicated calculations are used. However, even in this case it provides only approximate values of internal dose.

Being incorporated during some period of time in organs and tissues, radionuclides provide a certain dose. Such absorbed dose may be compared with the biological effects caused by external irradiation. In this case it is considered to be a measure of radiation danger. However, absolute dose values may vary significantly.

The pathway of radionuclides into an organism plays very important role in forming of internal irradiation dose. The absorption of radionuclides via inhalation is the most dangerous among other pathways and radioactive - are considered to be the most complicated form of absorption. External irradiation due to aerosols is negligible in comparison with internal one. During the respiration aerosol particles are captured by air flow and through trachea and bronchial tubes enter alveolar tissues, further lymphatic system and, finally, blood. It is suggested, that from 50 to 75% of inhalated particles retain in respiratory tracts. In such a case the respiratory system and lung are considered to be the critical organ.

The size of particles, their loss rate from lung tissue, types and energy of ionizing radiation, the radioactivity distribution according to the size of radioactive particles, the pattern of settled aerosol particles distribution, etc. mainly determine the dose rate. Mentioned above factors create problems in direct determination of absorbed dose caused by aerosols. For this reason, dosimetry of radioactive aerosols actually turns into radiometry that is the determination of aerosols activity in air.

Thus, internal irradiation dose may be approximately estimated if the air consumption rate, the radioactive aerosol concentration in air, the rate of its deposition in lungs and types of radioactivity is known. It is known, for example, that humans consume and breathe out 20000 liters per day at average.

However, the air pathway of radioactive substances into an organism and, consequently, a dose rate is only important during the fall-out period. Later, however, the contaminated fodder and water are the main factors that determine the dose rate of internal irradiation. The dose formation of any organ or tissue is governed by radionuclide loss and accumulation. The dose rate is governed by a chemical form of a radionuclide, a type of a chemical compound with associated radionuclide, and other factors mentioned above.

Since many factors listed above is hard to take into account for dose estimation various models are proposed to use. One of such approaches is so called mathematical “chamber” model. According to the concept of this model the radionuclide concentration in tissue at any moment is determined by direct and reverse processes, i.e. accumulation and loss of radionuclide. The proposed model may be considered as a formation of some amounts of radionuclides within a certain area of an organism (organ or tissue) that are likely connected by transport communications, e.g. the row of chambers (the name of models), where radionuclides accumulate. The inflow and the outflow of radionuclides take place through these chambers. Such separate model chambers may be compared with real areas of an organism, e.g. organs or tissues through these chambers. For example, transfer of radionuclides with a blood flow may be described by a model, where blood-vessels serve as transport communications, and chambers are such areas of an organism, where exchange of radionuclides takes place.

Such mathematical analysis of chamber models allows estimating the concentration and the speed transfer of radionuclides within an organism. The data of the concentration and the intake rate of radionuclides from the environment into an organism are considered to be incoming data. External environment is considered to be one of the chambers. The next step of the model is to calculate the amount of radionuclides taken in and to estimate the internal irradiation dose. It may be done by the solution of the linear equation system, i.e. the balance of metabolite rate that contains radionuclides. Undoubtedly, it is a very difficult task and obtained results are rather conditional. Nevertheless, it gives the general idea about dose orders caused by incorporated radionuclides.

Obviously, the problem of incorporated radionuclide dosimetry concerns mainly animals and humans. The plant is considered to be one of the possible sources of the dose formation. Although, being taken up by plant, radionuclides are nonuniformly distributed within plant body providing high levels of irradiation in some tissues and organs.

Recently, methods of biological dosimetry for the estimation of received doses by a man have been developed. The most widely used method based on almost linear dependence between a dose received by a man and a number of chromosome aberrations in lymphocytes of peripheral blood that is an original detector of ionizing radiation inside an organism. There is evidence that data obtained by such method are quite reliable and correspond to data obtained by modern methods based on the instrumental dosimetry measurements and calculations. Biological dosimetry allows registering the total dose of external and internal irradiation. Nowadays methods of biological dosimetry may be a useful tool on the territories contaminated by radionuclides of Chernobyl origin, where doses of internal irradiation reach 95% of the total dose.

Biological dosimetry methods become absolutely indispensable for estimation of internal irradiation doses in plants. There is a clear dependence between a number of cells with chromosome aberrations in meristem and a dose. Such method allows estimating the internal irradiation dose in plants, since a dose in plants on the contaminated territories is formed mainly due to the root uptake of radionuclides. As a biological “dosimeter” meristem of primary rootlets of seeds produced by plants that are grown on the contaminated territories is used. The dose formed by incorporated radionuclides may be found when real and experimental data of dose-effect curves are compared. Thus, curves showed in Fig. 69 evidence that plant growing at ^{137}Cs contamination level of 2 000 kBq m^{-2} obtains a dose of internal irradiation that equals about 4.7 Gy of external γ-radiation.

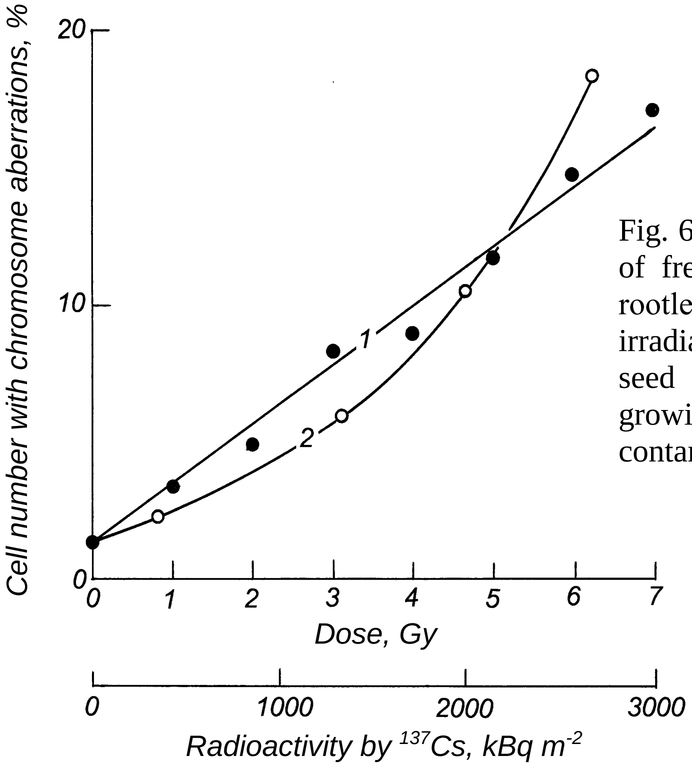

Fig. 69. The comparison of dose dependences of frequency of chromosome aberrations in rootlets meristem of bean seeds at external γ-irradiation in the laboratory experiment (1) in seed rootlets obtained from the plants growing in areas with different levels of the contamination by ^{137}Cs (2).

8.5. Prognostication of radionuclide uptake by agricultural products

Relative contribution of the incorporated radionuclides to the total dose received by population of Ukraine after the Chernobyl accident increases with time (Fig. 70). The responsibility of agricultural workers concerning the production of safe foodstuffs also increases, since agricultural food products as well as processing products are main constituents of human nutrition. Other sources such as fish, game, forest products, etc. are of minor concern, since its contribution to the nutrition most of population is relatively small.

The knowledge of radionuclide concentration in soil, water, agricultural plants and animals is necessary to adjust to its transfer and accumulation; to reduce the radiation doses that would be received through the consumption of contaminated food. Mentioned above adjustment is based on the prognostication of radionuclide uptake by plant from soil and by animals with fodder.

Prognostication of radionuclide uptake and accumulation by agricultural plants followed by the implementation of measures preventing their further move through migration within food chains is the main task of agricultural radiobiology and radioecology for today. Such prognostication requires detailed information of the radionuclide contamination specificity of the territory as well as the reference data about factors affecting radionuclides uptake by plants, e.g. soil types, its nutrient state, plant species, etc. There is the number of other factors affecting radionuclide uptake by plants, but many of them are hard to take into account and to control. These are weather conditions (precipitations that determine radionuclide mobility), uptake rate of radionuclides by plants (precipitations, air movement, and temperature), and biomass accumulation rate by plants (precipitations, temperature, and insolation).

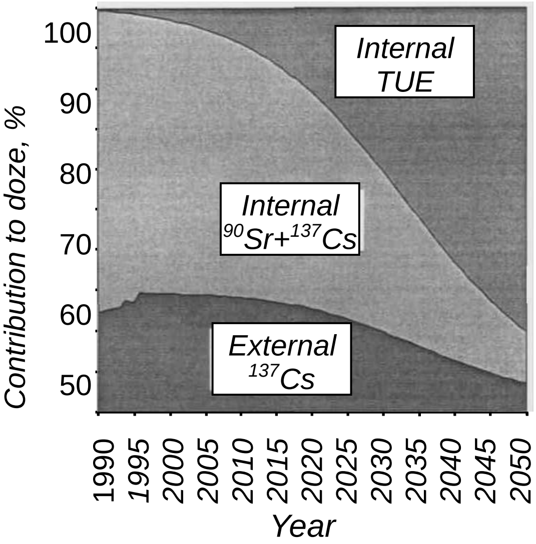

Fig. 70. Relative contribution of various radionuclides and irradiation to the total dose obtained by population in Ukraine (TUE – transuranium elements; O. Bondarenko, 2002).

8.5.1. Prognostication of radionuclide uptake by plants

There are also some basic methods used for rough estimation of possible contamination level of agricultural plants by the radioactive substances.

Accumulation factor (AF) or transfer factor (TF) are among the most widely used methods that allow estimating the radionuclide uptake by various plant organs depending on the specific soil characteristics. Table 24 shows mean values of AF for ^{90}Sr by some types of agricultural plants depending on the soil type. As we've already mentioned AF is defined as the ratio of the specific radionuclide activity in the plant tissue (usually some edible organs or over ground parts) and the soil with dry masses of each material usually must be taken into account:

$$AF = Bq\ kg^{-1}\ DW\ Plant\ /\ Bq\ kg^{-1}\ DW\ soil.$$

The given AF value and activity concentration per soil unit (A_s) the activity concentration per plant unit (A_p) may be written as:

$$A_p = A_s \times AF$$

Comparing obtained value with the value of permissible level for specific plant, the outcome may be reacted by the suitability of specific soil for production.

Table 24. Mean values of accumulation factor (AF)* of ^{90}Sr for some agricultural plants growing in different soil types (B. Annenkov, E. Judintseva, 1991)

Plant	Soddy-podzol soils				Chernozem leached
	loamy sand	sandy loam	sandy clay loam	clay loam	
Wheat (grain)	0.70	0.35	0.20	0.12	0.06
Potatoes	0.35	0.17	0.10	0.06	0.03
Read beets	1.20	0.58	0.34	0.20	0.10
Cabbage	0.90	0.50	0.22	0.16	0.07
Cucumber	0.35	0.17	0.10	0.06	0.03
Tomato	0.14	0.07	0.04	0.02	0.01
Clover (hay)	20.00	11.00	6.00	4.00	2.00
Timothy-grass (hay)	7.00	3.50	2.00	1.20	0.60

* The AF values for potatoes and other vegetables are provided on the wet weight base, other – on dry weight base.

TFs for great variety of agricultural plants and soil types will be provided in the next chapter. These values may be used in a similar way.

This method can be used for prognostication of any radionuclide accumulation by plants. Thus, the only AF or TF values are necessary. The more precise and differentiated they are regarding different plant species and their kinds as well as soil types, where plants grow, the more precisely radionuclide accumulation in plant products can be prognosticated. It is very important to work out average CR and TF values.

In practice, it is even easier to foresee the radionuclide uptake by agricultural plants using special tables as one of those, provided below (Table 25). Approximate values of ^{90}Sr and ^{137}Cs content in the plant tissue of concern are shown. Data provided for plants that were grown on the typical for Ukraine soil types at the ground deposition of ^{137}Cs 37 kBq m^{-2} (1 Ci km^{-2}) are shown in this Table. Since there is a direct relationship between radionuclide content in plants tissue and in soil, there is a need to correct data provided in the table by corresponding correction factor accordingly.

If no information about the concentration ratio or radionuclide content in plants at certain ground deposition level is provided, the possible amount of radionuclides in agricultural products is determined experimentally by “shoot” method. For this laboratory test is carried out. Before sowing the field, the same soil (taken in the field from 10–15 cm depth) is used for an experimental laboratory sowing. Experimental plants are harvested, after being grown for 15–30 days, and radionuclide content is determined on dry weight base. It gives a value of possible radionuclide accumulation by vegetative mass of plant. The activity in plant organs and tissues of concern (grain, fruits) may be calculated by using corresponding correction factors.

Table 25. Content of ^{90}Sr (numerator) and ^{137}Cs (denominator) in the harvesting part of agricultural plants (Bq kg^{-1})* at the ground deposition of ^{137}Cs 37 kBq m^{-2} (1 Ci km^{-2}) (E. Judintseva, 1989)

Plants	Harvesting part	Soddy-podzol soils				Grey soils, chestnut and meadow soils	Grey forest soils	Chernozems
		sandy	sandy loam	sandy loam and sandy clay loam	clay loam			
Winter wheat	Grain	74 15	37 7.4	22.2 2.22	11 1.1	7.4 0.74	15 1.85	3.7 0.37
Winter rye	Grain	74 15	37 7.4	22.2 2.22	11 1.1	7.4 0.74	15 1.85	3.7 0.37
Oat	Grain	333 29.6	222 15	110 4.8	51.8 2.22	37 1.85	74 3.33	15 1,1

Barley	Grain	296 22.2	185 15	110 4.8	55.5 2.22	29.6 1.85	66.6 3.33	15 1.1
Pea	Grain	518 248	260 37	148 11	74 5.92	58 3.7	111 7.4	22.2 1.85
Maize	Green forage	925 22.2	444 11	222 3.7	110 1.85	89 1.48	148 2.6	44.4 0.74
Vetch-oats mixture	Green forage	333 66.6	222 33.3	129.5 11	66.6 5.55	92.5 7.4	37 9.25	11 3.7
Potatoes	Tubers	1480 15	96.2 7.4	63 3.7	29.6 1.1	11 2.96	37 2.96	3.7 1.85
Red beet	Root-crops	370 74	222 37	110 14.8	59 7.4	74 5.55	74 9.25	11 2.6
Cabbage	Heads	92.5 29.6	44.4 15	22.2 7.4	11 3.7	7.4 2.6	15 1.85	3.7 1.5
Flax	Straw	296 29.6	185 15	110 7.4	55.5 3.33	- -	66.6 1.85	- -

* for a grain and straw – on a dry weight base, other – on a wet weight base

There are also another ways to foresee the expected radionuclide content in agricultural plants at the harvest time. However, all of them have limitations that require preliminarily specifications and, in some cases, conducting of special researches. Of course, any reference concentration ratios or transfer factors require certain correction depending on the weather conditions, precipitations, etc.

8.5.2. Prognostication of radionuclide uptake by animals

Existing methods of radionuclide absorption prognostication by agricultural animals are based on similar calculations. If the fodder contamination level is known, the content of radionuclides in any animal tissues or organs may be found using the same approaches (CR and TF).

In Table 26 CRs that is a portion of radioactivity transferred from the forage to animal tissue are shown. The approximate value of animal products may be obtained by multiplying these values with average radioactivity values of forage.

Reference data about possible content of radionuclides in the animal products are shown in Table 27. Reference data for animals also require certain correction depending on the ground deposition of radionuclides.

Table 26. Maximum values of transfer factor (TF) of radionuclides from the fodder to animal products, % of daily absorption per 1 kg or 1 litter (N. Kornejev, A. Syrotkin, 1987)

Radionuclide	Beef (muscles)	Pork (muscles)	Poultry meat	Eggs (melange)	Milk
^{90}Sr	0.08	0.06	3.2	22.0	0.14
^{131}I	0.72	2.7	20.0	0.44	1.0
^{137}Cs	20.0	30.0	440.0	43.0	1.0
^{239}Pu	0.0001	0.0003	0.002	0.33	0.0002
^{241}Am	0.0004	0.001	0.007	0.39	0.0003

8.6. Norm setting of radionuclide content in agricultural products

Thus, using approaches listed above it is possible to foresee the approximate level of radioactive contamination of agricultural products of plant and animal origin. The main goal of the prognostication (if necessary) is to provide countermeasures on the radioactively contaminated territories to reduce radionuclides absorption by agricultural plants and animals. It concerns changes in technologies of crops production, introduction of various measures to reduce radionuclide uptake by plants, changes in fodder base for animals, improvement of animals keeping, changes in rations and other measures that will be described in more details in the next chapter. Prognostication of radionuclide absorption by agricultural plants and animals followed by appropriate countermeasures application is based on the permissible levels (PL) of radionuclide content in foodstuffs, especially in agricultural products.

The essence of norm setting of radionuclide content in agricultural products is to reduce its sorption by plants and animals below the permissible levels. For example, according to PL-2006 (“Permissible levels of radionuclides ^{137}Cs and ^{90}Sr content in foodstuffs and drinking-water”, issued in 2006), the ^{137}Cs content in vegetables should not exceed 40 Bq kg^{-1}. Let’s consider the situation that accumulation of ^{137}Cs by certain types of vegetables, e.g. potassiphils such as red beet or cabbage exceeds permissible levels.

There are few options here: the first option is to grow vegetables on the less contaminated field; the second possibility is to apply potassium fertilizers; the third is to replace these vegetables with other ones that have lower CR values. Similar approaches may be utilized, when the reduction of radionuclide transfer to agricultural animals is required.

Table 27. Radionuclide concentration in animal products (Bq kg^{-1}) at keeping animals on fodder obtained on sandy podzol soils at the ground deposition of 37 kBq m^{-2} (1 Ci km^{-2}) (B. Annenkov, E. Judintseva, 1991)

Products	Fodder type	^{90}Sr	^{137}Cs
Beef	Bulking	2.22	51.8
	Concentrated	1.11	25.9
Pork	Bulking	0.74	21.6
	Concentrated	0.37	18.5
Mutton	Bulking	3.70	77.7
Poultry	Concentrated	0.74	14.8
Egg (one)	Concentrated	0.074	0.11
Milk	Bulking(20:50:30)*	87.0	14.8
	Semi concentrated (20:30:50)*	25.9	11.1
	Concentrated (15:15:70)*	18.5	7.4

* ratio among coarse, rich and concentrated forages

However, reducing the radioactive contamination of agricultural products of animal origin seems to be more important, since the contribution of animal products accounts about 70% of the total dose to human nutrition. There are two basic requirements to the norm setting of radionuclides content in agricultural products of animal origin: firstly, radionuclide uptake should not induce the negative effect on animal health that, in turn, may cause the decline of their productivity and the inhibition of reproduction ability; and, secondly, radionuclide content in animal products should not exceed PLs.

Nowadays in Ukraine there is no reason to claim that absorption of radionuclides by productive animals may reach levels causing the development of any radiobiological effects or any signs of radiation sickness. Besides, any reveal of radiobiological effects or signs of radiation sickness may be eliminated by breeding practice (rejection of animals, their breeding limitation etc.). Such measures allow avoiding negative consequences of radiation-induced damage associated with the productivity of animal breeding. Therefore, the level of radionuclide absorption by agricultural animals is mainly limited by the necessity to obtain clean animal products.

The conditions of milk and meat production are completely different. Milk is mainly produced by cattle. Meat is mainly produced by young animals of cattle, pigs and less by poultry and sheep. However, feeding practice differs even for diary and meat cattle. The ration of milking cows consists mainly of concentrated fodder and different sub-fodders; the ration of meat producing cattle comprises herbage pasturage during the period of pasturing and coarse forage used during indoor keeping. Radionuclide transfer from the fodder to milk and meat is different. These factors as well as essential differences in milk and meat consumption determine different ways of radionuclide absorption by a man and evidence the necessity of norm setting of radionuclide transfer into the ration of beef and diary cattle.

Permissible levels of radionuclide content in the forage for agricultural animals are similar to plants and determined by their permissible levels in a human nutrition. It is not a problem in the case of specific radionuclide, specific animal product, and if an animal fed by only one specific type of forage. In this case the permissible level of radionuclide in the ration of animals (PL_{RA}) may be calculated from simple equation:

$$PL_{RA} = PL_P/TF,$$

where PL_P is a permissible level of radionuclide in a product, TF is a transfer factor.

Usually norm setting takes into account more than one radionuclide (most frequently ^{90}Sr and ^{137}Cs). Human nutrition comprises different types of meat and milk products and eggs. The ration of agricultural animals also consists of many components: grass, hay, straw, silo, concentrates, etc. that are different for specific types, species and strains of cattle. There are also essential regional differences in the ration of animals and humans nutrition as well as among rural and urban people. Therefore, the calculations of permissible level in the ration of animals are getting more complicated.

There is no need to give examples of such calculations in this textbook. The data concerning the contribution of a specific radionuclide to the total level of ration contamination, ration and nutrition composition as well as some other information of concern may be calculated by using special equations (formulas).

Difficulties of norm setting of radionuclides transfer from the forage to animal products give rise to use various mathematic model computations. In such model all animal products are considered to be equal to a certain amount of, for example, milk, and forage is considered to be equal to a certain amount of, for example, hay. The result of such norm setting may be rather approximate. However, it may show tendencies correctly enough.

Generally, norm setting of radionuclide transfer in the soil-plant-forage system, when radionuclides enter an animal organism with fodder and water, is one of the most difficult and important problem in a modern agricultural radiobiology. However, still there is lack of knowledge in radionuclide behaviour within an animal organism, especially under the condition of some radionuclide complex effect. It makes difficult to estimate correctly permissible radionuclide content in fodder; and consequently, it does not allow estimating correctly a dose received by an animal and a man.

There is a plenty of data describing transfer of radionuclides from the environment to plant products. The relationships between fall-outs intensity and radionuclide content in soil, accumulating ability of radionuclides by various plant types and their transfer in animal products. Knowledge of this dependence is very important in terms of reduction of radiation doses that can be received through the consumption of contaminated food by people living in the contaminated areas. It is necessary for the implementation of countermeasures to reduce radionuclide content in food products.

Mentioned in the beginning of this chapter effects of radioactive substances incorporated into an organism give an idea about danger of radiation to living organisms. Therapeutic measures are ineffective to eliminate these substances from an organism. Therefore, the only way is to prevent such substances from being entered an organism. According to the scheme of radionuclide migration in the environment and within an area of agricultural production (Fig. 55) it may be done at any stage of their pathway to a man. Undoubtedly, the prevention of their sorption in the soil-plant-animal system seems to be the most effective way. These questions are directed to the agricultural practice and they will be described in the next chapter.

Control points to chapter 8:

1. Determination of the concept of incorporated radionuclides.
2. Specificity of radionuclide sorption by tissues and organs of plants and animals.
3. High danger of some types of radiation caused by the action of incorporated radionuclides.
4. The reasons of prolonged action of incorporated radionuclides on an organism.
5. The factors affecting radionuclides uptake and accumulation by plant and animal organisms.
6. Specificity of radiobiological effects in a plant caused by incorporated radionuclides.
7. Specificity of radiobiological effects in an animal organism caused by incorporated radionuclides.
8. The reasons of great local accumulation of radioactive iodine in an organism of vertebrates.
9. The reasons of great danger of radioactive strontium accumulation in mammal organisms.
10. Hot particles and their action on an organism.
11. Dosimetry of incorporated radionuclides.
12. The essence of biological dosimetry method of ionizing radiation.
13. Prognostication methods of radionuclide accumulation in agricultural plants.

14. Prognostication principles of radionuclide accumulation by organs and tissues of animals.
15. The essence of norm setting of radionuclide sorption and accumulation in agricultural plants
and productive animal organisms.

9. RADIOACTIVE SUBSTANCES MIGRATION IN THE ENVIRONMENT

9.1. General principles of radioactive substances migration in the environment. 9.2. Atmospheric dispersion and deposition of radionuclides. 9.3. The migration of radioactive substances in soil. 9.4. Plant uptake of radionuclides from soil. 9.4.1. Uptake by above-ground organs. 9.4.2. Root uptake. 9.4.3. Behaviour of radionuclides in forest ecosystems. 9.5. Transfer of radionuclides to food producing animals.

Thus, as we mentioned in chapter 3, the accidental release of nuclear fusion products in the environment as a result of nuclear weapon tests as well as the release under normal operation, accidental release from nuclear reactors and nuclear processing plants are especially dangerous. Such accidental release may lead to local and global contamination of the earth surface and of all living organisms for many years.

Most of the artificial isotopes entering the environment are short-lived radionuclides and undergo decay during some hours or months. The long-lived radionuclides, such as ^{90}Sr (half-decay period is 29 years), ^{137}Cs (half-decay period is 30 years) and ^{239}Pu (half-decay period is 24 380 years) and some other radionuclides of Chernobyl origin are considered to be especially dangerous for people and all living organisms today and in the nearest future. These radionuclides will be referred to in this chapter.

As we mentioned in chapter 1, radioecology is a science that studies the concentration and migration of radioactive substances in environment and the effect of radioactivity on living organisms.

Thus, *agricultural radioecology is a section of general radioecology that studies uptake of radionuclides through biological chains in the objects of agricultural production and following effects on agricultural plants and animals as well as agrocenosis*.

The objectives of general and agricultural radioecology follow from its definition. Generally, they are similar, and it is difficult to draw a line between environmental and agricultural objects. The special practical objective of agricultural radioecology is to reveal the territories contaminated by radionuclides; transfer of radioactive substances by food chains; mitigation of ecological relationships within any part of their pathway due to cleaning up the territory or using another measures; reduction of the radionuclide transfer from environment to agricultural products.

9.1. General principles of radioactive substances migration in the environment

The radioactive substances deposited on the earth surface enter biological cycles and natural turnover of the elements. Through the food chains they enter a human body. It is very important for agriculture specialists to be acquainted with the radionuclide pathways by food chains depending on the nutrition peculiarities of cultural plants and food producing animals.

The general scheme of the radionuclide pathways in the environment is shown in Fig. 71. As follows from the scheme radionuclides deposited on the earth surface are concentrated in three main objects of the environment: soil, plants and water sources.

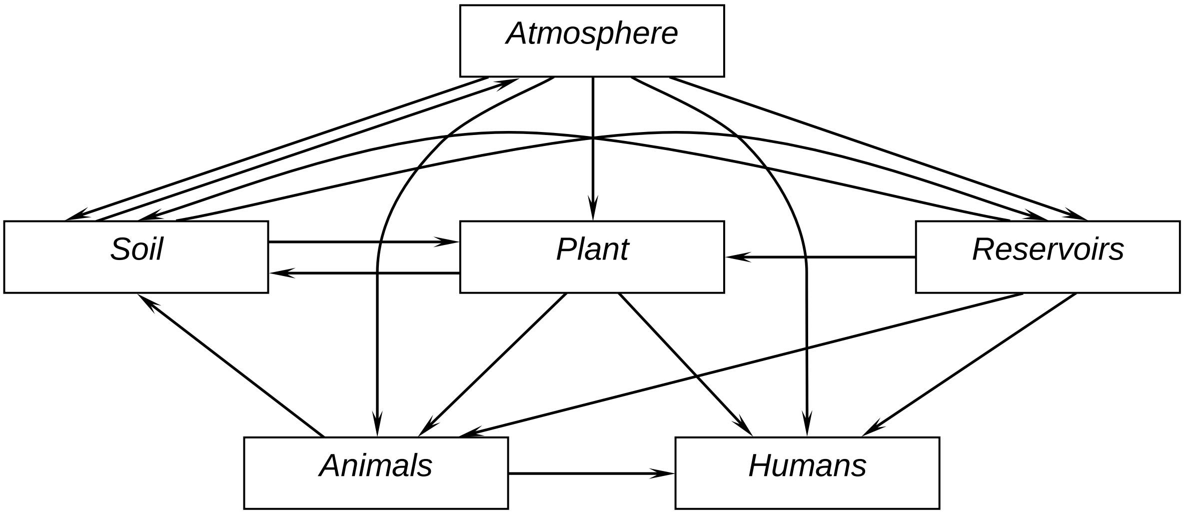

Fig. 71. Pathways of radionuclides migration to the environment.

Being dissolved in the water of atmospheric precipitations, irrigate water or being mechanically mixed with water flows the radioactive substances infiltrate to the deep soil layers.

Airborne radioactive particles with high density (more than 1) when entered water surface fall down on the bottom and concentrate in silt deposits. With time, however, some substances dissolve causing the contamination of water.

Airborne radioactive particles deposited on the plants may be adsorbed through the plant surface by means of diffusion or may enter plants through the pores.

Entering plants radionuclides are involved in the metabolism and may be accumulated in organs being a food source. Later, the main part of the radionuclides enters a plant from soil through the root system. Some amount of radionuclides may migrate to plants from the contaminated water during the flooding period and due to irrigation.

The contaminated plants are the main radionuclide pathway to agricultural animals with fodder. The contaminated water from opened reservoirs is another source of radionuclide uptake for animals.

Finally, radionuclides may enter a human body with contaminated food or water.

When contaminated fodder enters the animal body, the major part of radioactive substances does not assimilate and is not accumulated in animal tissues, but excretes together with faeces. The radioactive substances accumulated in plants may return to the soil by similar pathway with composts, ash, etc.

The concentration of radioactive substances in various subjects during transfer in the environment alters and, as a rule, decreases. For instance, the content of radionuclides in plants is lower in comparison with soil where they grow; the content of radionuclides in milk and meat is lower in comparison with the fodder.

However, the concentration of radionuclides in plants may be higher in comparison with soil where they grow. In this case the accumulation of radionuclides takes place.

The *accumulation factor (AF)* or so called *transfer ratio* (TR) and sometimes *transfer factor (TF)* are used as a measure of radionuclide uptake by an organism. This is defined as *the ratio of the specific radionuclide activity in the plant tissue (usually some edible organs or above ground parts) and in the soil with the dry masses of each material usually being taken into account*. The soil part is the surface soil, i.e. 10–20 cm of the soil profile. The bulk root density is usually found in these soil layers. As for animals it is *the ratio of the specific radionuclide activity in the animal tissue and the equivalent volume of fodder*.

The definition of AF (as the most commonly used) is the following:

AF = Bq kg^{-1} DW Plant / Bq kg^{-1} DW soil □dimensionless□

Another definition of TF based on radionuclide activities on both a mass and an area basis is:

TF = Bq $\mathrm{kg^{-1}}$ DW Plant / Bq $\mathrm{m^{-2}}$ soil □$\mathrm{m^{-2}/ kg^{-1}}$ DW□

Both measures come to an agreement with each other but they differ in numerical range.

The study of radionuclides behavior in the environment has a practical significance. Radioactively contaminated foodstuffs may become the main source of internal irradiation of a man. Some biological and food chains of radionuclides transfer are examined below.

9.2. Atmospheric dispersion and deposition of radionuclides

Not always, but very often, the atmosphere is the first place where potentially dangerous materials such as gas, aerosols, or fine particles enter. However, the atmosphere is the place that promotes the migration of radionuclides and their transfer for a long distance.

There are four main factors that determine the migration of radionuclides in the atmosphere: the height of radionuclide release, wind flow, gravity and atmospheric precipitation. Depending on the interaction of these factors or, at least, some of them the local, tropospheric and stratospheric fall-outs are distinguished.

The local fall-outs take place when radioactive substances release at the height of up to 4 km. They disperse mainly within lower layers of the atmosphere and continue about a few days in the case of a single release. The radioactive cloud follows the wind direction and results in the formation of so-called “track” on the Earth surface. Usually, local fall-outs deposit within the area with a radius of about 30 km. For this reason, the radius of an emergency zone around nuclear processing plants is 30 km. However, the radioactive cloud may be spread over 30 km zone due to the strong wind.

The tropospheric fall-outs are the release of radioactive substances at the height of up to 10 km. The troposphere winds transfer the radioactive fall-outs from the west to the east and radioactive cloud may go round the terrestrial globe for 2–6 weeks. The Chernobyl accident is an example of troposphere fall-outs. During 15 days after the accident the ascending flow of fire products raises the radioactive substances into the troposphere up to 7 km. The fall-outs from lower layer of the atmosphere were found after 1–3 days in many countries of West Europe and fall-outs from higher layers were found after 10–12 days in

Japan, Canada and USA. Within the period of about two weeks the radioactive cloud went round the terrestrial globe to the north hemisphere and come back to Europe from the west.

The stratospheric or global fall-outs are the release of radioactive substances at the height of 10–12 km and above. This is the result of atmospheric nuclear weapon testing. The radioactive products of the explosion (the smallest as well as the finest particles) may persist in the stratosphere for some years. The cosmic fall-outs are the result of nuclear weapon testing in space. In the beginning of 1960s the former Soviet Union and the USA performed 10 nuclear bomb tests at the height of about 200 km. The fission products still enter the Earth surface.

The dispersion of released radioactive particles is rather great and varies from one-hundredth to some tens of micrometers (10^{-6} meters). Such particles may be transferred for a distance of tens thousands kilometres, but, finally, they will fall out to the Earth surface under gravity forces. The knowledge of the radionuclide particle transfer depending on their size has a practical meaning to predict the contamination level of the territory and possible involvement of radionuclides in trophic chains. It is connected with the great surface area contact of particles with the environment, their high solubility and, therefore, high ability to enter biological cycles.

The atmospheric precipitations may speed up and enhance the fall-outs resulting in unexpectedly heavy contamination of a territory. For this reason, “dry” and “wet” depositions are distinguished. The “dry” fall-outs mean the deposition of airborne radioactive particles and gases present in the lowest layers of the atmosphere onto the underlying surface and vegetation by means of gravity. The “wet” fall-outs mean the deposition of radioactive substances with rain and snow. The proportion of “dry” or “wet” deposition depends on many factors, but is mainly determined by season. “Wet” deposition during warm spring-summer season increases their solubility, the migration rate to soil and the uptake by plants.

There is one more deposition process called occult, or hidden, which can be important given wind-blown cloud or fog at ground level. Water droplets are often large enough because they are blown through the vegetation and they are deposited on the foliage, carrying the pollutants with them.

9.3. Migration of radioactive substances in soil

Soil forms the basis of almost the whole agricultural production and is of great interest concerning its contamination with a variety of substances, both natural and man-made. Soil is the main source of natural radionuclides for biosphere and as shown in Fig. 72, it is the main chain, where artificial radionuclides are deposited from the atmosphere.

The migration or transfer of radionuclides to soil is an aggregate of processes leading to their movement in soil and their redistribution in the depth and horizontally. There are two types of migration: the vertical and horizontal that take place simultaneously and, therefore, have to be considered together.

The ability of radionuclides to migrate to soil and to enter the biological cycles depends on the radionuclides themselves, on soil and various factors of the environment.

The role of physical and chemical affinities of radionuclides. There are several physical and chemical forms of deposited radionuclides in the environment: aerosols, hydrosols, particles adsorbed on the various materials etc. Their mobility depends on the forms of deposited radionuclides. Thus, after the Chernobyl accident there were three types of fall-outs: solid highly radioactive aerosols with different dispersion, gaseous face of radionuclides and radionuclides of graphite matrix. The last specific type of radioactive particles was formed during the burning of graphite blocks used as a neutron moderator in nuclear reactors.

There are two main groups of factors that determine the mobility and bioavailability of radionuclides. The first group determines so called “aging” of radionuclides. The essence of radionuclide “aging” consists in either diffusion of radionuclides in crystal grade of some minerals, or the formation of various compounds and aggregation of small particles in bigger ones that reduces their migration rate to soil. The “aging” of caesium radionuclides that reduces their bioavailability for plants, is well known.

The second group of factors may increase the mobility of radionuclides and hence their bioavailability. Thus, soil water, soil microflora, oxygen and other factors may affect the coarse-dispersed particles and transform them to small-dispersed particles. Released radionuclides undergo transformation in soil solution from inaccessible forms to more soluble and therefore easily available for plants.

The chemical properties of soil that determine their ability to adsorption, the formation of complex compounds are of great importance. Finally, such properties determine the radionuclides behaviour in soil and its bioavailability. Thus, the higher ion charge, the stronger it is fixed by soil and the more stable compounds are formed with an organic matter. However, such relationship is less pronounced if atomic mass and ionic radius increase. The ions of radionuclides are taking up by plants more intensively if they are free in comparison with hydrated or solvated state.

The effect of soil-texture and mineralogical composition. It is well known, that plants growing in water culture take up radionuclides more intensively in comparison with the plants that grow in soil with the same level of radioactivity. This is due to soil solid face that takes up and retains the radionuclides. Such ability will vary depending on soil type, soil-texture, and mineralogical composition. These soil properties mainly determine bioavailability of radionuclides and their migration in soil.

The sorption ability of soil increases with the increase of a soil-texture dispersion. The curves (Fig. 72) show that the content of a clay fraction (diameter < 0,001 mm) within the same soil type affects the radionuclide uptake by one order of magnitude. The silt fraction fixes fission products most efficiently.

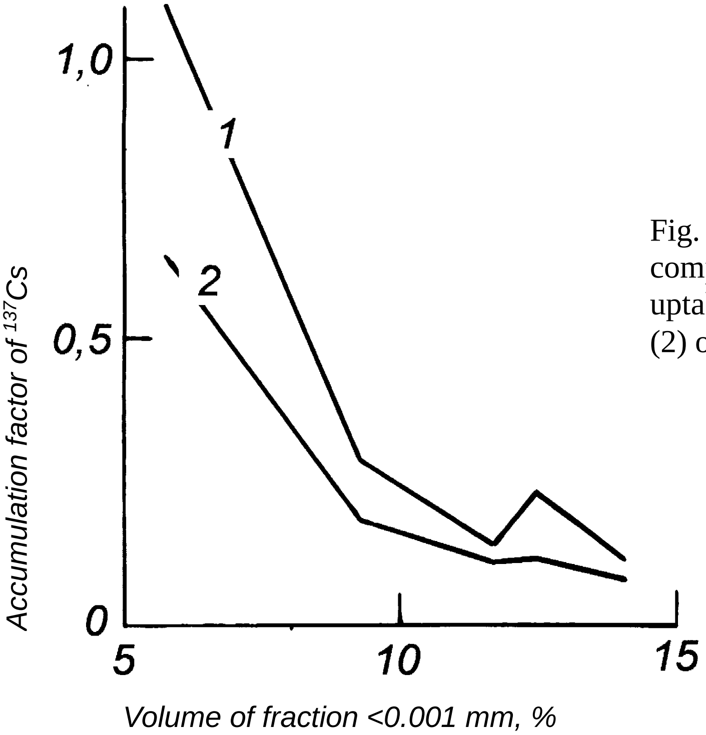

Fig. 72. The effect of a soil-texture composition of soddy-podzol soil on the uptake of ^{137}Cs by straw (1) and grain (2) of oats (R. Alexakhin et al., 1991).

Apart of this, small-dispersed and silt fractions of soil contain minerals of montmorillonite group and micaceous clay minerals, particularly illite. Illite has a staked-layer structure that creates surfaces where simple ion-exchange sorption can take place (so-called planar sites). The prevailing minerals of sand, even fine ones are quartz and feldspars. Their sorption affinities are very low.

Fine dusty and silt particles of highly dispersed fractions of soil also enriched with an organic matter that, in turn, affects the radionuclide migration. High humus content decreases radionuclide uptake by plants that is related to the ability of humic and fulvic acids to absorb radionuclides and form complex compounds.

An organic mater fraction decreases in coarse dust fractions. Fine sand fractions contain very little amount of an organic matter.

Organic (peat) soils instead contain up to 90% of an organic matter. However, they mainly contain dead semi-decomposed plant residues and a very little humus and fine dispersed mineral fraction. Such soils are characterized by a low content of exchangeable cations, low cation exchange capacity and, consequently, a low ability to retain radionuclides.

Generally, the listed above soil properties determine a specific level of soil to absorb and retain radionuclides. According to their ability to absorb and retain radionuclides the soil types may be ranked in the following increasing order: an organic (peat) soil > podzols > soddy-podzol > forest grey > meadow soil > grey > chestnut > chernozems.

The role of agrochemical properties of soil. Normally, the radionuclide content in soils is extremely low. For example, at the level of ^{137}Cs content in soil of 3.7×10^{4} Bq m^{-2}, which corresponds to 1 Ci km^{-2} (the level of ^{137}Cs content in soil, which is considered to be contaminated by ^{137}Cs), the mass concentration of ^{137}Cs in ploughing layer is about 3.9×10^{-12}%, and of ^{90}Sr even less 2.4×10^{-12}%. It corresponds to the value of 10^{-5} g m^{-2}, or 10 g km^{-2}. An activity concentration in a soil solution of 1 Bq l^{-1} of ^{90}Sr or ^{137}Cs corresponds to ca. 2×10^{-15} M l^{-1}, whereas median concentration of Ca, K and Mg in a soil solution is in the order of 1 mM l^{-1}. Such low concentrations of radionuclides in soil mean that radionuclides behaviour depends on the concentration of their stable isotopes and elements, having similar physical and chemical properties and on chemical properties of soil. Generally, a number of substances naturally occurring in soil are considered to influence the uptake of radionuclides.

The pH reaction of a soil solution affects the radionuclides behaviour. For example, in the case of ^{137}Cs and ^{90}Sr an increased soil acidity results in extra release of nuclides from a soil matrix and make them more mobile and consequently more available for root uptake. The bioavailability of ^{59}Fe, ^{60}Co and ^{65}Zn decreases when pH rises. These radionuclides turn from the ionic forms into various hydrolyzed and complex compounds with low bioavailability.

The content of exchangeable Ca in soil (Ca defines so called "carbonaceous" soil properties) determines the migration and bioavailability of radionuclides to great extend. The carbonates content is rather high in many soils spread in semi-arid regions. High Ca content in soil inhibits ^{90}Sr uptake by plants. Data (Table 28) evidence that increased carbonate content in chernozem from 0 to 3.2% decreases ^{90}Sr uptake by plants by a factor 1.3–2.5 and increases ^{137}Cs uptake.

Table 28. Accumulation factor (AF) of ^{90}Sr and ^{137}Cs for agricultural plants depending on "carbonaceous" properties of chernozem (R. Alexakhin et al., 1985)

Plants	Carbonates content, %			
	0	0.7	2.2	3.2
^{90}Sr				
Cabbage (head)	0.19	0.16	0.17	0.08
Tomatoes (fruits)	0.36	0.22	0.16	0.25
Onion (bulb)	0.98	0.80	0.85	0.74
Maize (silage)	0.88	0.58	0.59	0.74
^{137}Cs				
Cabbage (head)	0.04	0.06	0.06	0.12
Tomatoes (fruits)	0.04	0.06	0.08	0.14
Onion (bulb)	0.05	0.05	0.06	0.07
Maize (silage)	0.04	0.05	0.10	0.07

The low ^{90}Sr uptake by plants on calcareous soils may be explained by two reasons. Firstly, non-exchangeable fixation of radionuclide occurs at a high level of carbonates. Secondly, strontium and calcium are chemical analogues that imply competition between these two ions. Thus, calcium content in the earth crust (2.96%) exceeds several orders of magnitude of that of strontium (3.4×10^{-2}%) and may discriminate strontium uptake by plants, including its radioactive isotopes.

The sorption of ^{90}Sr in soils is enhanced by the increased concentration of CO_3^{2}, PO_4^{3-} and SO_4^{2-} anions as well as by co-precipitation of Sr compounds having low solubility and, hence, low assimilability. Therefore, ^{90}Sr bioavailability in soils with the high content of exchangeable forms of phosphorus and sulphur is low.

Soils enriched with exchangeable potassium show the low migration rate and, hence, low bioavailability of ^{137}Cs. On the one hand, it is connected with the exchange reactions when potassium ions are exchanged for all available for exchangeable cations of soil. It is the process that leads to a long-term fixation and retention of radiocaesium in soils. On the other hand, caesium and potassium are chemical analogues that imply competition between these two ions (as we mentioned above for strontium).

The sorption of radionuclides by soil also depends on the content of corresponding stable isotopes, i.e. the higher content of stable isotopes is the less radioactive isotopes are fixed in soil and the higher their bioavailability is. This effect may be explained by simple dilution of radionuclides in soil due to stable isotopes resulting in fewer fractions of radioactive elements in the total fixation.

The special attention has to be paid to ^{40}K that is one of the main natural radioactive “contaminant” of soil and the biosphere. The content of ^{40}K in a ploughing layer is rather high (about $2.7–21.6×10^4$ Bq m^{-2} (0.7–5.8 Ci km^{-2}). The highest level of ^{40}K activity revealed in soils developed on an acid magmatic material and soils that contain minerals enriched with potassium (biotite, muscovite orthoclase). Due to human activities the flows of potassium as well as ^{40}K in the biosphere increase. Thus, an average of K fertilizer application rate is 60 kg ha^{-1}, it provides about $1.35×10^6$ Bq of ^{40}K. ^{40}K content at a single application of potassium fertilizers does not increase so much, but it will affect K balance in soil in a long-term perspective.

The migration of ^{40}K in soil, its uptake by plants and following biological pathway within the environment objects are determined by the behaviour of its stable carriers, i.e. ^{39}K and ^{41}K. In turn, potassium behaviour in the environment depends on the mentioned above soil properties: “carbonaceous” soil properties, pH, cation content and, first of all, sodium, anion concentrations, etc. However, any decrease of ^{40}K uptake results in the decrease of potassium uptake in general. Potassium is essential and one of the main biogenic elements.

The effect of weather and climate. The air mass movement, precipitation, temperature of the environment and some other phenomena that are weather and climate conditions play a certain role in radionuclides transfer in the atmosphere as well as in soil.

The wind, its speed and the direction, influences the radionuclide distribution. The wind lifting from the earth surface carries away the light soil fractions and transfers radionuclides from one place to another resulting in a fast secondary contamination.

There are three main types of radionuclide transfer due to the wind lifting: *the real wind lifting is the air mass movement above surface; the local wind lifting is the air mass movement caused by the specificity of the relief, forest plantations, buildings, etc.; the mechanical wind lifting is caused by agricultural machineries during soil cultivation, transport, etc.*

The most important factor is wind speed. It affects the efficiency of radioactive particles transfer. The lifting of soil particles is especially considerable from the dry surface, ploughed fields, as well as slopes, under the wind.

At the moment of fall-outs the season is the next factor that determines the interaction of radionuclides with soil. Winter, low temperatures and solid precipitations minimize such interactions. Positive summer temperatures and high soil humidity enhance the interaction of radionuclides with soil.

Radioactive particles deposited on the soil surface are involved in the vertical migration and percolate to some depth that has practical importance. Firstly, it decreases a dose rate above soil surface. Secondly, it reduces the secondary transfer and, therefore, the contamination of the territory with wind and water flows. Thirdly, the "dilution" of radionuclides affects their uptake by plants. At the same time, deep percolation of the radionuclides may cause the contamination of ground waters.

The migration rate of radionuclides depends on many soil factors, listed above, but the amount of precipitations seems to be the main factor that determines the speed of vertical migration of radionuclides in soil.

The soil particles of various sizes may percolate with water flows through the cracks formed during the dry weather, earthworms' drainage, etc. This is an ordinary filtration, i.e. the solution flow through the porous environment under the gravity forces. There is also a diffusion movement, i.e. the translocation of the radionuclides in the direction of gradient concentration (levelling); the convective translocation, i.e. the vertical translocation of radionuclides with water caused by the change of its density or salinity.

Generally, the vertical migration of radionuclides is very slow process. Thus, in the regions around the Chernobyl NPP on the non-ploughed soddy-podzol sandy loam and sandy clay loam soils over 15 years after fall-outs about 90% of the radionuclides are still located in the 10–13 cm layer (Fig. 73). Soil, having higher clay content, high cation exchange capacity, shows slower migration rate. Any soil type evidences higher ^{90}Sr migration rate in comparison with ^{137}Cs. This is the result of higher strontium solubility and caesium "aging".

The weather and climate conditions mainly determine the horizontal radionuclide migration, i.e. their horizontal transfer on the earth surface. The heavy rain may result in the radionuclide washing off together with soil to ground waters with the following contamination of rivers, lakes, sources of drinking water and water for irrigation. Similar situation may take place during winter season when thick snow layer is formed. The fast snow thawing at the low filtration rate of water through frozen soil enhances the horizontal radionuclide transfer.

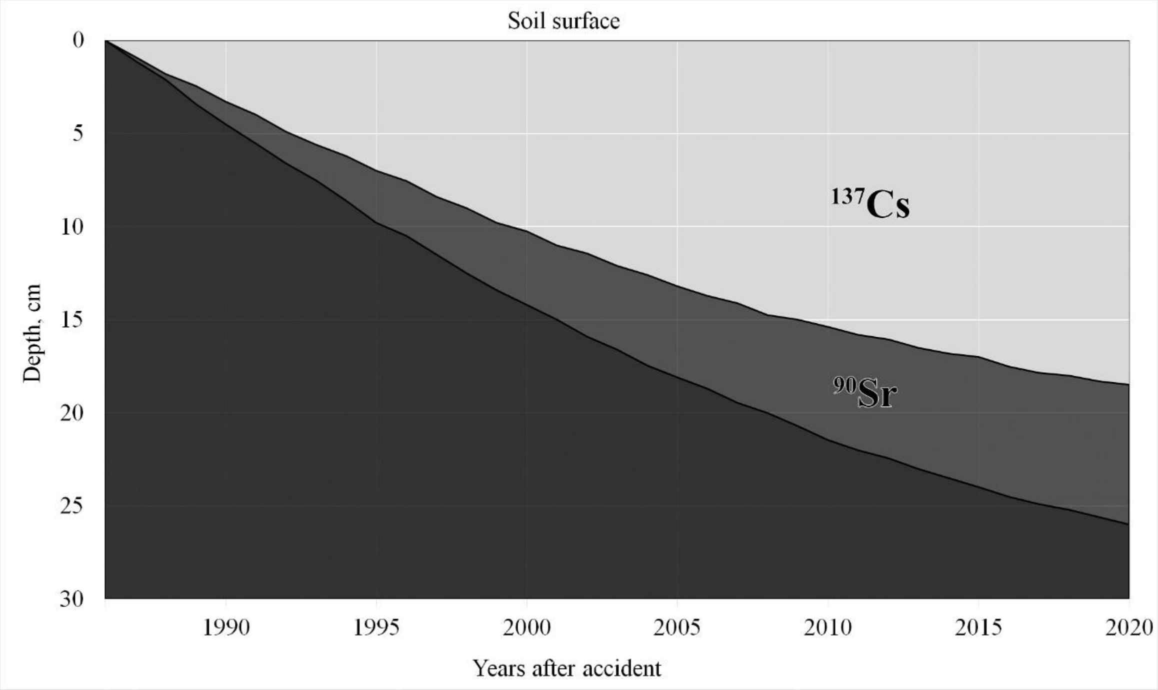

Fig. 73. The rate of the vertical migration of ^{137}Cs and ^{90}Sr in soddy-podzol soil after the Chernobyl accident.

The horizontal transfer of radionuclides is affected by relief and vegetation. The specific unevenness of the soil surface, forest plantations as well as luxuriant growth of plants may retain completely surface radionuclide washing off. On the contrary, the deep slop and the absence of vegetation enhance the radionuclide running off.

9.4. Plant uptake of radionuclides from soil

Plants may accumulate great amounts of radioactive substances, especially ^{90}Sr and ^{137}Cs without any sign of radiation-induced damage. Such heavily contaminated crops very often may be useless as a food or fodder. Therefore, it is very important to study the uptake, accumulation and the distribution of radionuclides within reproductive organs of agricultural plants.

It has been noticed that ^{90}Sr behaves in a similar way with calcium, and ^{137}Cs behaves in a similar way with potassium. The maximum concentration of ^{90}Sr is higher in plants enriched with calcium, e.g. well known calciphils plants of leguminous family, some representatives of *Rosaceae* and *Ranunculaceae* family. The highest ^{137}Cs concentration is in plants enriched with potassium, e.g. potassiphil plants such as potatoes, beets, cabbage, maize, oats, fibre-flax, sunflower, etc.

We've already mentioned that strontium and calcium belong to the same second main subgroup of the periodic element system of D. Mendeleyev. Both caesium and potassium belong to the first group. Chemical elements are joined together in groups on the base of similar chemical properties. For this reason, strontium has analogous chemical properties of calcium, caesium has analogous chemical properties of potassium as well as other elements of those groups.

There are two main pathways of radionuclides uptake by plants: through the over ground organs (mostly foliage uptake) and under ground uptake by roots. Both over ground and under ground (root uptake) plant parts account for the input of nuclides to plant tissues.

9.4.1. Uptake by above-ground organs

Nuclides can be deposited on the external plant component directly from the atmosphere by wet or dry deposition, via suspension from soil, and via contamination from either dispersion or irrigation waters. The migration to the soil via these sources directly or via dead plant material also occurs.

The possibility of radionuclides uptake by above-ground organs was discovered long time ago in experiments with uptake of mineral elements by above ground organs. It was found out that foliage uptake (by the leaf surface) and flower uptake are the most effective. There is one more type of radionuclides uptake. It occurs by superficial roots from a turf, which is peculiar to the plants having such type of roots.

Foliage uptake is typical for most of plants but some of the xerophytes species, i.e. plants covered by thick cuticularized membrane with a few guard cells (stomata) and leaves, modified to spikes. Plants are able to take up elements via the leaf surface both via stomata (gases) and via the cuticle (ions).

The efficiency of the leaf tissue uptake depends on the composition of the cuticle, ending up in a specific permeability to different ions. There is no close correlation between the thickness and the permeability of the cuticle. The permeability is promoted by a high relative humidity, since the cuticle is in its most opened and swollen condition. The permeability depends on plant species and, for example, submerged plants often have a much higher uptake due to the high penetration of the cuticle.

Water has to be present on the leaf surface. Leaf moistening of various plants depends on many factors: leaf shape, conditions, cuticle thickness and fat content, leaf age, water content in a leaf. The longer a contact of moisture with leaf surface is the higher radionuclide uptake. Dampening duration depends on the temperature, humidity, air movement and other factors affecting evaporation rate. Young leaves are more penetrable for radionuclides in comparison with old ones. Thick cuticle together with elevated fat content serves as a barrier for radionuclides.

Flower uptake that depends on the flower size, its location in the floscule and location on the plant may be important for some species. It is quite clear, that big flowers of *Rosaceae* as well as floscules of cereals placed on the opened parts of a plant take up more radioactive substances in comparison with plants having small rarely placed flowers. Radioactive substances may be trapped by flower mechanically with the following input in a fruit. Namely, such situation was observed in Ukraine in the spring of 1986, when fall-outs coincided with the flowering of fruit trees in gardens.

Some part of taken up radionuclides may stay in the area close to the penetration site, some of them enter transport flow system, move from one place to another and accumulate in plant organs, including those that form the yield and are used as a food. The accumulation rate depends on chemical properties of radionuclides, their physiological role in plants, plant species and their physiological state. Caesium and iodine isotopes are more mobile than isotopes of strontium, cerium, ruthenium, zirconium and barium. Being entered the plants, ^{137}Cs as well as potassium (its analogue) moves quickly within plant organs and is mainly accumulated in grains of cereals and leguminous, in potato tubers and fodder root-crops.

About one fourth of the total amount of ^{137}Cs foliage uptake by maize is accumulated in seeds. About 20% of the ^{137}Cs foliage uptake is accumulated in seeds of sunflower. The ^{90}Sr accumulation at foliage uptake accounts only one hundredth or one thousandth percent (Table 29).

There is no wonder that being essential element, potassium reveals high ability for the movement within a plant. Such potassium analogues as caesium, rubidium, sodium and lithium show similar behaviour.

Calcium is a nutrient element in plants. It is mobile and is necessary for cell division, cell wall and membrane functions. However, the role of calcium in a plant less observed. Therefore, strontium accumulates in fewer amounts.

The uptake by above-ground organs may continue during the whole vegetation period and depends on leaves development that, in turn, is determined by its stage at the moment of fall-outs.

The size of original retention of ^{90}Sr solution by oats and vetch plants applied at different stages of their development by means of irrigation is shown in Table 30. It reveals that the increase of biomass results in two-fold retention of radionuclide. The vetch plants retained three times higher amount of radionuclide in comparison with oat plants, whose biomass is 40% higher than vetch plants have. Thus, vetch plants retain 4–5 times higher ^{90}Sr per 1 g of dry weight that is due to the fact that vetch plants are more leafy and have more complicated leaf composition looked like edged with fur.

Table 29. The content of radionuclides in organs and parts of sunflower applied at the 16th leaf (I. Guljakin, E. Judintseva, 1973)

Organs and organ parts of plants	Amount of applied radionuclide, %	
	^{137}Cs	^{90}Sr
Leaves below 16th leaf	1.27	0.080
Leaves above 16th leaf	4.75	0.045
Stem below 16th leaf	3.70	0.006
Stem above 16th leaf	7.03	0.003
Flowers	2.64	0.012
Pulp of basket	18.46	0.010
Seed membrane	15.47	0.008
Seed nucleus	3.58	–

Above-ground organs uptake of radionuclides from radioactive particles deposited on a plant surface affected by weather conditions. Deposited radioactive particles may be blown away by the wind and washed out by the rain. The retention of these particles is mainly determined by an organ shape and its mechanical properties.

Table 30. The role of retention of ^{90}Sr solution by oats and vetch plants applied at different stages of their ontogenesis (N. Kornejev et al., 1977)

Plants	Development stage	Plant biomass, g dry weight per pot	Retention of radionuclide applied, %
Oats	Full bushing out	8.8	9.8
	Beginning of milk maturity	108.9	20.6
Vetch	Branching	6.2	33.2
	Full lower bean	76.6	60.5

The wind lifting of radioactive particles from the soil surface, its translocation with rain and irrigation water promote the secondary contamination of above-ground parts of plants. It is necessary to keep in mind, when measures for reducing radionuclide uptake by plants are implemented.

The major part of Chernobyl fall-outs deposited during the first two-three weeks from the end of April and the beginning of May, when winter crops, naturally occurring as well as sowing grasses and fruit trees were subjected to the contamination of over ground organs. The rest of agricultural crops were mainly contaminated by means of mentioned above secondary contamination. The contamination caused by root uptake from already ploughed agricultural lands was insignificant.

Generally, the contamination level of vegetation under the direct deposition of radionuclides on growing above-ground parts of plants is mainly determined by the amount of fresh fall-outs. On the contrary, the root uptake rate is mainly determined by the total amount of radionuclides deposited on soil surface. Generally, the root uptake increases with the time, when above-ground organs uptake decreases.

9.4.2. Root uptake

Soil is a medium that absorbs many elements and substances, including radionuclides. The upper organic rich soil layer characterized by the high cation exchange capacity also shows the highest ability to take up radionuclides. In the semi-natural environment radionuclides are mainly deposited in the upper 5–10 cm of soil profile. In cultivated soils radionuclides more or less are uniformly distributed within ploughing layer.

Therefore, its biological uptake and turnover depends on the soil binding properties and on plant properties of root uptake.

The ability of a plant to take up radionuclides depends on many factors simultaneously: species, root system development, stage of a plant development, its physiological state, soil humidity, nutrient state, etc. Being bound in soil and plants as well as fixed in root zone, radionuclides are prevented from leaching.

The mechanism of radionuclide root uptake differs from that of nutrient uptake. It is mainly due to the fact that most of the fusion decay products are not essential elements for plants and are taken up in trace amounts.

The uptake of radionuclides and its following distribution within plant organs is determined mainly by its chemical properties. The isotopes of caesium and strontium as chemical analogues of potassium and strontium are taking up by plants in relatively great amounts (Table 31).

Table 31. Radionuclides accumulation factors (AF) (R. Alexakhin, 1992)

Radionuclides	AF	Radionuclides	AF
^{35}S	20–60	^{141,144}Ce	6×10^{-4}–3×10^{-3}
^{45}Ca	$(4–6)\times10^{-2}$	^{147}Pm	3×10^{-5}–3×10^{-4}
^{954}Mn	0.02–15	^{195}W	0.13–0.3
^{55,59}Fe	$(1–8)\times10^{-2}$	^{210}Po	3×10^{-5}–3×10^{-4}
^{60}Co	4×10^{-3}–5×10^{-2}	^{210}Pb	0.05–0.43
^{65}Zn	3.3–15	^{226}Ra	1×10^{-3}–4×10^{-2}
^{90}Sr	0.02–12	^{232}Th	1×10^{-3}–7×10^{-1}
^{91}Y	3×10^{-5}–7×10^{-4}	^{237}Np	$n\times10^{-2}$–$n\times10^{-1}$
^{95}Zr	3×10^{-3}–8×10^{-2}	^{238}U	1×10^{-3}–1×10^{-1}
^{103,106}Ru	$(2–3)\times10^{-3}$	^{238}Pu	1.6×10^{-4}–1×10^{-1}
^{115}Cd	$(4.3–8.5)\times10^{-2}$	^{239,240}Pu	$n\times10^{-8}$–10^{0}
^{134,137}Cs	0.02–1.1	^{241}Am	$n\times10^{-6}$–10^{-1}
^{140}Ba	$(2–5)\times10^{-2}$	^{244}Cm	$n\times10^{-4}$–$n\times10^{-3}$

Radionuclides of ^{60}Co, ^{91}Y, ^{103,106}Ru, ^{141,144}Ce, ^{147}Pm and actinides are accumulated in much lower quantities, i.e. several orders of magnitude. Sulphur and some other macronutrients (iron, manganese and zinc) have higher values of CR. ^{137}Cs and ^{90}Sr move within a plant easily and quickly when the rest of radionuclides are accumulated mainly in plant roots (Table 32).

Table 32. The distribution of radionuclides within wheat organs at root uptake
(I. Guljakin, E. Judintseva, 1973)

Radionuclides	Content in plant, %		Content in above ground organs			
	Roots	Above ground parts	Stem	Leaves	Ears without grains	Grains
^{137}Cs	40.9	59.1	49.9	27.4	18.0	4.7
^{90}Sr	19.3	80.7	53.4	35.9	6.7	4.0
^{144}Ce	99.2	0.8	45.8	33.3	16.7	4.2
^{60}Co	91.1	8.9	66.2	4.3	16.7	12.8
^{91}Y	99.5	0.5	39.5	41.9	18.6	0
^{96}Nb	99.2	0.8	75.0	25.0	0	0
^{95}Zr	99.92	0.08	69.8	23.3	4.6	2.3
^{106}Ru	99.97	0.03	45.5	45.5	9.0	0

Radionuclides are distributed within over ground parts of a plant differently. About a half of radionuclides taken up by a plant are accumulated in a stem. Fewer amounts of radionuclides are accumulated in leaves and even much less (a few percents in grain). Thus, the further the way between root and organs is the less amounts of radionuclides is accumulated (e.g. cereals and leguminous plants producing grains). Situation is getting worth when productive organs are leaves and especially under ground organs such as root-crops and bulbs. Such products show higher level of contamination.

As we mentioned above the transfer factors (TF) and the concentration ratios (CR) are established to quantify the process of soil-to-plant transfer of radionuclides.

The values of TFs and CRs for most of the radionuclides, such as ^{144}Ce, ^{106}Ru and many others are in the range of one tenth and one hundredth and very seldom approach to one that indicates no accumulation. However, for ^{90}Sr and ^{137}Cs such values for some potassiphils and calciphils may reach high values and even one.

Mean extrapolated data of transfer factors (TFs) for agricultural plants for many years are shown in Table 33. Much higher TFs values for ^{90}Sr in comparison with ^{137}Cs evidence binding of the last by soil.

Radionuclides uptake by plants depends directly on its amount in soil. And it is reverse for their chemical analogues. Thus, the increased amount of potassium in soil reduces ^{137}Cs uptake (Fig. 74). Calcium concentration in soil determines ^{90}Sr uptake by plants respectively (Fig. 75). It is very important to understand the uptake processes for farming.

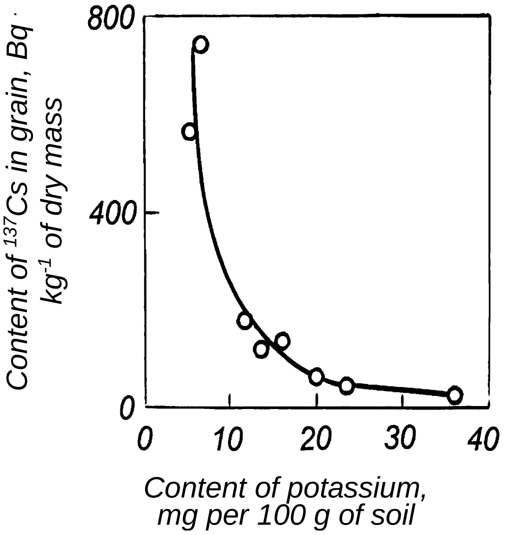

Fig. 74. The effect of exchangeable potassium in soil on the accumulation of ^{137}Cs in barley grain (E. Judinyseva, E. Levina, 1982)

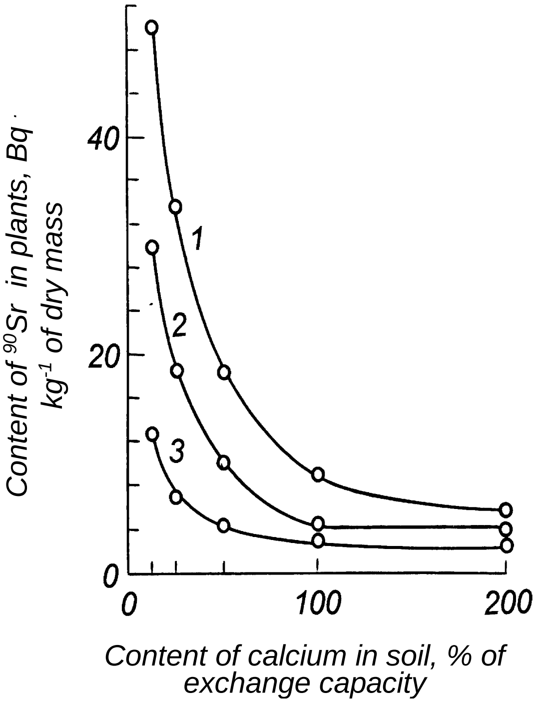

Fig. 75. The effect of exchangeable calcium in soil on the accumulation of ^{90}Sr in pea straw (1), beet tops (2) and oats straw (3) (L. Frideriksson et al, 1958).

Table 33. The average values of transfer factors (TFs) for ^{137}Cs and ^{90}Sr in crops on different soil types, Bq kg^{-1}: kBq м$^{-2}$ (B. Prister et al., 1998)

Plants	Yield	Soddy-podzol soil			Gray forest	Leached chernozem	Peat and peat-gleyic
		sand and loamy sand	sandy loam and sandy clay loam	clay loam			
^{137}Cs							
Winter wheat	grain	0.2	0.03	0.03	0.03	0.02	1.5
	straw	0.3	0.06	0.03	0.06	–	–
Barley	grain	0.1	0.05	0.02	0.03	0.03	1.0
	straw	0.2	0.13	0.06	0.06	–	–
Maize	vegetative mass	0.2	0.1	0.1	0.3	0.04	0.8
Lupine	vegetative mass	9.2	2.5	–	–	–	–
Potatoes	tubers	0.1	0.6	0.04	0.04	0.03	0,4
Red beet	root-crops	0.5	0.4	0.1	0.08	0.05	1.5
Clover	hay	3	1	0.75	0.6	0.05	13
Tomatoes	fruits	0.06	0.03	0.03	0.03	–	–
Buckwheat	grain	0.75	0.08	0.05	0.05	–	–
Natural grasses	hay	20	7.5	–	4.5	–	–
^{90}Sr							
Winter wheat	grain	1	0.6	0.3	0.4	0.2	0.1
	straw	5	3	1.5	2	1	0.5
Barley	grain	5	3	1.5	1.8	0.8	0.4
	straw	25	15	7.5	9	4	2
Pea	grain	7	4	2	3	1.3	0.6
	straw	35	20	10	15	6.5	3
Buckwheat	grain	5	3	1.5	1.7	0.5	0.2
Maize	vegetative mass	12	6	3	4	2.4	1.2
Potatoes	tubers	2.6	1.7	0.8	1	0.3	0.1
Red beet	root-crops	6	3	1.6	2	0.7	0.3
Cabbage	head	1.2	0.6	0.3	0.4	0.2	0.1

9.4.3. Behaviour of radionuclides in forest ecosystems

The release of radionuclides into the natural environment (especially forests) is global issue. Forest ecosystems have rather complex structure (multi-layered soil structure, the existence of different plant species, complex interaction between plants and animals) and, for this reason, are received a low remediation priority. However, the long-term impact of contaminated forests can be quite significant, since forest is an effective reservoir for pollutants.

The forest ecosystems can be divided into four major components: tree over storey, under storey, organic layer and soil. The tree component (or over storey) consists of high standing trees. Tree can be classified according to the type and the behaviour of foliage and canopy. Two distinct types of foliage are needle-leafed and broad-leafed. The foliage and canopy play the important role in the interception of fall-outs. The under storey consists of vascular plants growing under the canopy of the over storey. These plants have a well developed conducting system for water and nutrients and they usually consist of roots, stem and leaves. The organic layer is a composite compartment that transforms newly formed organic matter into decomposed and humified substances. Thus, it includes both decomposed organic materials (forest litter, humus) and decomposing plants (lichens, moss and fungi). This layer is characterized by the high accumulating ability. Forest soil has a complex structure with several horizons distinguished in the organic layer.

When radioactive particles deposited on the canopy, the vertical migration under gravity forces, rain and air movement begins. As a result radioactive substances reach under storey and soil surface. The speed of such migration depends on the fall-outs, their physical and chemical properties, chemical properties of radionuclides, type and age of tree over storey, weather conditions, year season, etc.

Most needle-leafed trees keep their needles all year around, shedding and replenishing them over several years. The half-time of needles (defined here as the time required for the tree to renew a half of its coverage) varies for different tree species. For Scottish Pines, it is found to be about 3–5 years. Most broad-leaved trees are characterized by replenishing their leaves annually. So, some years later after fall-outs the major part of the deposition reaches understorey and soil surface. The major part of radioactive substances occurs in the upper 10–15 cm layer of forest soil. The root uptake of radionuclides begins 4–5 years later in deciduous forest and 8–10 years later in coniferous forest.

The uptake mechanisms for crops and woody plants are similar, but the accumulation of radionuclides is different. Perennial woody plants accumulate radionuclides in bark, wood, branches and needles. The major part of radioactivity occurs in leaves and the minor part is in woody parts of a tree. However, the closed cycle of radionuclides in the system of leaves-forest litter-soil-roots-stem-leaves, for many years result in the contamination of wood and consequently different manufactured woody articles (Fig. 76). When plantations are planned, it is important to select tree species with low rate of radionuclides uptake. For instance, spruce and oak accumulate greater amounts of ^{90}Sr in comparison with pine and larch; acacia accumulates greater than birch that is related to its potassiphilness and calciphilness and other biological properties.

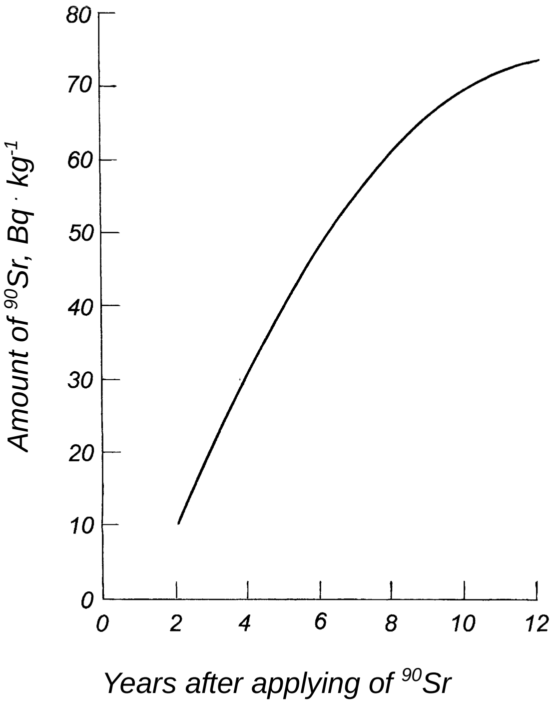

Fig. 76. The dynamics of ^{90}Sr uptake by pine wood with time. Single application of radionuclide (37 kBq m^{-2}) in forest. Soddy-podzolic soils. (R. Alexakhin, M.

9.5. Transfer of radionuclides to food producing animals

Animals can be contaminated by three different ways: through the skin, by inhalation, and most by ingestion. Inhalation is potentially more important than skin absorption because the lung surface and the size of gaseous exchange are more permeable to a wide range of elements. The skin absorption is usually not the main way of the contamination, although lesions can provide a direct entry for radionuclides into an animal circulation system. The most important transfer pathway into animals is the ingestion of contaminated fodder, soil and drinking water.

Sorption via drinking water is generally a small contributor to the total radionuclide absorption. It is normally restricted to soon after an accident. Radionuclide sorption via soil can be significant but the ability to absorb radionuclides with soil is generally low. Therefore, radionuclide content in animals is determined mainly by the ingestion of contaminated fodder and by processes influencing their absorption and retention.

The quota of radioactive substances in an animal organism does not differ from that of stable elements which normally present in fodder. Being entered into gastro-intestinal (GI) tract fodder undergoes mechanical, biological alterations and transforms into nutrient substances. There are *two stages of radioactive substances metabolism.*

The *first stage* is the transformation of substances into easily digestible forms. There are all substances and conditions in gastro-intestinal tract necessary for such transformation: mechanical destruction and reducing to fragments in a stomach; great amount of various enzymes that provide splitting of proteins, fats and hydrocarbons to smaller fragments; and, finally, acid environment (due to a stomach juice) that provides the transformation of radioactively contaminated fodder in easily digestible forms.

The *second stage* of metabolism is the absorption of radionuclides from the gastro-intestinal tract. The degree of absorption from the gastro-intestinal tract (GIT) is generally the most important factor in determining the extent of radionuclide contamination of animal tissues and milk. Ruminants have a four-compartment stomach: the fermentation of chewed vegetation and some absorption of breakdown products occur in the first two compartments (rumen and reticulum). The anaerobic reducing environment of the rumen can lead to changes in radionuclide speciation and, therefore, bioavailability. The fermented rumen fluid passes into the omasum and abomasum and are subjected to enzymatic digestion that is similar to the processes in monogastric animals. Fermentation occurs in non-ruminants, but its importance is lower than in ruminants.

Usually absorption is considered to be different in dietary intake and faecal output, determined as a proportion of dietary intake. The absorption of radionuclides is measured in ruminants as the *absorption coefficient* (A_t) that takes into account the endogenous secretion of radionuclides into the guts. For some radionuclides this approach provides an accurate estimate of the absorption. However, it is too insensitive to measure absorption from sources with a low availability and negative values of the absorption. It occurs because the calculation does not take into account the excretion of absorbed radioactivity from blood into faeces. For some radionuclides, the endogenous secretion into the gastro-intestinal tract from the circulatory system, e.g. via saliva, is a significant way of the excretion. For example, the endogenous excretion of radioactive caesium in ruminants is about 20–25 % of absorbed one.

For many radionuclides, the form, in which they are ingested, determines how available they are for subsequent absorption. The importance of the chemical form depends on three most important mobile radionuclides: radioactive iodine, radioactive caesium and radioactive strontium.

Table 34 shows the variation of absorption coefficients for some animals. Thus, the absorption of ^{131}I for ruminant animals reaches 100%, for pigs it reaches 1.3–3 times lower. In contrast to that, radioactive caesium absorption reaches 100% for pigs, but it is 1.3–2 times lower for ruminants. The absorption of ^{59}Fe and ^{60}Co for hens is much higher in comparison with ruminant animals. Generally, elements with high atomic mass that are not essential elements or analogues of essential elements are poorly absorbed in the GIT.

Table 34. The absorption coefficient (A_t) of radionuclides in the gastro-intestinal tract of adult animals, % of dietary intake (A. Syrotkin, 1991)

Radionuclide	Beef cattle	Lambs	Goats	Pigs	Hens
^{3}H	92	70–100	70–100	70–100	95
^{45}Ca	11	35	20	–	50-60
^{54}Mn	0.5–1	46	1–20	7–20	20–44
^{59}Fe	4	1–20	1–20	1 721	72
^{60}Co	2.4	3.5	5	3	35
^{65}Zn	11	10	1–20	51	64
^{89,90}Sr	6–16	7–10	3–14	13	50–80
^{88,90}Y	0.05	0.05	1	1	<1
^{95}Zr	<0.1	<1	<1	<1	<1
^{103,106}Ru	2	0.2	0.1	1	3

^{131}I	100	100	70–100	33–76	75–80
^{134,137}Cs	50-75	57	68	100	67
^{140}Ba	5	1–20	1–20	1–20	1–20
^{141,144}Ce	0.1	0.04	1	0.5	<1
^{210}Pb	0.01	–	–	–	–
^{238}U	1.2	<1	<1	1.9	1.5

In very young animals, the permeability in the GIT is higher than in adults, especially in newly-born animals. In young animals, the absorption of many poorly absorbed radionuclides can be a factor of 1000 times higher than for adult animals. It is due to different guts permeability and less demand for minerals in adults. However, these differences disappear when regarding radiation exposure via animal products to a man.

Nevertheless, the absorption rate is rather high and about 10–15 % of the initial radioactivity stays in the stomach within 24 hours after dietary intake.

Once absorbed, radionuclides penetrate the circulatory system and are distributed into various tissues of the body. For many of radionuclides that are bio-transformed within the animal, more than one form may circulate in blood. In some cases, radionuclides are bio-transformed within the tissues and subsequently present within the animal in more than one form. Other radionuclides (e.g. radioactive caesium) remain in an ionic form after the absorption.

Different radionuclides are accumulated in different tissues. As a rule, radionuclides retain in such organs and tissues that contain stable isotopes with similar chemical properties. Since elementary composition of animal tissues is well known, it is possible to predict radionuclide accumulation in animal organs and tissues.

There are *three main types of radionuclides distribution in an organism of vertebral animals: skeletal, diffusive and reticuloendothelial*.

Skeletal type is typical for radionuclides of alkaline earth metal group, mainly calcium and strontium. Barium isotopes as well as such radioactive elements as radium, plutonium, uranium etc. may accumulate in the mineral part of skeleton. Diffusive type is typical for alkali metals: potassium, sodium, caesium, rubidium as well as hydrogen, nitrogen, carbon. Reticuloendothelial distribution (reculoendothelial system, the system of connective cells tissues of an organism of backboned animals and a man that are able to phagocytosis, i.e. killing of alien cells including a pathogenic bacteria; it includes some cells of bone marrow, lymphatic glands, tonsils, spleen, liver, adrenal gland, hypophysis, etc.) is typical for rare earth elements such as cerium, promethium, zinc, thorium and partly for transuranic elements.

The major iodine storage organ in the body is the thyroid. It is actively absorbed by the mammary gland and transferred into milk. The stable iodine state of an animal affects directly the behaviour of radioactive iodine. Animals with a low stable iodine state accumulate proportionally more in the thyroid whereas other with an excess of iodine may secrete proportionally more to milk.

Radioactive strontium behaves as a Ca analogue and is, therefore, accumulated in a bone, and also is transferred into milk. Strontium, radium, plutonium and the rare earth elements are all accumulated in a bone.

Radioactive caesium is an analogue of potassium and, therefore, is found in all soft tissues, where muscle is the most important one for the transfer of the contamination to humans. The influence of an animal potassium state on radioactive caesium behaviour is unclear, although it appears to be considerably lower in comparison with calcium influence on the radioactive strontium behaviour**.**

Liver and kidneys are common storage tissues for many pollutants, including some radionuclides (e.g. actinide elements).

The influence of radioactive substances on an entire organism as well as on specific organs depends on the residence time of radionuclide in an organism. The rates of the absorption and the loss of radionuclides vary between different tissues. The rate of radionuclide loss from tissues, when an animal does not receive contaminated fodder, is termed the *biological half-time* (T_{biol}). It defines the time required for the radionuclide activity concentration in a given tissue compartment to be reduced by one half excluding physical decay. For some radionuclides, it seems to be associated with the metabolic turnover rate of different organs. For others, it is controlled by the stable element state, for instance, radioactive strontium is released at an enhanced rate from bone during periods of calcium deficiency (e.g. peak lactation in dairy animals). The ratio of the accumulation rate and the loss of some radionuclides depend on the activity concentration that continues to increase while the animal receives contaminated fodder for a considerable period afterwards. In general, smaller animals have more rapid turnover of radionuclides than large animals.

The average data in Table 35 show biological half-lives of some radionuclides for humans. Similar data with some variations due to biological variability of a certain organism might be expected for animals.

Table 35. The half-life ($T_{1/2}$) and biological half-time (T_{biol}) for a man

Radionuclides	Storage organ	$T_{1/2}$	T_{biol}.
^{3}H	Whole body	12.33 years	12 days
^{14}C	Whole body	5479 years	10 days
	Bones	5479 years	40 days
^{24}Na	Whole body	0.63 days	11 days
^{32}P	Whole body	14.3 days	267 days
	Bones	14.3 days	3.16 years
^{35}S	Whole body	87.1 days	90 days
	Bones	87.1 days	1.64 years
^{42}K	Whole body	0.52 days	58 days
^{60}Co	Whole body	5.21 years	9.5 days
^{90}Sr	Bones	29 years	50 years
^{131}I	Whole body	8 days	138 days
	Thyroid gland	8 days	138 days
^{137}Cs	Whole body	30 years	70 days
^{140}Ba	Whole body	12.8 days	65 days
^{210}Po	Whole body	138.4 days	30 days
^{226}Ra	Bones	1 616 years	44.9 years
^{235}U	Whole body	712 000 000 years	100 days
	Bones	712 000 000 years	300 days
^{239}Pu	Whole body	24 383 years	178 years
	Bones	24 383 years	200 years

It is necessary to estimate the radionuclide level in animal-derived foodstuffs, because contaminated animal products can influence significantly to the radionuclide intake of humans. Nowadays, the contribution of milk and meat as a ^{137}Cs and ^{90}Sr source reaches about 70% of human nutrition. Perhaps, the most basic approach to determine transfer of a radionuclide from the diet to the tissues of an animal is to define the ratio of the activity concentration in a tissue to that in the diet, i.e. *transfer coefficient (C_{ft})* that is similar to *absorption coefficient (A_t)*. However, it does not take into account how much an animal actually ingests. Thus, it is suggested to describe the *transfer coefficient* as the transfer of radionuclides to milk of dairy cattle, where the transfer coefficient (F_{in} for milk and F_f for meat) is defined as the equilibrium ratio between the radionuclide activity concentration in animal products and the daily intake of the radionuclide. It reduces the variability of transfer values between animals.

The transfer coefficient for some radionuclides to milk and meat of cattle is shown in Table 36. The maximum values are reported for ^{32}P, ^{14}C, ^{35}S, ^{3}H, ^{40}K, ^{45}Ca, ^{131}I, ^{134,137}Cs that are considered to be the main milk constituents and chemical analogues of the elements involved in metabolic activity. The transfer coefficient for ^{90}Sr is low that is due to the discrimination by chemical analogue of calcium.

Table 36. The transfer coefficient (C_{ft}) of radionuclides from the nutrition to milk and tissues of an animal (muscle), % of the daily intake of the radionuclide (E. Teverovsky et al., 1985)

Radionuclides	Milk	Meat	Radionuclides	Milk	Meat
^{3}H	1	–	^{90}Sr	1.5×10^{-1}	4×10^{-2}
^{14}C	2	–	^{131}I	1	4×10^{-1}
^{32}P	3	–	^{137}Cs	1	8
^{35}S	2	–	^{144}Ce	1×10^{-4}	1×10^{-4}
^{40}K	1	–	^{238}U	5×10^{-2}	1×10^{-4}
^{45}Ca	1	1×10^{-1}	^{239}Pu	1×10^{-5}	1×10^{-4}
^{65}Zn	6×10^{-1}	-	^{241}Am	4×10^{-5}	–

In general, the transfer coefficients for younger, smaller animals are higher than those for larger, adult animals. Transfer coefficients for specific radionuclides were generally assumed to be a constant for a given animal species. For instance, one value is used for adult sheep regardless of their size or physiological state although separate and higher values are generally used for young animals. Recent evidences resulting from the studies following the Chernobyl accident showed this assumption to be inappropriate for many radionuclides. In particular, the transfer coefficients vary with physical-chemical form (i.e. source), stable element state, physiological state (lactation, non-lactation, etc.), growth rate and feeding level.

The highest C_{ft} values were shown by caesium isotopes, i.e. the chemical analogue of potassium, the ion of which is involved in generation and conduction of bioelectrical potential in muscles and in the control of their contraction. Caesium ion is also involved in such activity.

Radionuclides of rare earth and heavy metals as well as transuranics showed low accumulation rate in milk and animal tissues.

The biological half-life for mammals is mainly determined by the character of metabolism. Thus, for humans the biological half-life of ^{90}Sr is an age dependant and varies from 25 (for children) to 70–75 years (for adults), and of ^{137}Cs (in muscles) from 30 to 90 days correspondingly. The average data are shown in Table 29. The half-life of radionuclides does not depend on any factor and is, therefore, constant.

The half-life value of radionuclides has to be taken into account to estimate the level of organism cleaning from radionuclides, since the radionuclide amount as well as radioactivity level depends on decay and residence time. An effective half-life of radionuclides is used (T_{eff}). It is calculated according to the equation:

$$T_{eff} = T_{1/2} \times T_{biol} / T_{1/2} + T_{biol},$$

where $T_{1/2}$ – half-life of radionuclides and T_{biol} –biological half-time.

It is natural that contamination ways of radionuclides as well as their migration within a mammal organism are similar to ones in human. The specificity of some radionuclides and their action on a human body are investigated in radiation medicine.

Control points to chapter 9:

1. The objectives of agricultural radioecology nowadays.
2. The main ways of radionuclide migration in the environment and objects of agricultural production.
3. The accumulation factors (AFs) and transfer factors (TFs) of radionuclides.
4. The factors that determine radionuclide migration in the atmosphere.
5. The main types of radionuclide migration in soil.
6. The role of physical and chemical affinities of radionuclides in their migration in soil.
7. The effect of soil-texture and mineralogical composition of soil in radionuclide migration.
8. Soil agrochemical properties and their effect on radionuclide migration and uptake by plants.
9. Weather and climate conditions and radionuclide migration.
10. The ways of radionuclide uptake by plants.
11. Uptake of radionuclides by over ground organs of a plant.
12. Types of wind lifting of radionuclides.
13. Factors that determine the transfer of radionuclides from soil to plants.
14. Plant specificity and uptake of radionuclides.
15. Behaviour of radionuclides in forest systems.
16. The ways of radionuclide uptake by animals.
17. The absorption coefficient and the transfer coefficient of radionuclides from nutrition to milk and tissues of an animal.
18. The biological half-life.

10. FARMING ON THE TERRITORIES CONTAMINATED BY RADIONUCLIDES

10.1. Basic principles of farming on the territories contaminated by radionuclides. 10.2. Measures to reduce radionuclide transfer from soil to plants. 10.2.1. Soil tillage. 10.2.2. The application of chemical agents and fertilizers. 10.2.3. The change of plant in a crop rotation. 10.2.4. The change of irrigation regime. 10.2.5. Application of special agents and countermeasures. 10.3. Measures reducing radionuclide transfer in animal products. 10.3.1. The improvement of animals feeding. 10.3.2. Working out of rations. 10.3.3. The application of additives and other supplements to the ration. 10.3.4. Organizational measures. 10.4. The reduction of radionuclide content in plant and animal products by primary technological processing. 10.4.1. The decontamination of plant products. 10.4.2. The decontamination of animal products.

Farming is an inseparable and natural life style of rural population. Living on contaminated by radionuclides territories, it is advisable and possible only in the case of existing radiological situation that allows safe carrying out of all necessary work in field-crop cultivation, stock-raising and other areas as well as manufacturing of high quality food and other products.

For town-dwellers the agricultural products manufactured on contaminated territories make less threat in comparison with the rural population. Since, radiation level in food products reduces during its storage, distribution on the national scale, compounding with “clean” products, technological processing into other products; and other measures.

Nevertheless, the consumption of agricultural products got on the contaminated by radionuclides territories is the main source for human irradiation. For this reason agricultural production on such territories has to be based on the technologies that provide the reduction of radionuclide migration to the food chain to exclude the possibility for expansion of the contaminated territories and to provide radiation safety of local population.

10.1. Basic principles of farming on the territories contaminated by radionuclides

Farming on the contaminated by radionuclides territories has to be carried out according to the regulations of corresponding normative documents that regulate the terms and conditions of labour activity and residence of population on the territories with elevated levels of radioactive contamination; keep the basic principles of radiation safety, and basic sanitary regulations and work with the radioactive substances; provide the production of agricultural products within permissible levels.

The main goal of agricultural production on the territories contaminated by radionuclides is manufacturing of safe agricultural food products. The consumption of such food products without any limitations should not exceed an average annual effective equivalent irradiation dose for a man. It is achieved due to the introduction in production process of such measures:

1. General increase of agricultural production upholding measures of radiation safety.
2. The implementation of special radioprotective measures to reduce transfer of radionuclides to plant and animal products.
3. The change of agricultural production to provide the exception of some types of products with elevated content of radionuclides.

If the implementation of such measures does not guarantee getting products that meet requirements of sanitary and hygienic norms, farming is stopped.

The important principle of farming on the contaminated territories is to prevent radioactive substances spreading outside the contaminated areas. It may be achieved through forest planting and carrying out different types of land-reclamation measures. Such measures, however, should not cause negative changes of soil fertility, quality of produced food and other undesirable consequences.

The removal of agricultural products outside the contaminated territory has to be reasonably limited. But it should not be a barrier for using products outside the area that meets requirements of sanitary and hygienic norms.

10.2. Measures to reduce radionuclide transfer from soil to plants

To prevent radionuclide transfer from soil to plants, i.e. to slow down their transfer on the initial and the most important chain link, is one of the main problems of modern agricultural radioecology as well as general radiobiology, because it is directly connected with the radiation protection of a man.

The number of measures to reduce radionuclide transfer from soil to agricultural plants may be used depending on soil properties, ground deposition level, types of cultivated agricultural plants, ways of the harvest use, etc. Measures that may reduce radionuclide transfer to the plant products and fodder in many times are divided into two groups:

1. Generally accepted measures that foresee the ordinary field-crop cultivation or even promote to increase the soil fertility, yield growth and its quality; and, at the same time, reduce radionuclide transfer to plants.

2. Special measures that exceptionally reduce radionuclide transfer to plants.

Such division is rather conditional because the generally accepted measures may be interpreted as special ones and vice versa. Generally, there are five basic complex approaches that reduce radionuclide transfer to plants. They include generally accepted measures and special ones such as special mechanical, agro-technical, agro-chemical, chemical and biological measures, soil tillage, application of chemical land-reclaiming agents, fertilizers, changes of plants in a crop rotation, changes of the irrigation regime, applications of special agents and measures.

10.2.1. Soil tillage

After the fall-outs radioactive substances are mainly concentrated in the upper rather thin soil layer. In the case of relatively low level of ground deposition the soil tillage by ordinary mill cutter machines or heavy disk harrows as well as ploughing with an ordinary tractor-driven mould board plough to a depth of about 20–25 cm may be sufficient. The mixing of the contaminated superficial soil layer with deeper one sharply reduces spreading of fall-outs outside the contaminated area by wind and reduces substantially plant contamination by air.

Deep ploughing with an ordinary tractor-driven single furrow mould board plough to a depth of about 50–75 cm is an effective countermeasure on the highly contaminated soils. Ploughing brings the contamination out of the root zone of some plants and reduces external irradiation in the area. The contamination in the upper 20 cm can be reduced by factor 10–20 (Fig. 77). Deep ploughing brings the contamination out of the zone of some plants' uptake and reduces external exposure in the area. The method is expensive and can only be achievable on limited scale where ploughing is possible. Although in Japan this method is widely used in the Fukushima NPP area.

This method is achievable on a large scale, where ploughing is possible. Benefits are rapid way to reduce both internal and external dose from large areas of soil. Subsequent ordinary ploughing (to ca. 25 cm) normally does not bring much contamination back to the surface. Constraints are that subsequent deep ploughing may bring a part of the contamination back to the surface. The method does complicate contaminants removal. The method may greatly affect soil fertility especially those that have shallow fertile layer (soddy-podzol soils) and should be accompanied by the use of fertilizers.

In the case of very high contamination the application of turf harvester to skim off a thin contaminated top layer (3–5 cm) from a meadow is recommended (Fig. 78). The method is achievable in selected smooth open areas of soil with a mature grass mat, and it usually does not affect soil fertility. Application of such approach in Japan allowed reducing ^{137}Cs activity concentration in the soil by 75% and an ambient dose level by 52% (Fig. 79).

The application of this method results in waste production ca. 20–30 kg m^{2} (solid), which must be transported away to the depository place and deposited. Therefore turf harvester can be recommended for high ground deposition level.

Fig. 77. Deep ploughing with tractor-driven reversible mouldboard plough (Japan, 2011).

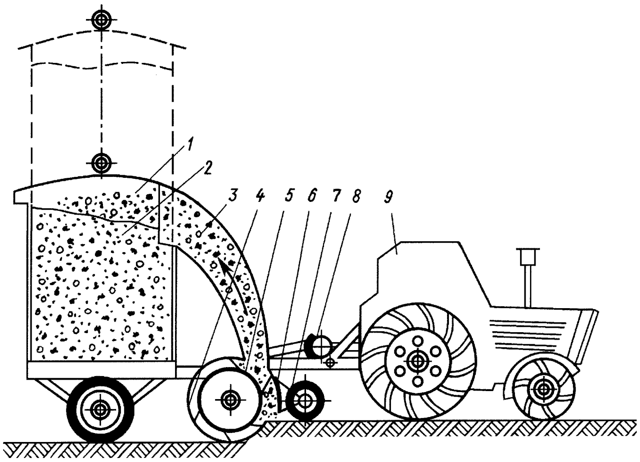

Fig. 78. Earth harvester scheme: 1 – bunker for soil, 2 – soil, 3 – soil pipe-line, 4 – roller for levelling of soil, 5 – milling cutter-drum, 6 – cover-damper, 7 – bearing roller, 8 – power shaft, 9 – tractor.

Fig. 79. Removing of topsoil in area contaminated by radionuclides (Japan, 2011).

Skim-and-burial ploughing method is another countermeasure that can be recommended for limited heavily contaminated areas. Method allows reducing plant contamination uptake and external exposure with minimized fertility loss. Firstly, a skim colter places the upper 5 cm of soil in a trench made by the main ploughshare. Then, the main ploughshare digs a new 50 cm deep trench and places the lifted subsoil, which is not inverted, on the top of the thin layer of topsoil in the bottom of the trench of the previous run. The skim coulter simultaneously places the top layer from the next furrow in the new trench.

Most of the mentioned above methods connected with soil tillage, belong to specific measures and are considered to be effective only during the first year after fall-outs. If previous conventional ploughing was performed and superficial contaminated layer was mixed within the arable layer depth then, such measures are not applied. During the following years the application of chemical agents and fertilizers is effective.

10.2.2. The application of chemical agents and fertilizers

The roles of chemical agents that improve the physical and chemical properties of soil as well as the role of organic and mineral fertilizers, which supplies the nutrient elements to plants, are not affected by radionuclides contamination. However, such agents may acquire new functions, connected with their physicochemical and chemical properties. Proper use of these agents reduces noticeably the radionuclide uptake by plants.

Liming and the role of calcium. Radioactive substances often enter the environment in insoluble and low soluble unexchangeable forms. Later, they become soluble and exchangeable in the presence of water and oxygen. Low soil pH attributes to radionuclide solubility, and acid soils show high transfer of radionuclides from soil to plants in comparison with neutral or alkaline soils. Liming not only maintains the levels of exchangeable calcium and magnesium and provides the chemical and physical environment that encourages the growth of most common plants, but it also reduces radionuclide uptake by plants.

Strontium behaves in soil like the macro nutrient calcium. Liming increases pH and reduces root uptake of ^{90}Sr. The effect of liming depends on actual pH or base saturation and on cation exchange capacity (CEC) of the soil. Liming releases K^+ to the soil solution and slightly reduces root uptake of ^{137}Cs. Liming from pH 5 to pH 7 may decrease plant uptake of ^{90}Sr by factor 2 on sandy soils, 3 on loamy soils and 4 on clay soils, from pH 4 to pH 6 by factor 6 on organic soils. Liming may also decrease uptake of ^{137}Cs by factor 1.3–1.6 (max. ca. 3). Thus, liming is achievable on a large scale and effective on acid soils.

Liming is applied on podzol, soddy-podzol, and some peat-bog soils and, to less extent, on grey forest soils. Lime requirement of soddy-podzol and grey forest soils of Ukrainian Polissya at humus content up to 3% may be defined by pH values of soil solution and soil texture (Table 37).

Liming of acid soils is considered to be one of the main methods to reduce radionuclide transfer from soil to plants. According to studies performed during

19 years after Chernobyl accident liming reduced ^{90}Sr activity concentration in potatoes by factor 5–10, in hay of leguminous grasses by factor 6–8, in vegetables by factor 4–6, in berries by factor 3–5. The effect is less pronounced for ^{137}Cs.

Table 37. Lime requirement defined as the amount of $CaCO_3$ t ha^{-1}

Soil texture	pH of soil salt extract					
	4.5	4.6	4.8	5.0	5.2	5.4–6.0
Sandy-loam and light-loamy	4.0	3.5	3.0	2.5	2.0	2.0
Medium-loamy	6.0	5.5	5.0	4.5	4.0	3.5

Liming is effective on acid soils. Alkaline soils may be ameliorated by gypsum ($CaSO_4 \times 2H_2O$). Neutral soils may be ameliorated by the application of balanced amounts of lime materials and gypsum. However, the effect of gypsum application to reduce radionuclides uptake by plants is not well studied.

Potash fertilizers. Caesium behaves in the soil solution like the macro nutrient potassium. Binding of caesium in soil is very complex. The fixation of ^{137}Cs as a free carrier in fall-outs increases with the content of clay and decreases with the content of organic matter. K-fertilization decreases plant uptake of ^{137}Cs.

K-fertilization is necessary and should be made as soon as possible after fall-outs both on grass land, arable soils during soil treatment. The method is practicable and is achievable on a large scale and crop yield increases on soils with originally low potassium status.

The effect of K-fertilization on ^{137}Cs uptake by crops is highly dependent on the actual K-status in soil and is the most efficient on nutrient deficient peat lands. Fig. 80 shows relationship between level of crop yield contamination by ^{137}Cs and initial K-state of soil. The effectiveness of K-fertilization decreases with increasing of potassium dose. However, increased doses of potash fertilizers (by factor 2–3 in comparison with ordinary dose) reduce ^{137}Cs plant uptake by factor 3–6 (Fig. 81). Thus, K-fertilization reduces ^{137}Cs activity concentration in vegetables and potatoes by factor 4–8, in the grain of cereals and leguminous by factor 3–6, in forage grass, straw and fibre-flax by factor 3–7.

Potassium fertilization had also effect on ^{137}Cs uptake by plants and fungi growing in a forest ecosystem. Thus, ^{137}Cs level in plants such as heather (*Calluna vulgaris*), lingonberry (*Vaccinium vitis-idaea)* and bilberry (*Vaccinium myrtillus*) growing in forest in central Sweden on K-fertilized plots 17 years after application of the K fertilizer was significantly (40–61%) lower than in corresponding species growing in a non-fertilized control area.

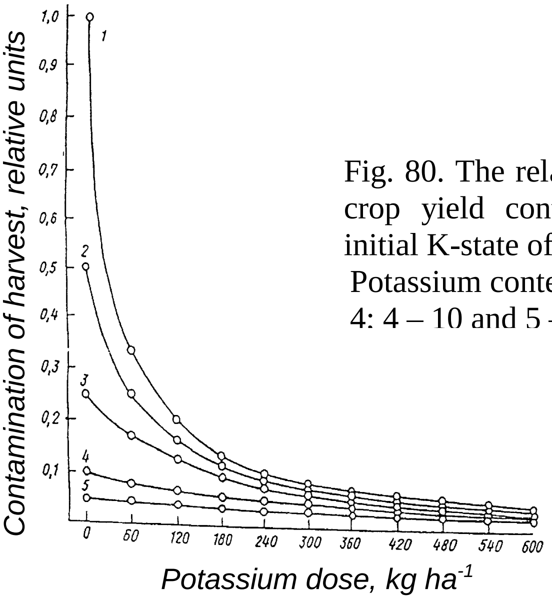

Fig. 80. The relationship between level of crop yield contamination by ^{137}Cs and initial K-state of soil (P. Bondar, 1996). Potassium content in soil: 1 – 1; 2 – 2; 3 – 4: 4 – 10 and 5 – 20 mg per 100 g of soil.

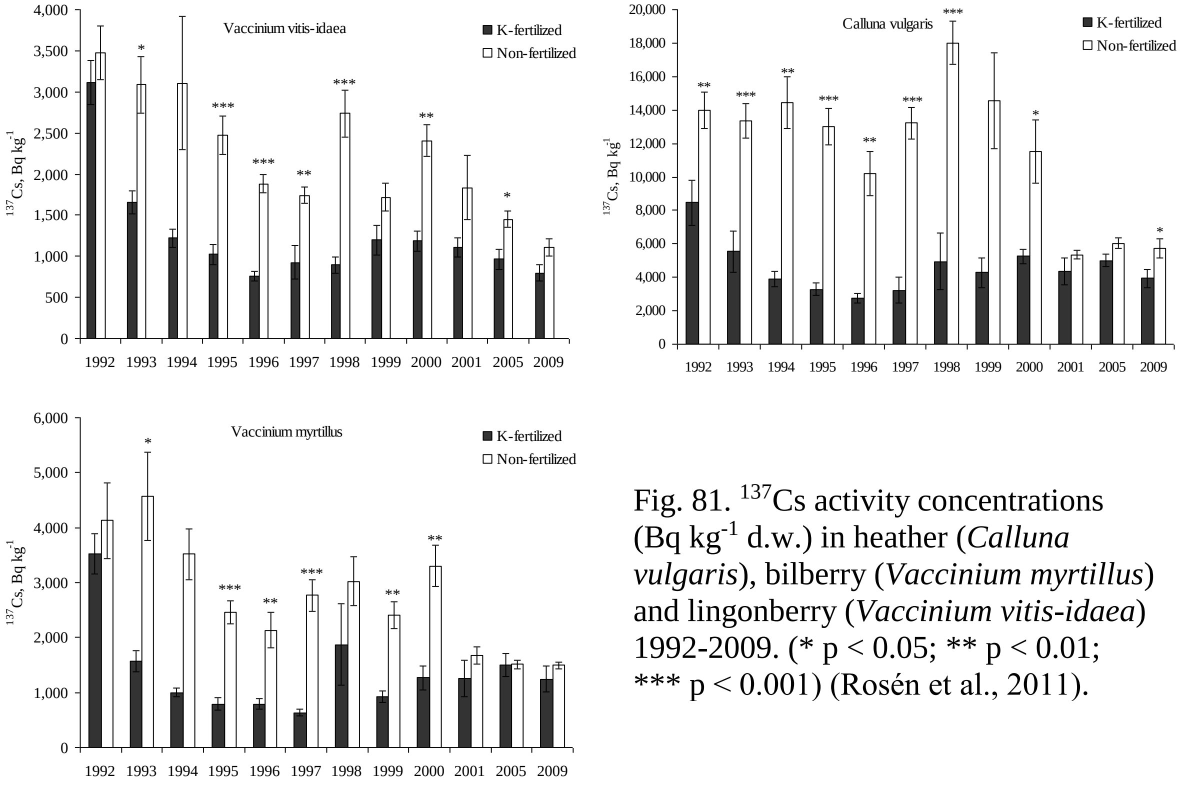

Fig. 81. ^{137}Cs activity concentrations (Bq kg^{-1} d.w.) in heather (*Calluna vulgaris*), bilberry (*Vaccinium myrtillus*) and lingonberry (*Vaccinium vitis-idaea*) 1992-2009. (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$) (Rosén et al., 2011).

The ^{137}Cs activity concentration in fungal sporocarps growing on fertilized plots was also substantially (21–58%) lower compared to those growing in a non-fertilized control area. K-fertilization applied to over ground organs also decreases ^{137}Cs uptake by plants substantially.

K-fertilization reduces ^{90}Sr uptake by plants, especially on podzol and soddy-podzol soils. Thus, the application of potash fertilizers on soddy-podzol sand and loamy sand soils reduces ^{90}Sr uptake by cereals yield, potatoes and vegetable plants by factor 2–3. The decrease of ^{90}Sr uptake is due to well known distinctive antagonism between potassium, on the one hand, and calcium and strontium, on the other hand.

Phosphorus fertilizers. Phosphorus acid salts interact with strontium (or other elements of the second group) and form weakly soluble and even insoluble compounds such as secondary and tertiary phosphates, e.g. $Ca_3(PO_4)_2$. It is assumed that the application of phosphorus fertilizers reduces ^{90}Sr transfer from soil to plant. A number of studies indicate that phosphorus fertilizers reduce ^{90}Sr plant uptake by factor 2–6. The fertilizers containing calcium and potassium phosphates are shown to be the most effective. Thus, the application of potassium phosphates results in the reduction of both ^{90}Sr and ^{137}Cs plant uptake. Other phosphates (ammonium, sodium and magnesium) mainly affect ^{90}Sr uptake.

In the contrast to ^{90}Sr data about phosphorus fertilizers effect on ^{137}Cs plants uptake are contradictory.

The application of phosphorus fertilizers, e.g. superphosphate on leached chernozems enhances ^{137}Cs plant uptake by factor 1.5–2. There is no such effect on poor soddy-podzol soils. The application of phosphorus and nitric fertilizers without potassium often enhances ^{137}Cs plant uptake, e.g. on chernozems by factor 4.

Nitric fertilizers. The application of nitric fertilizers on contaminated by radionuclides soils requires a special interest. There are data about the increase of both ^{137}Cs and ^{90}Sr uptake by plants, when nitric fertilizers are applied. It is suggested that the application of nitric fertilizers causes acidification that, in turn, increases nutrient elements mobility and their bioavailability and radionuclides as well. Ammonium nitrate as well as urea $CO(NH_2)_2$ are traditional fertilizers for Ukraine and most of the European countries. Urea $CO(NH_2)_2$ dissociates producing ammonia and carbonic acid that shifts the pH value to the left.

Therefore, the normally recommended rate of nitric fertilizers the application on the contaminated by radionuclide soils or even less amount is expedient. It is also recommended to apply higher doses of phosphorus and potassium fertilizers instead (by factor 1.5–2) to compensate crop yield and reduce ^{137}Cs and ^{90}Sr uptake by plants.

Microfertilizers. Micronutrients play many complex roles in plant nutrition. The application of microfertilizers reduces radionuclide uptake by plants, especially, on soil showing micronutrients deficiency. Heavily contaminated soils of Polissya and north forest-steppe zone of Ukraine are characterized by having micronutrient deficiency. Micronutrients affect radionuclide uptake by plants in different ways. Being the chemical analogues of radionuclides, some of them can compete with radionuclides for plant uptake. They may affect the permeability of cellular membrane by radionuclides with certain ionic radii, charge, and geometry of coordinating and electronic configurations; activate or inhibit the transport systems of some radionuclides; form complex compounds with various substances, including those that are physiologically active and may affect the radionuclide uptake by plants and their following transportation within plant organs. Listed above effects may be especially pronounced on soils with natural or man-made micronutrient deficiency. The application of microfertilizers in such soils gives the best results. Thus, the application of zinc, manganese, copper and cobalt in the soil before the sowing or on the over ground organs in the soddy-podzol soils reduce ^{137}Cs and ^{90}Sr uptake by lupines, pea and oat plants by factor 1.5–2.

Organic fertilizers. Organic fertilizers increase a soil holding capacity (the finer or colloidal fractions of both inorganic and organic matter), which, in turn, reduces radionuclide uptake by plants. Besides, organic fertilizers contain balanced amounts of macro- and microelements, many of which reduce radionuclide uptake by plants. Poultry dung, for example, contains elevated amounts of calcium.

The application of manure, composts, low-laying peat and sapropels on loamy sand and sandy loam soils is especially effective. Thus, organic fertilizers prevent transfer to plants not only ^{90}Sr and ^{137}Cs but also many other radionuclides such as ^{106}Ru, ^{144}Ce, ^{239}Pu and ^{241}Am that do not have chemical analogues-antagonists among the nutrient elements.

The application of organic and other local fertilizers requires keeping certain rules. Manure, compost and ash collected on the heavily contaminated territories may serve a source of secondary radionuclide contamination of soil. Sapropels also may be highly contaminated due to the concentration of radioactive particles washed out from the catchment areas. Such fertilizers should not be used in fields with low ground deposition level that are used for production of potatoes and other vegetables and are directly used for human nutrition and very often without cooking. Contaminated organic fertilizers may be used for production of industrial crops, seed-producing crops and for forage crop rotations.

Thus, proper application of chemical agents together with fertilizers on contaminated soils is important countermeasure that prevents radionuclide uptake by plants. It is also important to keep in mind that lower radionuclide concentration in crop yield may be achieved by reducing of radionuclide transfer from soil to plants as well as due to dilution by the increase of yield.

10.2.3. The change of plants in a crop rotation

As we mentioned in chapter 9, plants differ in their ability to accumulate radionuclides. One of the options is to select properly the plant sorts and plant types in a crop rotation.

Calciphile plants and, first of all, such leguminous as lupine, alfalfa, clover, vetch, pea, kidney bean accumulate both calcium and „by mistake” its chemical analogue strontium, including ^{90}Sr. Cereal crops accumulate less calcium and, therefore, less amount of ^{90}Sr. As a result plants growing in the similar environment accumulate radionuclides in different ways. The difference may be of one or even more orders of magnitude. The vegetative organs of food grains and leguminous accumulate much more ^{90}Sr in comparison with seeds.

The root crops and tuber-bearing plants that constitute the main part of human nutrition, accumulate higher amount of ^{90}Sr among other vegetable plants (Fig. 82, B). Potatoes, red roots and cabbage take up the highest amount of ^{90}Sr relatively to its contribution to the nutrition.

Similarly, potassiumphilic plants, like lupine, maize, potatoes, beets, buckwheat and many other crops take up noticeable amount of potassium as well as its chemical analogues placed in the first group of the periodic system (stable caesium and radioactive isotopes ^{134}Cs and ^{137}Cs). ^{137}Cs activity concentration in edible parts of agricultural plants may be ranked in the following decreasing order: food grains and leguminous, i.e. buckwheat-soybean-beans-haricot-pea-oat-rye-wheat-barley-millet-triticale (hybrid wheat and rye)-maize; feeding-stuffs (green forage), i.e. lupine yellow-marrow cabbage-vetch; some industrial crops, i.e. garden radish-rape-sugar beets-sunflower-fiber-flax; vegetable, i.e. cabbage-red beet-lettuce-carrot-potatoes-cucumber-pumpkin-tomato (Fig. 82, A).

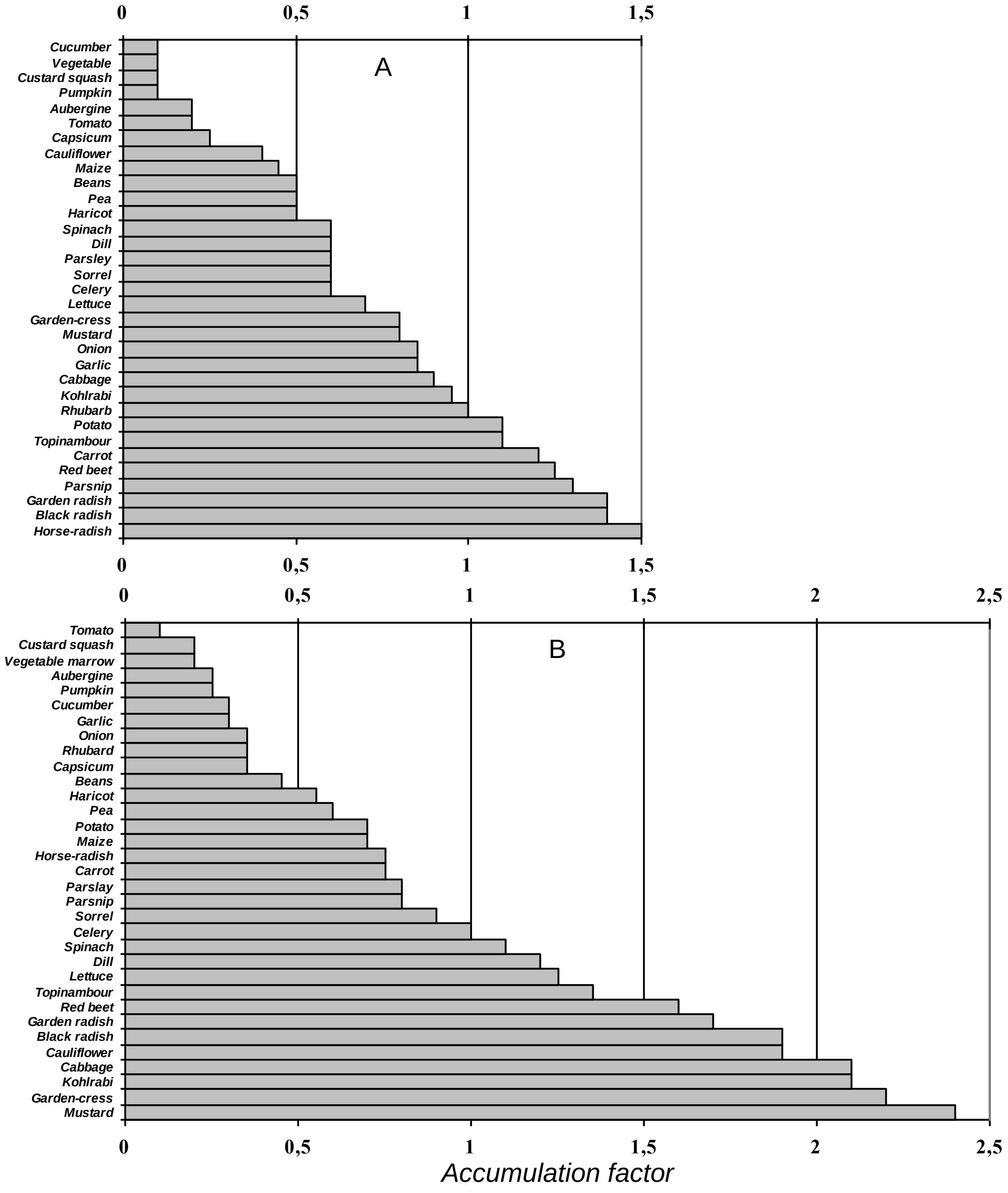

Fig. 82. Relative values of accumulation factor of ^{137}Cs (A) and ^{90}Sr (B) in edible parts of vegetable plants (I. Gudkov, 2002).

The difference in radionuclide uptake among agricultural plants increases in tens times. Thus, a difference in accumulation of ^{137}Cs in the grain of buckwheat and maize increases in 60 times, in productive organs of vegetable plants increases in 25 times. The ^{90}Sr activity concentration in hay of leguminous is 2–10 times higher to that in cereals.

There are also sort dependant variations in radionuclide uptake. Thus, some pea sorts differ in their ability to accumulate ^{90}Sr by factor 2.5; some spring wheat sorts differ in their ability to accumulate ^{137}Cs by a factor about 2. Sorts of winter wheat differ in their ability to accumulate ^{137}Cs by factor 5. Potatoes and maize sorts take up different (up to 3 times) amounts of ^{137}Cs.

To reduce foodstuffs contamination the species and sorts dependant ability of agricultural plants to accumulate radionuclides has to be taken into account in farming on the contaminated by radionuclides territories. For this purpose the set of agricultural crops in crop rotation is a subject to change. Agricultural crops showing high AFs have to be replaced with those having low TF values. In some cases a change of production direction is required.

According to Agriculture Institute of Ukrainian Academy of Agricultural Sciences recommendations as for the following crop rotations are suggested on the contaminated by radionuclides territories: on soddy-podzol sandy soils 1) winter crops on a green forage + maize on a green forage after hay harvest, 2) winter rye, 3) potato, 4) oat; on soddy-podzol sandy loam soils: 1) maize on a green forage and silo, 2) winter rye, 3) potato, 4) barley with an additional sow of perennial grass (cereals and leguminous mixture), 5) perennial grass, 6) winter wheat. There are no crop limitations on the grey forest loamy soils and chernozems.

10.2.4. The change of irrigation regime

Irrigation contributes radionuclide involvement in a biological cycle. Three main pathways through which irrigation affects radionuclide transfer to plants are:

1. Irrigation causes substantial changes in soil water regime affecting mobility and bioavailability of radionuclides.

2. Changes of the character of plant physiological and biochemical processes due to the increase of nutrient element uptake, in turn, affect radionuclide uptake.

3. Additional uptake of radionuclides by over ground organs of plants from the contaminated irrigating water.

Thus, irrigation may provide favourable conditions for radionuclide uptake by plants. Sources of radionuclides are water and soil.

Uptake of radionuclides by plants depends on the mode of watering. At the overhead irrigation (the most widely spread mode of irrigation in Ukraine is used on 95% of irrigated areas) by contaminated water radionuclides mainly are taken up by over ground organs of plants (leaves, flowers, garden-stuffs, stems). The radionuclide uptake in this case reaches maximum values. Radionuclides are taken up by roots under such conditions as at the superficial watering in furrows by filling in bars by means of submergence; at the sub ground irrigation, when water from the system of the sub ground moistening system is supplied by the capillaries directly to the root zone; at sprinkle irrigation, when water is supplied to soil surface in the area of root neck. In this case plants take up a fewer amount of radionuclides, since radionuclides are partly absorbed by soil. Some radionuclides are retained by the roots, by the walls of conducting vessels of the stem and by over ground plant organs.

In the case of watering by unpolluted water the overhead irrigation is preferable.

Watering by unpolluted water promotes deep washing out of soil, transfer of radionuclides from the upper to deeper soil horizons, where root system is mainly located that, in turn, increases radionuclides mobile and their bioavailability.

There are some general rules concerning the change of irrigation regime, when water contains radioactive substances. It mainly concerns lands requiring irrigation in south part of Ukraine. For irrigation purposes contaminated waters of Prypat’ river (Prypat’ is a Dnipro river tributary, where Chernobyl NPP is located, and it forms up to 40% of radioactive Dnipro flow) are used:

- if possible, a superficial watering is preferable;
- to reduce irrigation number within the limits of watering volume;
- when watering during first half of vegetation period is preferable;
- to avoid watering, especially by overhead irrigation during the period of forming and ripening of plant organs.

Mentioned above irrigation limitations may have a negative effect on plants productivity, because any deviation in an irrigation technology results in the violation of plant growing technology. However, it is compensated by obtaining of safety foodstuffs.

10.2.5. Application of special agents and countermeasures

There is a plenty lot of various relatively simple and complicated, natural and artificial agents that being added to soil reduce radionuclide uptake by plants. Two main classes are distinguished among them: adsorbents and complexonates. Adsorbents take up radionuclides making them be non-accessible for plants. Complexonates form complex compounds with radionuclides resulting in their low solubility and, consequently, low bioavailability for plants or, on the contrary, making them easily soluble that may be easily washed out from the root zone horizons of soil.

Adsorbents are naturally occurred minerals, e.g. zeolites that absorb radionuclides very effectively. Deposits of zeolites are found in Carpathians. ^{90}Sr and ^{137}Cs radionuclides are strongly bound by common clay (secondary) minerals (illites and vermiculites). Such clay minerals as montmorillonites and kaolinites have weaker affinities to bind radionuclides. Such minerals as flogopit, hydroflogopit, glauconit, ascanit, humbrin, biotit, and benthonit are considered to be an effective sorbents. In spite of its relative low price, such countermeasure is achievable on a limited scale, since the application of minerals are effective only if it's applied in great amounts, i.e. 0.5–1% of the total volume of arable layer that is about 10–12 tones finely grinded mineral per one hectare. Once applied material reduces radionuclide plant uptake by factor 1.5–3 for a few following years. Sometimes the application of minerals is considered to be land reclamation, since it improves substantially soil structure.

So-called „an active coal (slag variety) produced at anthracite coal burning has strongly pronounced adsorbing affinity. The application of two times less amount on soddy podzol soils results in a similar effect.

The application of aminopolycarbone acids and their derivates reduces the uptake of ^{239}Pu, ^{241}Am and other radionuclides by plants. Such agents form complex water soluble compounds with radionuclide promoting, in such a way, their washing out from soil. This countermeasure, however, is rather expensive and is not widely used so far.

Sprinkling of soil and plant surface by solutions containing special chemical compounds that form hardly soluble in water polymeric film on its surface, is the countermeasure directly reducing radionuclide uptake by plants. Such protective film prevents secondary contamination of soil surface due to the wind lifting and transfer of radioactive substances with air flows. It also reduces contamination of over ground organs of plants and of other organisms.

Mentioned above countermeasures are too expensive and, therefore, are achieved in a limited area.

Generalized data concerning some of the most effective countermeasures that reduce radionuclide transfer from soil to plants are listed in Table 38.

Table 38. The efficiency of some radioprotective countermeasures that reduce ^{137}Cs and ^{90}Sr transfer from soil to plants

Countermeasures	Types of soil	Reduction factor in comparison with the control	
		^{137}Cs	^{90}Sr
Liming	Soddy podzol Light grey, forest, peat	1.5–4.0 1.5–2.5	1.5–2.5 –
The application of double dose of phosphorus and potassium fertilizers	Soddy podzol, grey forest Peat	1.5–2.0 1.8	1.2–1.5 –
The application of organic fertilizers, 40 t ha^{-1} and more	Soddy podzol, grey forest, peat	1.5–3.0	1.5–2.0
Liming, organic and mineral fertilizers application	Soddy podzol and sandy loam, grey forest	2.0–5.0	–
The application of adsorbent minerals (zeolites, kaolinites, vermiculites, bentonites)	Soddy podzol, sandy and sandy loam	1.5–2.5	1.5–2.0

It is necessary to point out that any considered complex systems of countermeasures or any single countermeasure applied together do not provide corresponding decrease of radionuclide uptake by plants. Moreover, combined application of several countermeasures may alter substantially the transfer of radioactive substances and fission products to plants, and even cause the decrease of its efficiency in comparison with single application.

10.3. Measures reducing radionuclide transfer in animal production

Radionuclides (above 95%) enter an organism of productive agricultural animals mainly through the consumption of contaminated fodder. The uptake of radionuclides with water is negligible. Therefore, providing animals with “clean” fodder is the main prerequisite of stock-raising on territories contaminated by radionuclides. Unfortunately, it is not always achievable. Therefore, a strategy for the reduction of radionuclide transfer to animals should mean next major points: the improvement of forage base; working out of rations; the application of additives and preparations (preventing transfer of radionuclides to animal production) into rations; and some organizational measures.

10.3.1. The improvement of animals feeding

Radionuclide content in the ration of agricultural animals and its transfer to the animal production is mainly determined by many factors of their feeding and keeping. The uptake of radionuclides by fodder crops and other plants is determined by their biological specific differences and soil type. Radionuclide plant uptake is also affected by their distribution in soil. In cultivated soils radionuclides are homogenously distributed within an arable horizon. In virgin lands (meadows, pastures and hayfields) radionuclides are mainly concentrated (up to 90%) in the upper 4–6 cm of turf layer. As a result the radioactivity concentration of the upper soil layers in virgin lands many times higher then in cultivated soils. The accumulation of radionuclides in a root zone enhances their uptake by plants. Experimental data evidence higher soil-plant ^{137}Cs transfer in meadows in comparison with arable soils (Table 39).

The quality of pastures and meadows greatly affects contamination of animal production. Grazing animals keeping on pastures with weakly developed and knocked out herbage may intake unintentionally attached to the grass contaminated soil resulting in additional contamination of animal products. Such intake may be of high significance, i.e. 0.1–1 kg per day or about 200 kg per cow per pasturable season. Sheep, for example, may swallow up to 50 kg of soil. That’s why, the superficial and radical improvement of pastures and meadows are recommended.

Table 39. The accumulation factor (AF) of ^{137}Cs in fodder crops grown on meadow and cultivated soddy-podzol soils (A. Syrotkin, 1996)

Fodder crops	AF
Meadow grass: - green forage - hay	1.43 6.12
Timothy grass in a crop rotation: - green forage - hay	0.19 0.59
Perennial grass on hay	0.27
Maize silo	0.07

The superficial improvement, as a rule, is recommended on sandy soils if these lands cannot be ploughed due to erosion threat, or when herbages are composed of up to 50% of cereals and leguminous grass. The superficial improvement means liming, the application of nitric and an elevated amount of phosphorus and potassium fertilizers. Such countermeasure together with higher productivity of meadows and pastures reduces plant uptake of radionuclides by factor 2–4.

In other cases the radical improvement of meadows and pastures is required. It includes ploughing or deep cultivation by disk harrows for turf cutting and turn over, liming of acid soils, the application of nitric and elevated amount of phosphorus and potassium fertilizers. This improvement may reduce plant uptake of radionuclides by factor 2–10.

The formation of the herbage is an important element of meadows and pastures radical improvement. Early cereal mixtures accumulate less radionuclides in comparison with later ones. However, for intensive cattle grazing later cereal grass mixed with leguminous are found to be more effective. To balance with fodder protein addition, the sowing of red clover is mixed with later cereal grass and white clover with early cereal grass.

To reduce radionuclide uptake by fodder grown under conditions of crop rotation countermeasures listed in the previous section must be recommended.

On other hand, if animals are fed with harvested forage, cutting the forage plants at greater height significantly decreases the amount of attached contaminated soil.

10.3.2. Working out of rations

Ration composition plays the important role in radionuclide content reduction in fodder. Properly sorted out ration ensures the reduction of ^{90}Sr and ^{137}Cs content in milk, meat, eggs and subproducts by factor 2–5. The ration working out is based on the permanent control of fodder contamination by radionuclides. As we mentioned above the specific dependent ability of various crops to accumulate radionuclides has to be taken into account. The transfer factor (TF) of radionuclides from the nutrition to milk and animal tissues for specified radionuclides is also the subject of concern.

Thus, TFs of ^{90}Sr and ^{137}Cs in milk and beef, when animals are fed with a green forage prevailing ration, are 1.5–2 times higher in comparison with that one when animals are fed with cereals and coarse fodder prevailing ration. The hay type of cattle feeding results in greater ^{90}Sr and ^{137}Cs transfer from the fodder to meat and milk in comparison with mixed ration that comprises cereals, coarse fodder and hay or silo-concentrated product ration (Table 40). High activity concentration of ^{90}Sr is observed in the skeleton of calves and lambs born from the cows and sheep that are fed during the pregnancy period with hay ration. In lambs born from the sheep fed with mixed and concentrated product ration the radionuclide deposition in the skeleton is reduced by factor 4–4.5.

Table 40. The effect of feeding type on ^{90}Sr and ^{137}Cs transfer to a cattle organism and animal production, % (N. Kornejev et al., 1977)

Ration	Entered with ration		Content in meat		Content in milk	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Hay	100	100	100	100	100	100
Mixed	35	44	33	36	43	50
Silo-concentrated	18	48	20	18	50	57

To meet requirements for milk and meat production, the permissible levels of ^{90}Sr and ^{137}Cs are set for rations depending on the cattle species, age and productivity level. Maximum permissible levels (MPL) of radionuclide contamination are set for various fodder and soils used for fodder crops production.

Maximum permissible levels of radionuclide content in the ration may be found as the following: $MPL = PL \times 100C_{ft}$, where PL is a permissible level of radionuclide content in animal products (milk, meat), Bq l^{-1} (kg^{-1}) and CF is a concentration factor of radionuclide from fodder to milk and meat (organ or tissue) as the percentage in the ration per 1 kg of a product. Averaged data of C_{ft} are shown in Table 41.

Table 42 shows (as an example) the ration for a cow with permissible levels of ^{90}Sr and ^{137}Cs. In Table 43 permissible levels of ^{90}Sr and ^{137}Cs in rations of different types of animals that provide the production of animal products within the limits of permissible levels (PL-97) are shown.

Table 41. The average values of concentration factor (CF) of ^{90}Sr and ^{137}Cs for some types of animal production, % in the ration per 1 kg of product (B. Prister et al., 1998)

Type of products	Radionuclides	
	^{90}Sr	^{137}Cs
Cow milk: indoor keeping period outdoor keeping period	0.14 0.14	0.7 0.9
Beef	0.04	4
Pork	0.10	15
Mutton	0.10	15
Chicken meat	0.20	450
Eggs	3.20	3.5

Table 42. The approximate ration for cows with yield of 10 kg of milk per day and maximum permissible levels of radionuclides for indoor keeping period (L. Romanov et al., 1998)

Fodder	Mass, kg	^{90}Sr		^{137}Cs	
		Bq kg^{-1}	Bq day^{-1}	Bq kg^{-1}	Bq day^{-1}
Hay	3	2 600	7 800	100	3 000
Straw	2	1 850	3 700	370	740
Haylage of sowed grass	6	500	3 000	300	1 800
Mangel (-wurzel)	10	100	1 000	200	2 000
Silo maize	10	50	500	150	1 500
Concentrates	3	100	300	200	600
Together:	34		16 300		9 640

Table 43. Permissible levels of ^{90}Sr and ^{137}Cs in an animal daily fodder to obtain animal production within the maximum permissible levels (N. Lazarev et al, 1998)

Production	^{90}Sr		^{137}Cs	
	In a diet, Bq	In a product, Bq kg^{-1}	In a diet, Bq	In a product, Bq kg^{-1}
Cow milk	20 000	20	10 000	100
Beef	33 340	20	5 000	200
Pork	20 000	20	667	200
Mutton	20 000	20	667	200
Chicken meat	10 000	20	22	200
Egg (melange)	625	20	2 900	100

10.3.3. Application of additives and other supplements to the ration

The balanced mineral feeding prevents radionuclide transfer from the environment to an animal organism. Calcium and potassium feeding of animals and plants is of special interest. In an organism of vertebrates calcium is the main constituent of the skeleton, in mammal organism is the main mineral constituent of milk. Consuming fodder with calcium deficiency gives rise to take up its chemical analogues, i.e. elements of the second group of the periodic system, including strontium. Therefore, calcium deficiency increases ^{90}Sr absorption by animals. For this, calcium is used as a food additive to reduce the radiostrontium transfer to milk. The sources of calcium additives are numerous and cheap enough, e.g. calcium carbonate ($CaCO_3$) and calcium phosphate ($Ca_3(PO_4)_2$). However, if the Ca/P ratio of fodder becomes too high, it can affect an animal health. It is also inappropriate for use as a countermeasure for freely grazing ruminants.

Thus, calcium carbonate application in calve and piglet fodder during a month reduces the radiostrontium deposition into an organism by a factor about 2. The increase of the calcium content of fodder in 2–4 times reduces the radiostrontium level in milk by factor 1.5–3 depending on the initial level of calcium nutrition. However, some data show that the increase of the calcium content in cow fodder reduces ^{90}Sr content in milk by factor 8–12 (Fig. 83). The increasing of the calcium content of fodder in 2–4 times reduces the radiostrontium level in milk by factor 1.5–3 depending on the initial level of calcium in fodder. Supplements show the effect, when 80 g per day is added (that is a physiological norm). The following increase of calcium in a fodder does not affect radionuclide accumulation.

In contrast to plants fewer data are available about potassium that is contained in a fodder and its effect on the ^{137}Cs transfer to an animal organism. At least certain reduction of ^{137}Cs accumulation by animal tissues is expected, when potassium supplements are applied in a fodder. Such assumption is based on the exclusive role of potassium in many physiological and biochemical systems of an animal, e.g. cellular membrane functioning, carbon exchange, synthesis of many enzymes and hormones. Feeding-stuffs rich in potassium are maize silo, potatoes, mangel (-urzel), some types of leguminous crops and fodder cereal grass.

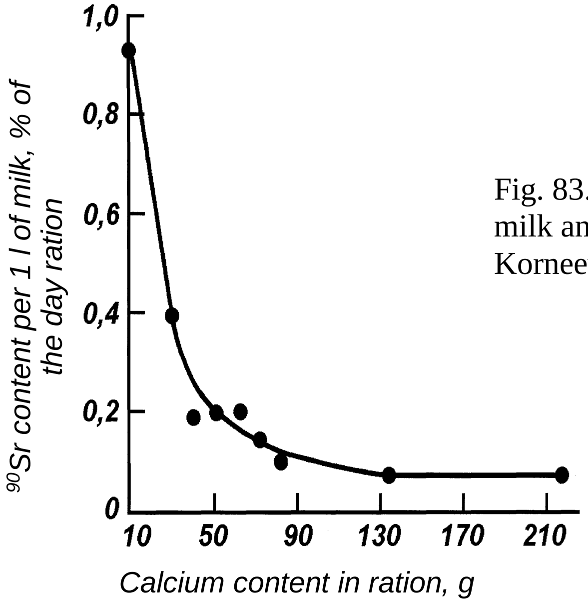

Fig. 83. The relationship between ^{90}Sr in milk and calcium in cow nutrition (N. Korneev, A. Syrotkin, 1987).

It is less known about the role of sodium to reduce ^{137}Cs transfer to an animal organism. Being a chemical analogue of caesium, sodium it is involved in many physiological processes of an animal organism. Based on the antagonistic relationships between potassium and sodium, it is suggested that ^{137}Cs uptake is affected by the potassium and sodium content in an organism, on the one hand, and their ratio on the other hand.

The application of microelements is considered to be an important factor to reduce radionuclide uptake by animals. Micronutrients are also known to increase animal radioresistance. It especially concerns soils of Polissya regions that show the deficiency of major macro- and micronutrients. Fodder crops, therefore, are also lack of major microelements such as iodine, fluorine, zinc, cobalt, manganese, copper, selenium and others. The application of listed above microelements in an animal nutrition may be the important countermeasure for stock-raising on the territories contaminated by radionuclides.

However, the application of countermeasures that reduce radionuclide transfer to plants, e.g. liming, phosphorus fertilizer application, increases microelement binding in soil that further reduces micronutrient uptake by fodder crops grown on these soils. If the micronutrient content becomes low, it can affect an animal health and cause a sickness commonly known as hypomicroelementhosis. Therefore, periodical application of microelements in animal nutrition based on their content in fodder, water, milk, blood and meat is recommended.

There are other substances-preparations that reduce radionuclide transfer from fodder to animal tissues. They are characterized by different chemical structures and belong to a large group of compounds that bind radionuclides in gastrointestinal tract and reduce their absorption from animal nutrition. They are called enterosorbents. Alginates (salts of algic acids) extracted from some species of brown algae have such properties. The application of alginate and even brown algae in animal nutrition reduces ^{90}Sr deposition in animal tissues by factor 1.5–2. Similar effect is shown by pectines, i.e. constituents of fodder root-crops such as beetroots, including mangel (wurzel), pumpkin, garden-stuffs of stone-fruits and semen-fruits.

Prussian Blue filters for milk decontamination that are applied in an animal gastrointestinal tract are especially effective in reducing of ^{137}Cs absorption of mammals as well as poultry. They are also known as ferrocyne, and their derivatives are ferrocyanides of iron, cobalt and nickel. Ferrocyne binds ^{137}Cs in digestive tract and forms insoluble compounds preventing its absorption through the stomach, small and large intestine walls and is followed by the elimination from an organism with metabolism products.

Ferrocyne is used for an animal organism as a powder either with forage or mineral elements or with different filling agents mixed with fodder mixture and as licked briquettes. Special waxen-ferrocyne boluses are widely used. 2–3 boluses are entered directly a paunch of each cow through the mouth at the beginning of pasture period using a simple device: a boluses injector. Being rubbed with each other in stomach boluses gradually release ferrocyne that is mixed with fodder and absorbs radionuclides preventing it from being sucked in blood. Boluses are effective during the period from 2 to 3 months.

Filtering highly contaminated milk through a Prussian Blue filter binds the Cs and, thereby, reduces Cs content in milk. The reduction of the radiocaesium content in milk by factor 5–10 may be achieved. Milk is filtered before going to the processing. One filter may be used to clean 100 l of milk.

Mentioned above zeolites or micas used as simple grinded minerals (clinoptylolite), being modified by special treatment (humolite), 10% of which added to concentrated forages, are also considered to be an effective enterosorbents. It reduces ^{137}Cs content in milk and meat by factor 1.5–3 and 1.5–9 respectively.

Substances that reduce radionuclide accumulation in an organism by blocking their incorporation in tissues by means of the competitive interaction, the sorption, and the formation of complex compounds or by other mechanisms are called radioblocking agents. It is necessary to distinguish them from radiodecorporants, i.e. substances that speed up radionuclide elimination from an organism. The last are not used in the stock-raising due to their high prices.

10.3.4. Organizational measures

Change production is one of the most radical among organizational measures. In severely contaminated areas, a mean for limiting the transfer of radioactivity to animal food products is to change the production line from milk to beef or, for example, pork. Analyses showed that the method can reduce the transfer of radiocaesium from a field to animal food products by factor 5–10 and, thereby, reduce a collective dose. Further, in contrast to milk that is produced continuously, meat is produced intermittently. It gives the possibility to avoid seasonal peak of activity concentrations in meat. If it is possible to feed with clean fodder over a period prior to slaughter a considerable reduction in meat activity can be obtained.

The other way to reduce radionuclide uptake is to replace small ruminants such as sheep/goats with cattle due to the fact that small ruminants accumulate higher radionuclide levels than cattle due to the difference in metabolism processes for these animals. The expected effect may vary depending on the activity levels and animals and can result in fivefold reduction. Such measure is preferable, if the infrastructure and knowledge of husbandry production take place. The pasture, where sheep/goats are grazing, can be used for cattle. However, the most efficient products, taking into account the reduction of radionuclide transfer, can not give the best economic turnover.

Clean fodder for animals before slaughter is another countermeasure to reduce animal product contamination. To give fodder containing radiocaesium as little as possible to sheep, goats or cattle for a pre-determined period (based on monitoring of a representative number of animals) before slaughter is preferable. Such measure is effective in the case of meat production of animals grazing in the contaminated areas. Biological half-life of, for example, ^{137}Cs in meat, depending on animal species, is to be from 9 to 18 days. Two-three months period is considered to reduce ^{137}Cs in animal products by factor 6–10 when clean fodder is given.

Under high contamination conditions, where cleaner fodder is not available, it is impossible to reduce animal meat contamination sufficiently to allow the consumption. However, the usage may be still efficient for non-food production of, for example, sheep (wool and leather). Horses or bees may be also kept for similar purposes. The radionuclide transfer to honey as well as to other products of bees-keeping is known to be low. The method is strictly not a mean of a dose reduction, but it is a way to continue animal farming under high contamination conditions. The specific contamination in washed wool may be as little as one-fifth of that in meat from the same sheep, and will only give rise to external exposure.

Average data about some radioprotective measures efficiency in the stock-raising are shown in Table 44.

Table 44. The efficiency of measures to reduce ^{137}Cs and ^{90}Sr transfer to animal products

Measures	Reduction factor in comparison with control	
	^{137}Cs	^{90}Sr
The superficial improvement of meadows and pastures	1.5–6	1.5–5
The radical improvement of meadows and pastures	1.5–10	1.5–5
Fodder with ferrocyne supplement	5–8	–

Fodder with zeolite supplement	2–5	–
Clean fodder for animals before slaughter for a month	2–4	–
Processing of milk for cream production	6–12	5–10
Cooking treatment of meat	2–4	–

In other words the counteractions should be taken to reduce the dose rate in an area. It depends on whether it can be done in a way that is cost-effective. That is, not only in terms of the traditional cost-benefit elements (essentially monetary operation costs versus saved dose), but also including non-radiological factors that may influence the decision. In short, it can be said that any action should be justified. Under certain circumstances small dose contributions may be easily and inexpensively averted. If it is so, they should be averted, as it is generally considered that radiation dose has no lower threshold with respect to the detrimental effect of radiation.

10.4. The reduction of radionuclide content in plant and animal production by primary technological processing

The application of mentioned countermeasures that reduce radionuclide transfer to agricultural plants and tissues of agricultural productive animals still do not always guarantee the production of foodstuffs within the permissible levels. However, it does not mean that such products must be destroyed. Some technological processes, e.g. the separation, allow localizing radionuclides in one component of the product that often is not the main one, but is a sub-product. It is also necessary to keep in mind that those radionuclides entering plants are transported within a plant and transferred from a plant to animal tissue as water soluble compounds. Consequently, radionuclides are mainly associated with water containing part of the product and, thereby, are passed to water solution, when subjected to the relevant technological process. Therefore, any technological processes that reduce water content (e.g. wringing out, filtration, centrifugation, but not drying, and concentrations) result in the product decontamination.

10.4.1. The decontamination of plant products

There are rather simple methods of plant production decontamination that does not require special facilities as well as those that require special equipment and remedies. Thus, all types of fresh foodstuffs and crop fodder of vegetative origin may be contaminated by soil particles containing various potassium and calcium salts as well as caesium and strontium ones. Most contaminated parts of root-crops, for example, are the head and the tip (in cabbage it is the cabbage-head, in onion it is the bottom, in lettuce species it is an over-root part. Washing, brushing, peeling, removing of outer layers of cabbages or lettuce, additional cleaning of grains before milling are effective measures to reduce radioactive contamination. The effect is based on the removable surface contamination. The decontamination effect is close to the fraction of mass losses of food products. The method eliminates or reduces the absorption of the whole mixture of radionuclide fall-outs deposited on growing strands of vegetables and fruits.

The external contamination of cereal crops from deposited radionuclides has a distinctive influence on the distribution of radionuclides in cereal grains after harvesting. Different activity concentrations are found in flour, dark meal and bran. Only contamination occurring immediately after harvesting is mostly found in bran. Control measurements of actual milling fractions show the distribution of different long-lived radionuclides, and indicate what can be achieved by changing milling yield reduced the use of bran, dark meal for products. The milling industry is well prepared for changes in milling yield, and also in changes of grain trade through the eventual use of bran as fodder. Some tens percent of dietary radiocaesium (and a considerable part of radiostrontium) received from grains can be avoided by (modified milling and) adjusted use of milling fractions for food products.

Cooking, soaking in dilute of NaCl and pickling of vegetables promote radionuclide transfer to syrup, brine and marinade.

Relatively high decontamination may be achieved by potatoes processing to starch. Starch production means the reduction of potato fragments followed by cell juice separation and using water to obtain starch grains. Most radionuclides are left in washing waters resulting in effective (up to 50 times) decontamination of starch. A similar way of starch production is used for grains of cereals.

Processing of plant products and fruits containing carbohydrates into the ethyl spirit eliminates practically all radioactive substances similarly to non-radioactive ones that remain in a fermentation residue. Radioactivity of obtained product is negligible.

Processing of contaminated sugar beets substantially reduces radioactivity concentration in the final product. Sugar beets processing includes the reduction to fine fragments of initial product followed by their washing with hot water, where sugar and radionuclides are transferred. The following steps are sugar isolation and purification (defecation, saturation, sulfofication (oxidation by which sulfur are converted into sulfates), evaporation, filtration, sugar formation and finally crystallization). They reduce radionuclide content in so-called “white sugar sand” by factor 50–70 in comparison with that in roots.

Processing of sunflower-seeds, flax, hemps and other types of plants to plant oil reduces radionuclides content in oil. It includes wring out of liquid fraction, extracting of fats, its distillation and cleaning. Extracting of fats is the main process, where organic solvents are involved in. Such radionuclides as ^{90}Sr, ^{137}Cs and others do not dissolve in organic solvents. The following processes of oil production, i.e. distillation, cleaning by settling, filtrations, hydratation, and, especially, refining allow obtaining uncontaminated plant oil.

If an area of soil is so heavily contaminated, so it is impossible to use for growing production for direct consumption, rape or sunflower (for oil), cotton, flax or other industrial crops may be grown.

Contaminated by radionuclides plant biomass useless for feeding can be processed to food and forage protein. This is a new biotechnology that is widely used in some countries but still has a limited application in Ukraine. This technology foresees obtaining protein directly from green forage by wringing out of cellular juice followed by the coagulation of protein from juice according to special technology. Obtained in such way protein contains tens times less radionuclides in comparison with the original plant and is an extraordinary valuable product for food industry as well as for the supplement to the concentrated forages for agricultural animals.

It is also a promising approach for utilizing of plant biomass used for phytodezactivation and phytoremediation of contaminated by radionuclides soils.

Not all mentioned methods of plant production processing may be called cleaning. Many of them give decontaminated, but different products. However, they evidence about many possibilities and options to use and utilize radioactively contaminated plant production.

10.4.2. The decontamination of animal products

Processing or treatment of animal production can substantially reduce radionuclide concentration and, therefore, a dose rate to humans. Even ordinary treatment of animal production may give a noticeable effect. The decontamination of milk that is the main dose forming factor, especially for children, is an example.

Thus, the separation of whole cow milk distributes radionuclides in milk into cream and whey. About 8–16% of ^{90}Sr, ^{131}I and ^{137}Cs activity remains in cream, and the rest of activity is transferred to whey. Double or three-fold washing out of cream by warm water and by fat free milk reduces ^{90}Sr by factor 50–100. Processing of cream to butter substantially reduces transfer of ^{90}Sr, ^{131}I and ^{137}Cs to butter. Activity of ^{90}Sr, ^{131}I and ^{137}Cs in butter was found to be 35, 75 and 50% according to their concentration in cream. Melting again of butter allows complete removing of ^{90}Sr and ^{137}Cs and reduces ^{131}I content by factor 1.1. Processing of milk to a fat free cheese reduces ^{90}Sr and ^{137}Cs activity concentration by factor 1.9, and ^{131}I up to 1.7. Thus, processing of contaminated milk to cream and butter is an effective way to reduce radionuclide content in final milk products. Table 45 shows an average data of milk processing efficiency.

Table 45. Transfer of ^{90}Sr and ^{137}Cs from contaminated milk to milk products (Sobolev et al., 1998)

Product	% *	
	^{90}Sr	^{137}Cs
Whole milk	100.0	100.0
Fat free milk	92.0	85.0
Cream	8.0	15.0
Buttermilk	6.5	13.5
Fat free cheese	12.0	10.0
Butter	1.5	2.5
Milk fat (melted again butter)	<0.1	<0.1

* activity in the whole milk is assumed to be 100%

Milk processing products differ in radionuclide content of ^{90}Sr that is mainly concentrated in products enriched with proteins, and ^{137}Cs that remains in whey and buttermilk. Fats do not form complexes with alkaline and alkaline earth metals resulting in transfer of small amount of radionuclides to cream and negligible amount to butter.

The curve on Fig. 84 shows relations between fat and protein content in cream and ^{90}Sr and ^{137}Cs activity. Increasing of fat and protein in cream content reduces ^{90}Sr and ^{137}Cs concentration by factor 2.7 and 2.3 respectively. Iodine halogen, however, behaves differently since fats and proteins are iodophilic. As a result iodine is bound to fats and protein (protein-bound iodine).

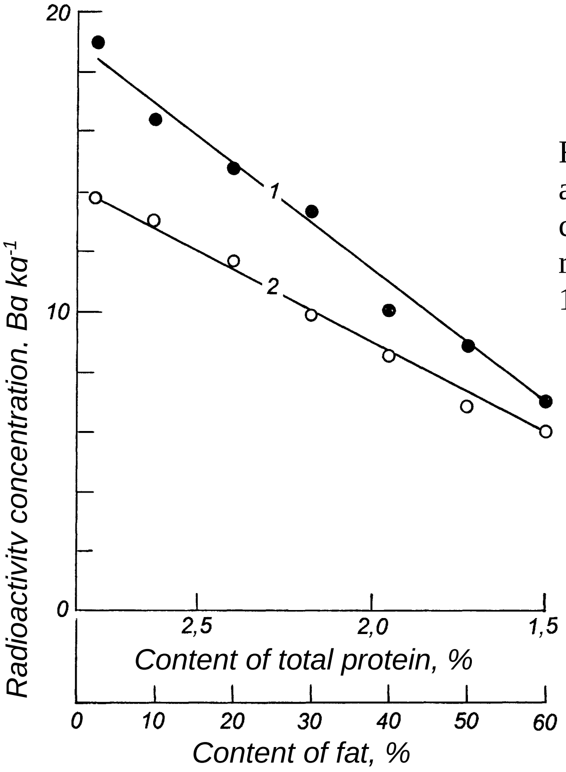

Fig. 84. Relationships between ^{90}Sr (1) and ^{137}Cs (2) activity concentration in cream and fat and protein content as a result of milk processing (F. Fedin et al., 1992, 1993).

That is why, ^{131}I can be concentrated in butter as well as in other fats. However, due to its short half-life period (8 days), manufacturing of food products (including butter) being stored for several months is one of the methods that allows achieving the reduction effect on short-lived radionuclides, e.g. ^{131}I that decays in six weeks period to insignificant level. Such method was widely used in 1986 that allowed avoiding the great milk losses.

Some methods allow reducing radionuclide content in milk without the change of its original chemical composition and properties. It is known that the application of pyrophosphates results in binding of about 80% of ^{90}Sr from milk. Using of ion exchange resins is a quick and effective method of the milk decontamination from other radionuclides. Thus, one volume of well known anionite Dauex 2 allows extracting above 95% of ^{131}I and 50% of ^{90}Sr from the milk volume of 230 litres. Facilities for ^{137}Cs extracting from milk by means of ferrocyne sorption are available.

However, electro-dialysis method allowing the extraction of up to 90% of ^{90}Sr from milk seems to be most effective. An electro-dialysis through the anion exchange membranes allows extracting up to 99% of ^{137}Cs and up to 70–90% of

^{131}I. The method is reasonably expensive. Prime cost of milk increases by about 10%.

Cooking treatment by means of meat parboiling is an effective measure of the meat decontamination (Fig. 85). However, parboiling of bones does not affect ^{90}Sr content, since strontium similarly to calcium, is involved in bones structure. Only negligible amount of radiostrontium is released to the solution (0.01–0.2%). Parboiling of 7-months bull-calf meat releases ^{90}Sr and ^{137}Cs up to 60 % from meat to beef-tea. The addition of a citric and lactic acid to milk increases radionuclide release up to 75–85%. Similar yield is observed, when chicken meat is boiled. About one half of the total amount of radionuclides releases to chicken-broth within first 10 min. Further boiling of chicken meat causes lower radionuclide release rate from meat. There is no need to boil meat longer time and first portion of chicken-broth may be discharged.

Prolonged (10–12 h) washing out of meat with running water and light salting is another method to reduce the amount of radioactive substances in meat. Soaking of meat pieces (200 g) in dilute of (5%) NaCl brine, using two successive treatments of 2 days each reduces meat contamination from radioactive caesium. 20% of the radioactive caesium in contaminated meat remains in the edible fraction of meat. The method is applicable to both household cooking and food industry. Soaking of meat pieces in acidified by oxalic and citric acids water solution is another measure reducing radionuclide content in meat depending on pieces size, soaking time, number of treatments, acidity of solution and, finally, level of meat contamination, chemical properties of radionuclide.

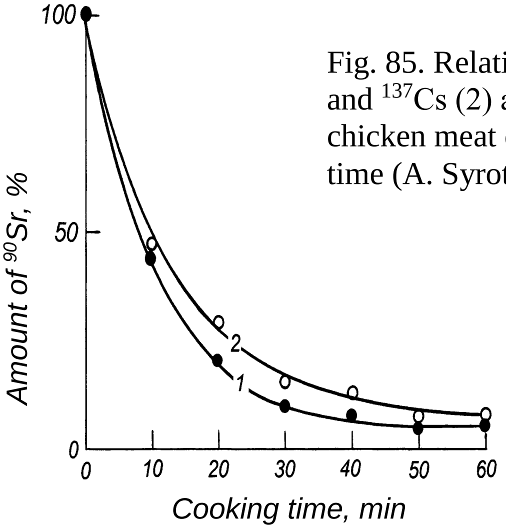

Fig. 85. Relationships between ^{90}Sr (1) and ^{137}Cs (2) activity concentration in chicken meat depending on boiling time (A. Syrotkin et al., 1994).

About 95% of ^{137}Cs remains in the cracklings when animal fat is melting again, thus, reducing radionuclide content in melted fat by factor 20.

The method of light salting of fish foresees brining file in dilute of (5%) NaCl solution in cool or cold store for shorter (8 h) or longer (□ 48 h) time. The brine is discarded after the treatment. 20% of radioactive caesium received from fish remains in edible product after a treatment of 2 days; 50% after a treatment of 8 h.

Parboiling of fresh mushrooms in excess of water (about fourfold volume of water in comparison with mushrooms) is another method to reduce radioactivity level in mushrooms, i.e. boiling time of 3 minutes, discarding the water and rinsing mushrooms with plenty of cold water. Major part of ^{137}Cs is removed from *Lactarius* type of mushrooms. The fraction of initial activity remaining in edible part of mushrooms is about 10%.

Substantial part of ^{137}Cs activity concentration allocated in fungal mycelium is also water soluble. Thus, in studies of M. Vinichuk et al., (2005) about 29% of ^{137}Cs activity concentration in fungal mycelia was found as water soluble with a range of 11 to 41%. Additionally 24% of the ^{137}Cs activity from mycelia was released by 1 M ammonium acetate extraction. Together, water and 1 M ammonium acetate extraction released about 53% of the total ^{137}Cs activity in the mycelia. In fruit bodies of mycorrhizal fungi, 68% of the total ^{137}Cs inventory was found to be water soluble at room temperature and 93% at 80°C.

Dried mushrooms may be soaked in boiled water that is poured onto mushrooms in a bowl, and the water is allowed to cool to the room temperature. Discarding the water before cooking mushrooms reduces the radioactive caesium activity of edible food significantly. Mushrooms contribute the intake of radioactive caesium after the treatment of 10–20% of the activity ingested without the treatment.

To estimate the decontamination level of the production due to countermeasure, the decontamination factor (DF) is introduced that is the relation between activity concentrations of the specified radionuclide in the decontaminated production to that in original one. Table 46 shows DF's values of different processing technologies and treatments.

We are about to finish the investigation of some countermeasures that can be utilized on the territories contaminated by radionuclides. Discussed above methods show the possibility to use a broad spectrum of countermeasures that reduce radionuclide transfer from the soil to agricultural plants and animals and, finally, to humans for the contaminated agricultural environment. This strategy requires quick assess of the situation to determine the needs of countermeasures.

Table 46. The decontamination factor (DF) of animal production processing (meat of beef, pork, mutton, and rabbit meat) for ^{137}Cs (L. Matola, M. Dolgy, 1993)

Methods of production treatment	DF
Baking	0.5-0.8
Cooking	0.25-0.5
Stewing	0.5-0.6
Frying	0.5-0.8
Salting	0.1-0.6
Pickling	0.1-0.3
Canning	0.5
Sausages production	0.25-0.95

The system of considered above applied countermeasures do not give simple arithmetic adding up of radioprotective effects. However, it allows substantial reducing of radionuclide accumulation by agricultural plants and animals that, in turn, reduces a collective dose for people living on the contaminated territories.

Control points to chapter 10:

1. Problems of agricultural production on the territories contaminated by radionuclides.
2. The main complex approaches to reduce radionuclide transfer to plants.
3. Methods of soil treatment to reduce radionuclide transfer to plants.
4. Liming and gypsum application to reduce radionuclide transfer to plants
5. The effect of fertilizers application on radionuclide transfer to plants.
6. The organic fertilizers application to reduce radionuclide transfer to plants
7. Species dependent accumulation of radionuclides by plants.
8. Principles of crop selection for rotations on the contaminated by radionuclides territories.
9. Basic rules of irrigation on the contaminated by radionuclides lands.
10. Basic measures to reduce radionuclide transfer to animals.
11. The essence of agrotechnical measures of meadow and pasture improvement.
12. The role of the diet to reduce radionuclide transfer to animals.
13. The effect of alkaline and alkaline earth metal content in the ration on radionuclide transfer to animals.
14. The role of enterosorbents to prevent radionuclide absorption in a gastrointestinal tract of animals.
15. The essence of animal production change on the contaminated by radionuclides territories.

16. Permissibility basis for breeding of horses, wild animals, bees on the territories highly contaminated by radionuclides.
17. The essence of using clean fodder to animals before slaughter.
18. Possibilities of cooking treatment in the decontamination of plant and animal production.
19. The main technological methods of product processing to reduce radionuclide content in plant and animal production.
20. Primary technological processing of milk contaminated by radionuclides as a basic method of the milk production decontamination.
21. Possibilities for the decontamination of milk.
22. The methods of the meat decontamination.

11. RADIATION PROTECTION OF THE ENVIRONMENT

11.1. Radiation protection of soils against radioactive contamination. 11.1.1. Land-reclamation and erosion control measures on the territories contaminated by radionuclides. 11.1.2. Phytodezactivation of soils. 11.2. Radiation protection of plants against radionuclide uptake. 11.3. Radiation protection of animals against radionuclide uptake. 11.4. Radiation protection of the aquatic environment against radionuclide uptake. 11.4.1. Radionuclide accumulation in the continental water environment. 11.4.2. Radiation protection of the aquatic environment. 11.5. The reduction of radionuclide absorption and accumulation in a human organism. 11.6. The role of forest in protection of the environment against radioactive contamination. 11.7. Strategies of radiation protection of forest ecosystems.

During the second half of last century, a huge amount of ionizing radiation of a man-made origin appeared on the Globe. The main input of artificial radioactivity on a globe scale comes from nuclear weapon testing in the atmosphere. As a result, all living organisms on the Earth began to receive an additional, above background, irradiation. In addition to this world wide dispersion of radioactivity, smaller areas were subjected to increased irradiation levels. Since 1960 on the East-Ural radioactive trail the comprehensive studies on consequences of nuclear failure on South Ural in 1957 accompanied by the release of large quantities of radioactive material into the environment and mass irradiation of living organisms occurred. A radiation danger for the environment was demonstrated by nuclear accidents in Great Britain, in the USA and in Chernobyl NPP. The enhancement of radiation levels in the regions contaminated in the result of nuclear accidents is of particular ecological significance. In these regions dose rates and cumulative doses may reach values that cause radiation damage of organisms, injury to some communities and the ecosystems and even causing death.

Radiation protection standards were developed primarily for humans; and the principal reason was to protect individuals, their progeny, and mankind as a whole against cancer and genetic sickness. For the majority of non-human organisms the primary problem is to protect ecosystems with their economic and aesthetic potential by maintaining populations of the species indigenous to the ecosystems. So, in the case of fishery resources it is accepted to have some mortality of individuals in the harvesting of populations for food purposes, but until recent years, there was a little effort to control the landed amounts to remain the populations relatively stable.

Generally accepted assumption was that if humans were adequately protected, other living organisms were likely to be sufficiently protected. This assumption is known as *anthropocentric conception* formulated by the ICRP (1990) and states that: “The Commission believes that the standard of the environmental control necessary to protect a man ensures that other species are not harmed. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering the whole species or creating imbalance between species”. The concept is fully logical and it is practically impossible to argue with it.

However, during the last 15–20 years the failure of this conception has become evident. As a result, the problem of radiation protection has got a new vision: the problem of the environment radiation protection starts dominating among many environmentalists and radioecologists. It is known that mankind existence and survival is directly connected with the saving of nature that undergoes the increase of technogenesis pressure, including the release of radioactivity from enterprises of nuclear fuel cycle. Therefore, the *eccentric conception* was formulated, where accents were shifted towards the protection of environment components, especially living components of the biosphere, i.e. the biota.

The protection of non-human species requires new approaches in the field of radiation protection. Some efforts were made to define limits to protect populations in the ecosystems. To evaluate the potential significance of the impact of increased radiation level on a population the following three ways were proposed: (a) the established dose rates may be compared with the variation in the natural radiation background, or indeed, the natural background itself; (b) the comparison may be made with the dose rates that are likely to produce significant detrimental effects on populations of organisms in laboratory or field studies; (c) if and when limits are set on the incremental dose rates for the purposes of environmental protection, the comparison may be made against these criteria.

One more principle of environment radiation protection is a necessity to support the steady development of the biosphere that means the integral saving of basic parameters of steady development of natural and semi-natural environment under circumstances, when technogenesis pressure is increased. This term does not introduce any quantitative descriptions so far, and is used at present rather as the philosophical concept which calls to pay attention to the value of radiation protection of the environment contaminated by the radioactive substances and damage of its living components by ionizing radiation.

As we’ve already mentioned in the previous chapter, to prevent completely the migration of radioactive substances released in the biosphere component (usually the atmosphere, considerably rarely the hydrosphere), though trophic chains are impossible. However, following one of the derivative radiobiology problems, i.e. to reduce damaging action of ionizing radiation on living organisms, it is possible to reduce substantially transfer of radionuclides as a source of ionizing radiation in the biota and, first of all, in a human organism. We mentioned above some practical (applied) aspects of this problem concerning the protection of agricultural plants and productive animals as a source of foodstuffs, contributing to the internal dose for a man. In this chapter less attention will be paid to these biota objects and the environment as a whole. More attention will be paid to the abiotic environment as an important link of radionuclide migration to biotic components.

11.1. Radiation protection of soils against radioactive contamination

From previous chapters it is obvious that the protection of soils under the conditions, when the contaminants from airborne release reaches an area, is possible, if an area is covered before the deposition, e.g. with plastic sheets or with the condition of greenhouse. In this case, soil contamination level will be greatly reduced. Sheets for covering should be waterproof, although in the case of dry deposition, synthetic fiber covers would have some effect. Covering of all areas would be impossible; however, limited areas might be covered in the very earliest phase of an emergency. However, after the deposition of contaminations some measures creating barriers for radionuclide migration to the earth surface, i.e. limiting their distribution, protecting in such a way uncontaminated or less contaminated areas are provided. One of the most effective approaches is implementation of the system of land-reclamation and erosion control measures.

11.1.1. Land-reclamation and erosion control measures on the territories contaminated by radionuclides

As it was discussed in chapter 5, the relief of an area and separate landscape-geographical features of the territory play an important role in the migration of radioactive substances in the environment and, in particular, the uptake of radionuclides by agricultural plants. They may enhance radionuclide movement of both horizontal and vertical migration and, accordingly, affect their transfer to the plants. In this respect conditions in the Chernobyl region after the accident are rather unfavorable. Firstly, this region is characterized by relatively high amount of precipitations, plenty of water sources, high level of ground waters, and high probability of soils flooding during the spring flood and summer-autumn thundershowers that increase horizontal and vertical migration of radionuclides with the solid liquid flow. Secondly, there is rather weak aggregated ability of soil particles that are mainly sandy and sandy loam varieties showing low humus, silt faction and clay mineral fraction content. The last results in transfer of radionuclides by wind and water on large distances and causes secondary contamination of less contaminated „clean" areas accordingly. Thirdly, although 40–50% of the Polyssia region is covered by forest that is much higher in comparison with other regions of Ukraine, the wind and water erosion occur on the opened arable agricultural lands at far less wind and water speed in comparison with loamy and clayey soils.

Highly eroded and contaminated by radionuclides lands of Polyssia region require the application of erosion control measures on such types of soils. It includes the set of interconnected and intersupplementary hydro-, agro-, and forest-, and land-reclamation measures. The major of them are the following:

1. The conduction of drainage land-reclamation that provides the lowering of ground waters level resulted in reducing of vertical and horizontal migration of radionuclides with water flows. However, conducting such measures should not result in over-drying of soils, since over-dried soil are prone to wind erosion, especially on widely spread in Polyssia peaty-boggy soils. These lands require conducting of land-reclamation measures that are drying-wetting by character. Such measures as snow retention and control of snow melting on the fields are desirable.
2. Ploughing with an ordinary tractor-driven single furrow moldboard plough to a maximum possible depth (ca. 45 cm) with the following soil treatment without soil layer turnover on heavily contaminated by radionuclides land prone to erosion.
3. Turf-cladation and afforestation of opened sites excluded from land-use due to high level of radioactive contamination to reduce wind lifting and transfer of radioactive soil particles with wind and water flows.
4. The prevention of ravine and gorge formation by water retaining constructions for throwing down waters, fixing of ravine bottom, terracing of slopes, using of soil protective crop rotations on the slopes from 4 to 12º with such main components as perennial grasses on green forage, winter wheat in addition sow of perennial grasses, corn. Generally, mechanical

tillage of soil that destroys its structure and enhances soil erosion has to be reduced, especially on the catchments.

5. The application of lime in the combination with manure and mineral fertilizers on agricultural lands that are currently used, the implementation of other measures to save and enrich humus soil layer that plays the important role in fixing and retaining of radioactive substances.
6. The introduction of precautionary measures against fire, since ashes radioactivity is in several orders of magnitude higher in comparison with the amount of radionuclides in soil where it originates. In the case of fire the ash particles may be transferred by wind on much longer distance than soil particles.

Wide application of mentioned above system of erosion control measures allows reducing considerably the spreading away of radionuclide “spots” on the territory. It slows down vertical migration of radionuclides in the objects of the environment and agricultural production, and, finally, reduces radionuclide transfer in food chains and, mainly, soil-plant transfer.

11.1.2. Phytodezactivation of soils

Other potential strategy for reducing radionuclide content in plants is to extract radionuclides from soil by using plants, i.e. “phytodezactivation”. Other terms such as “phytodecontamination”, “phytoextraction” or “phytoremediation” sometimes are used. Such approaches allow restoring contaminated lands. This relatively low-cost alternative has received considerable attention in recent years.

Phytodezactivation is a unique measure that allows physical cleaning up of soil from radionuclides. In such a way phytodezactivation is similar to that described in chapter 10 harvesting of upper soil layer. The method allows removing the upper 3–5 cm soil layer that is skimmed off. However, it is effective only as soon as possible after fall-outs and achievable in selected sites and is expensive.

A common phytodezactivation strategy involves removing radionuclides from soil and accumulating them in over ground parts of plants that can be easily harvested (phytoextraction). Such plants must be able to tolerate and concentrate high levels of radionuclides (hyperaccumulators showing high values of transfer factors) in their harvestable parts, if they are to be used on contaminated soils. In addition to this trait, an ideal plant for specific radionuclide phytodezactivation should be characterized by rapidly uptake of radionuclides from soil and should have a rapid growth and high biomass to decontaminate the contaminated site in a reasonable number of harvests. And, it should not be an attractive food source for herbivores (it should contain herbivore-deterrent substances). Another difficulty arises from radionuclide distribution in soil that may vary from site to site. Hence, root characteristics (e.g. depth and density of the root system) must be taken into account.

Although at present no natural plant has all of the desirable characteristics for radionuclide phytodezactivation, some successful cases of phytodezactivation of contaminated sites are reported. For example, lupine is a plant that meets some of the requirements. To some extent alfalfa, clover and some other leguminous plants meet requirements for phytodezactivation, since they show high accumulation factor (AF) for ^{90}Sr and ^{137}Cs. There are well known potassiphils as maize, sunflower, rape, amaranth that show high AF for ^{137}Cs, when grown as green forage; some grass mixture that includes meadow clover and white clover, timothy, meadow foxtail, smooth brome, meadow fescue, cock’s-foot grass. Some less widespread species also may be recommended, among which plants of leguminous family such as goat’s rue (*Galega orientalis* L.), forest peavine and meadow peavine (*Lathyrus silvestris* L., *L. pratensis* L.), as well as stinging nettle and hempy nettle (*Urtica dioica* L., *U. cannabiana* L.), girasole (*Helianthus tuberoses* L.), ragged cup (*Silphium perfoliatum* L.), prickly comfrey (*Symphytum asperum* Lepech.), knotweed (*Polygonum divaricatum* L.).

The use of conventional plants to decontaminate radioactively contaminated soils may take decades; several mutually non-exclusive means can be envisaged to ameliorate ^{137}Cs and ^{90}Sr phytoextraction efficiency. Farming may be optimized to enhance biomass, and, hence, radionuclide uptake. Various types of soil amendments (synthetic, natural or biological) may be added to enhance ^{137}Cs and ^{90}Sr phytoavailability. For example, as radioactive substances are solubilized at low pH, an artificial soil acidification can be performed. Some silicate bacteria may enhance the destruction of radioactive particles and the release of radionuclides. Another mean to increase the efficacy of radionuclide phytoextraction occurs through the genetic engineering of plants that accumulate higher levels of metal(loid)s.

As for caesium radionuclides (short-lived ^{134}Cs and ^{137}Cs) the phytodezactivation is the most effective in the first years after fall-outs on the soil surface. Since the mobility of radionuclides decreases with time because of fixation by soil components (so called “aging of radionuclides”), the accessibility and bioavailability decrease as well resulting in low phytodezactivaction efficiency. It mainly concerns soils showing high cation exchange capacity such as chernozems and to much less extent the most contaminated peaty-boggy and soddy-podzol soils of Polyssia. However, it is not applied to ^{90}Sr that keeps high mobility for decades.

Under the ordinary growing terms the annual removing of ^{90}Sr, ^{137}Cs, and ^{239}Pu as abiogenous elements is rather low – 0.1–1.5 %. However, removed amount of radionuclides can be much higher. In particular, the application of elevated amount of acid nitric fertilizers (an ammoniac nitrate is the most used nitric fertilizer in Ukraine and in most European countries) decreases soil pH, increases the soluble, NH_4NO_3-extractable radionuclide fraction and enhances their uptake by plants, on the one hand, and plant biomass, on the other hand. It is also recommended to avoid liming of acid soils. The application of phosphoric and potassium fertilizers as well as other means may reduce radionuclide accessibility and bioavailability for plants.

Plant uptake of radionuclides can also be enhanced through sorting out special types of crop for crop rotations showing high radionuclide phytodezactivaction ability, e.g. due to the excretion of root exudates or promoting radionuclide accessibility and bioavailability for following crops in the crop rotation. Root exudates containing, for example, low-molecular-weight organic acids may induce changes in the physiochemical characteristics of surrounding soil such as pH, moisture, electrical conductivity, redox potential, oxygen availability or microbial community. Hence, they may affect the solubility of various soil components (for example, caesium) and, thus, the availability of such components to plant roots. Y. Kutlakhmedov et al. (2000) in a greenhouse experiment found out that the cultivation of rape, corn, pea or sunflower increases radiocaesium accessibility and bioavailability for the following winter rye by factor 2–4. The consistent cultivation of pea and sunflower or corn and sunflower resulted in the sevenfold increase of AF in following rye crop in comparison with rye crop grown after bare fallow. However, results appeared to be less pronounced in the field experiment carried out within the 30-km exclusion zone around the reactor of Chernobyl NPP, although in some crops combinations due to a successfully selected precursor AF of radiocaesium in the following crop increased by factor 4.5.

Estimating potential phytodezactivation ability of studied crops, authors concluded that ^{137}Cs is the most effectively extracted by lupine (highest AF and biomass) and ^{90}Sr – by oily radish (*Raphanus* L.). Based on the same data phytodezactivation ability of lupin during one vegetation period is about 10 % of the total radiocaesium inventory in soil. Phytodezactivation ability of radish is rather weak (only 0.76% of radiostrontium is extracted). Authors suggested that it is due to relatively weak mobility of strontium within a plant in comparison with that of caesium similarly to its chemical analogues (calcium and potassium).

As indicated by five-year studies an optimal crop rotation system enabling the increase of radionuclide TFs to plants by factor 2–10 and harvest biomass from 40 to 80 t ha^{-1} allowed to reach four-fivefold decrease of ^{137}Cs, ^{144}Ce and ^{106}Ru in soddy-podzol soils during this period.

However, according to A. Kravets and Ju. Pavlenko (2000) phytodezactivation ability is severely limited. Based on the developed assessment model that allows dynamic quantifying of radionuclide migration in soil-plant system during a vegetation period, they were able to calculate uptake rate of radionuclides from soi l. Results obtained in this study evidence that phytodezactivation technology is only applicable (gives reasonable extraction time), if phytoextraction rate is at least 2–3 % per year (which is achievable). In this case, phytodezactivation of soil contaminated by radiocaesium and radiostrontium by using plant during 5–10 years after fall-outs is not achievable. According to the proposed model the half-time reduction of ^{90}Sr content in the upper arable layer of soddy-podzol sandy loam soil by means of phytodezactivation can be reduced by factor 2 and more in comparison with the natural reduction of radioactivity level.

Particular attention should be paid to possible phytodezactivation of ^{239}Pu and other long-lived transuranium alpha-emitters (half-life of ^{239}Pu is 24 000 years, while for ^{90}Sr it is 29 and for ^{137}Cs it is 30 years). Therefore, decontamination of this radioactive isotope by means of natural decay is non-perspective. According to present knowledge no specific plant species used for phytodezactivation of mentioned radionuclides from soil are known. Although some data available evidence that different plant species accumulate ^{239}Pu and other long-lived transuranium isotopes differently and generally in small amount. The point is that ^{239}Pu has no chemical analogues among biologically important chemical elements. Consequently, a plant takes up small quantity of ^{239}Pu, and it moves slowly within a plant. However, it does not mean that ^{239}Pu can stay in soil. It is necessary to mention a process that can result in the contribution of significantly more plant contamination than root uptake, even in the absence of a major atmospheric deposition event, e.g. soil splash. It is well recognized that root uptake often results in the transfer of only a small part of soil radionuclide burden to plant tissue. It especially concerns such element as plutonium that can have TF values as low as 4.0×10^{-7}. In this case the contamination of the external surfaces of plant stems and leaves with relatively small quantity of contaminated soil (together with its associated radioactivity) can elevate the gross activity concentration of a plant tissue dramatically. ^{239}Pu may enter an animal or a human organism through the skin by inhalation and, that is more important, by ingestion. It is believed that radiochemical toxicity of plutonium incorporated into an organism is hundreds times high in comparison with that of ^{90}Sr and ^{137}Cs.

Moreover, the information concerning transfer of plutonium as well as other transuranic elements (in particular americium, among which ^{241}Am with the half-live of 432 years that is next to plutonium environment contaminant) within a plant is the subject to the revision. Recent advances in understanding of molecular and biochemical mechanisms of ion uptake, extrusion and transfer suggest that these elements can be transported within a plant together with iron, manganese and cobalt. Thus, AF can reach values of 0.1–0.3 and even 1. The highest AF values are reported for plant species of leguminous family.

Regarding many points of view, lupine can be considered to be the most suitable plant (adapted to the local soil type and the environment, has high AF for long-lived radionuclides, has relatively high harvesting biomass) for phytodecontamination of heavily contaminated due to the Chernobyl accident soil of the Polissya region. It is also obvious that many other plant species mentioned above may be used for radionuclide phytodezactivation depending on specific radionuclide, soil types, local crop set, etc.

It must be stressed that natural process of spontaneous phytodezactivation of soil occurs. And a great amount of radionuclides on the territories contaminated by radionuclides is taken away with a harvest in agrocenosis. Relatively high rates of such phytodezactivation are observed on the meadows and pastures. Thus, fodder grass can take away about 10–12% of the total inventory of radionuclides in soil during the vegetation period. According to the data of hydro-meteorological service the level of contamination of pastures and hay lands by ^{137}Cs in 1997-1998 reduced by factor 2–3 in comparison with 1988-1991, taking into account its natural decay and migration within soil profile. Nowadays, 20 years after the accident, the distinct difference exists between the level of radioactivity of intensively cultivated agricultural lands, and soils that are not used for agricultural production, e.g. land of settlements, etc. Obviously, in this case radionuclides are involved in trophic chains. And under certain conditions there is a sense to accelerate the reduction of radionuclide content in soil by means of purposeful phytodezactivation and to protect humans from the additional irradiation.

Difficulties arising with plant biomass utilization are an obstacle to the wide application of phytodezactivation. This problem can be solved technologically. Not only scientific projects but also experimental installations are known. It allows burning plant biomass without the release of radioactivity into the environment. However, radioactivity of ash produced is very high. Obtained energy may be used for the production of electricity. There are also projects for obtaining, for example, biogas, protein concentrates, alcohol, and paper. Thus, there is no doubt that problem of phytodezactivation, i.e. the use of plants to restore contaminated by radionuclides territories as a unique and exceptional biotechnology (the concept of soil cleaning up by means of plants is a biotechnology in classic understanding) is one of the potential strategies for reducing radionuclide content in the environment. It is considered that this technology deserves to be pointed out among the complex systems and methods directed to minimize radionuclide transfer to plant products.

Phytodezactivation is one of few means that are used exactly to clean up soil from radionuclides. Most of other strategies reduce transfer of radionuclides from soil to plants through their immobilization in soil binding to other soil substances, the conversion to insoluble forms, and their displacement by chemical analogues removing in such a way from transport pathways, etc.

11.2. Radiation protection of plants against radionuclide uptake

Depending on soil type, level of radioactive contamination, chemical forms of radionuclides, biological features of plants, ways of their use (all plants or separate organs), etc. different measures may be applied to protect plants and to reduce radionuclide uptake. Most of them were discussed in detail in previous chapters. It must be stressed that most of them (apart some exceptions) do not reduce radionuclide content in soil. Most of these measures reduce radionuclide uptake by plants.

11.3. Radiation protection of animals against radionuclide uptake

As it was investigated in chapter 9 animals can be contaminated by three different ways: through skin, by inhalation, and, most importantly, by ingestion. Uptake through the skin is usually not an important way of contamination, although skin lesions can provide a direct entry for radionuclides into an animal circulation system. Protection measures against contamination of animals through ingestion were discussed in previous chapters.

11.4. Radiation protection of the aquatic environment against radionuclide uptake

11.4.1. Radionuclide accumulation in the continental water environment

The uptake and accumulation of radionuclides by aquatic organisms are determined by the chemical behaviour of radionuclides in the environment, the characteristics of the interfacial structures separating organisms from the environment and the physiological organization and functioning of organisms. The process that includes the uptake, compartmentalization and elimination of radionuclides from various environmental sources is called *bioaccumulation*. The accumulation of radionuclides by aquatic organisms is usually expressed in terms of transfer and concentration factors, and water is used as a reference base.

Radionuclides reach freshwater ecosystem by means of two principal ways: directly by deposition on the lake surface or by water from the catchment area. For most river systems, except probably the large continental rivers, the direct deposition onto river water surfaces can be ignored, since the exposure time is generally rather short. Radioactive fall-outs deposited onto the catchment can either remain dissolved in the soil water or it can be sorbed by soil particles. In solution it can easily be washed out from soil, by rainfall, into the nearest watercourse. As a result, in rivers and small lakes the radioactive contamination results mainly from the erosion of the surface soil layers in the watershed followed by runoff in the water bodies. In the 30-km zone, where relatively high levels of ground deposition of ^{90}Sr and ^{137}Cs occurred, the largest surface water contaminant was found to be ^{90}Sr. ^{137}Cs was strongly absorbed by clay minerals. Much of the ^{90}Sr in water was found in dissolved form.

The main pathways of potential human exposure from contaminated water bodies may occur directly through the contamination of drinking water, or indirectly, from the use of water for irrigation and the consumption of contaminated fish.

11.4.2. Radiation protection of the aquatic environment

To protect water reservoirs the earthen banks and dikes may be constructed. The aim of such constructions is twofold. Firstly, they protect water reservoirs from being contaminated by rainfall and thawing water, entering water reservoirs from contaminated territories. Secondly, this is a barrier against runoff from contaminated banks during spring high-floods.

To reduce radionuclide transfer with contaminated silt by rivers flows, the special pits-traps so-called „ground depositories" can be constructed that are actually diametrical ditch-like deepening on the river bottom between banks, various filtering coffer-dams, dikes and dams. Such countermeasures were implemented to diminish the Chernobyl accident consequences in 1986-1987 in Dnipro and its tributaries and showed rather high efficiency.

For aquatic systems, physical methods can be applied to reduce the radiological impact via ingestion of contaminated waters. The methods most commonly applied are diversion of surface waters, changes in abstraction sites, and alterations to the local hydrological system to control the level of the water tables. The extent to which such measures will be successfully depends on the scale of the accident and the degree to which radioactivity has become redistributed.

Among chemical methods, generally, isotopic dilution with stable elements or analogues may be recommended. Thus, liming of surface waters are thought to be effective to reduce strontium uptake. Addition of potassium to fresh water systems can reduce the impact of radioactive caesium via food chain. But the effects are variable according to the acidity and base state of the contaminated waters.

To reduce radionuclide content in relatively small reservoirs, e.g. ponds, non-costly sorbents made on the base of natural minerals that allow extracting of radionuclides from water, its precipitation and binding in sediments with following mechanical removing of sediments can be used.

According to radionuclide phytoextraction from soils by means of plants similar strategy can be introduced for reducing radionuclide content in the aquatic environment. This strategy is based on the method called *rhizofiltration* (Greek, rhiza stands for a root). The plants growing in aquaculture as well as other representatives of hydrobios, show high AFs for radionuclides. Thus, if the highest AF values in roots of some species of higher plants on sandy and sandy loam soddy-podzol soils for ^{90}Sr and ^{137}Cs were found between 10 and 20, in the aquatic environment values of AFs may reach hundreds and even thousands.

Table 47 summarizes concentration factors for some radionuclides in different groups of organisms in the freshwater environment.

Table 47. The concentration factor of selected radionuclides in the freshwater environment (P. Santchi, B. Honeyman, 1989)

Radionuclide	Half life	Source*	Phytoplankton
^{3}H	12.3 yr	C–A	1
^{7}Be	53 d	C	250
^{10}Be	1,500,000 yr	C	250
^{14}C	5,700 yr	C–A	9,000
^{22}Na	2.6 yr	C–A	100
^{32}P	14 d	C–A	10,000
^{40}K	1,300,000,000 yr	P	10,000
^{45}Ca	150 d	A	350
^{54}Mn	300 d	A	6,000
^{60}Co	5.3 yr	A	5,000
^{65}Zn	250 d	A	30,000
^{90}Sr	28 yr	A	200
^{90}Y	2,7 d	A	100
^{95}Zr	65 d	A	60,000
^{99}Tc	200.000 yr	A	40
^{131}I	8 d	A	1,000
^{134}Cs	2.1 yr	A	900
^{137}Cs	30 yr	A	900
^{210}Pb	22 yr	P	7,000
^{210}Po	130d	P	30,000
^{226}Ra	1,600 yr	P	2,000
^{239}Pu	24,000 yr	A	900
^{238}U	4,500,000,000 yr	A	20
^{241}Am	460 d	A	200,000

* Source of nuclide: C – Cosmogenic, P – Primordial, A – Antropogenic.

For this reason, some species of aquatic as well as over ground plants can be used for reducing radionuclide content in small reservoirs.

However, similarly to the phytoextraction of radionuclides from soil the problem of utilization of plant biomass contaminated by radionuclides arises.

Researches of the Institute of microbiology and virology of the National Academy of Sciences of Ukraine proposed the microbial biotechnology for cleaning up of sewage waters from radionuclides and heavy metals by means of using artificial microbial communities. This approach is based on the use of special preparations „Microbial biocatalyst" and „Mixed microbial communities". These preparations are waterproof granules composed of living microorganisms as well as nutrients required. Granules keep the structure and functions for 2–3 years. By passing contaminated water through the column with granules it is possible to clean water almost completely from such radionuclides as strontium, caesium, americium, plutonium and uranium. Obviously, the application of such technology is rather limited.

11.5. The reduction of radionuclide absorption and accumulation in a human organism

The concept of radionuclide absorption and accumulation reduction in a human organism to limit the formation of internal irradiation dose is based on three major principles: 1) the limitation of radionuclide absorption with foodstuffs and water; 2) blocking the absorption of radionuclide in a gastro-intestinal tract and their deposition in specific organs and 3) speeding up of radionuclides removing from the organism incorporated in living tissues. Generally, this concept does not differ much from the radiation protection system of animals described in previous chapters, however, some of the proposed measures that are not applicable for the radiation protection of animals due to economic or other reasons may be used in a complex of measures for the protection of a man.

It is clearly that the main purpose of all means and measures that serve to protect different environmental objects from the accumulation of radioactive substances (discussed in more detail in previous chapters, including chapter 10) are finally directed on the realization of the first thesis, i.e. the limitation of radionuclide uptake by a man with a food. The realization of the second and third principles generally requires keeping the principles of the rational nutrition. In some cases, depending on the physical and chemical properties of radionuclides of concern, the use of special additives may be recommended. They bind radionuclides and prevent its absorption in gastro-intestinal tract as well as promote their natural elimination from a human organism.

Regarding the initial forms of radionuclides that enter a human organism with food, most of them are getting soluble under acid secretion in the stomach. Being solubilized radionuclides are getting more available for absorption in gastro-intestinal tract. On the other hand, soluble forms of radionuclides make them enable to react and compete with other elements. It also results in binding of radionuclides with various compounds. Among these substances that are known by such common name as radioblocking agents the three main classes are distinguished: antagonists-competitors of radionuclides, enterosorbents and complexes forming agents.

As we've already mentioned in this book the antagonists-competitors for such radionuclides of major concern as, e.g., ^{90}Sr, ^{137}Cs and ^{131}I are calcium, potassium and iodine accordingly. ^{90}Sr is an example of such radionuclides that are in a soluble form and are chemical analogues to essential nutrient elements, and, therefore, follow its ecological pathways. ^{90}Sr, ^{140}Ba, ^{226}Ra and ^{45}Ca behave like calcium; ^{137}Cs, ^{86}Rb and ^{40}K generally follow the movement of potassium; ^{131}I resembles the movement of non-radioactive iodine, etc. Normally, foodstuffs that are optimally balanced with calcium and potassium promote the reduction of radionuclide absorption by tissues. Therefore, the deficit of these elements in the diet of people living on the contaminated areas should be avoided. Especially it concerns children, youth, who live on the contaminated territories. It mainly concerns such element as calcium that is the main mineral component of skeleton. A child organism especially requires this element for skeleton growth. In the case of calcium deficit this element is replaced (compensated) by its analogue, i.e. strontium, including radioactive isotope ^{90}Sr that clearly expresses chemical similarity to calcium. ^{90}Sr is characterized by all features connected with harmful effects on a living organism. Since metabolism of ^{90}Sr is similar to that of calcium, and, thus, it easily enters the frame of crystalline structure oxypatite, i.e. the structural base of bone tissue the, β-radiation of this radionuclide damages the red bone marrow (a critical organ of vertebrates and, hence, also haemopoiesis). ^{90}Sr itself is a fairly soft β-emitter ($E_{max\ \beta}$ = 0.6 MeV). However, its daughter ^{90}Y emits very hard β-rays ($E_{max\ \beta}$ = 2.26 MeV), which radiation is dangerous, since this radionuclide is produced continuously from ^{90}Sr that accumulated in the skeleton, emitting radiation with a high ionizing density.

The main source of calcium for a man is milk and milk products. Therefore, the milk and milk products are considered to be the important component of nutrition for people living on the contaminated territories. However, accent here has to be shifted to dehydrated milk products such as cream and sour cream. Although manufacturing of cheese transfers strontium from milk into cheese and whey. The leguminous plants such as pea, kidney beans, bobs, soy-beans, etc. are another source of calcium. Elevated amount of calcium is also found in the plants of Rosaceae family (wild rose, apricot, garden and wild strawberry).

The main source of potassium for a man is vegetables and fruits. Such widely spread and well known plants as cabbage, potato, table beets, buckwheat, corn and vegetable pepper, that accumulate relatively high amount of potassium must be the substantial part of the nutrition for people of the middle zone of Eurasia. Appreciable amount of these elements are found in grape and apricot. In this respect such fruits may be considered to be champions among other species cultivated in Ukraine. All these plants belong to so called potassiphils.

Generally speaking, all plant species are major sources of various microelements necessary for human organisms, many of which, first of all, iron, zinc, manganese, cobalt, copper, nickel and lithium reveal antagonistic properties in relation to strontium and caesium. Such elements may bind radionuclides in gastro-intestinal tract and prevent their absorption. Green vegetables, such as lettuce, spinach, parsley and celery contain quite a lot of microelements.

Well known absorber is an absorbent carbon that is widely used in medical practice at various food-poisonings, appeared to be ineffective as a mean of the absorption of uranium decay products including ^{137}Cs, and, especially, ^{90}Sr. Mentioned in previous chapters ferrocine was found to be an effective absorber for ^{137}Cs in gastro-intestinal tract. However, in contrast to the application for agricultural animals, where ferrocine may be widely used, in the system of radiation protection of a man this absorbent may be used only in special cases and under the medical control. The reason is that use of preparations made on the basis of ferrocine may cause some undesirable effects affecting such organs as liver, kidneys, spleen and may promote removing of potassium from an organism together with caesium.

Selective absorption of ^{90}Sr that leads to the reduction of radioactive strontium absorption in gastro-intestinal tract and prevents its deposition in an organism is shown by salts of algine acids – alginates. Alginates of sodium, potassium, calcium and magnesium are acid polysaccharides extracted from some types of algae, particularly red-ware (laminaria), cytosira. The special selective absorbents of ^{90}Sr are created on the basis of alginates. Thus, preparation „Algisorb" prevents the absorption of 60–85 % of ^{90}Sr in gastro-intestinal tract. As radioactive strontium is especially danger radionuclide for children, the alginates are used as additives to some child foodstuffs.

The alginates are also found as those, which may block calcium absorption. However, daily use of 3–4 g of sodium alginates by a child and 6–8 g by an adult reduces ^{90}Sr absorption by factor 3–3.5 and does not affect substantially calcium metabolism.

Alginates, mainly sodium salt, are used as additives for the production of emulsive substances that, in turn, are widely used as stabilizing agents for manufacturing ice-cream. Thus, such milk product as ice-cream, especially its high quality sorts, is reasonably considered to be foodstuff that has radioprotective affinities.

Mentioned above pectic substances showed similar effect. Relatively high content of such acid polysaccharides is found in many root crops, particularly in beets and carrot, in many plants of cucurbitaceae and, first of all, in pumpkins, in fruits of citric plants, in fruits of seminicole fruit trees such as apple-tree, pear-tree, quince, in some stone-fruits such as plum, apricot, wild rose, currant, cranberry.

Agar-agar has similar radioprotective affinities. It is well known for bacteriologists and microbiologists as highly molecular polysaccharide that is extracted from some types of red (crimson) algae and used for agar plates as nutrient media. Agar-agar is widely used in confectionary industry for manufacturing candied fruits jellies, pastila (kind of sweet made of fruit or berries), various fruit jellies and jams.

Perhaps, the simplest complexes forming agents are phosphorus compounds that are derivatives of phosphoric acids as well as some other substances that are able to form rather simple but hardly soluble or even fairly insoluble in water compounds (complexes) with many metals, mainly belonging to the second group of the periodic system of elements, including strontium. In turn, it greatly reduces radionuclides (^{90}Sr) bioavailability. Therefore, the phosphorus compounds being included in the human nutrition may bind considerable part of ^{90}Sr and promote it to pass by through the gastro-intestine tract without being absorbed. It shows that the administration of phosphates, e.g. glycerol-phosphate, into a man diet results in binding up to 25% of the total inventory of ^{90}Sr entered gastro-intestine tract.

Another source of phosphorus in human diet is fish, meat and nuts. A lot of phosphorus is found in grains of cereals, leguminous plants, oil-producing crops and lettuce plants.

Increased amount of both phosphorus and calcium in the human diet appears to be especially effective. The additive effect of these elements reduces ^{90}Sr bioavailability. It is obvious, that such effect is achieved due to different blocking mechanisms of these elements.

Specific selectivity for complexes formation with caesium and strontium is revealed in anthocyanes – pigments that are polyphenolic, or rather flavonoidic by nature and give the plants, mainly flowers and fruits, rarer leaves, specific red, brown, dark blue, violet up to the blackly-violet colouring. The phenolic glycosides forming complexes with potassium and calcium ions, and, consequently, with caesium and strontium, are considered to be chemical basis of all anthocyanes. The red tints provided by anthocyanes to the plants owe to the special compounds that form complexes with potassium ions. The pigments that provide dark blue and violet colours are complexes formed with calcium ions. Hence, such compounds form complexes with caesium and strontium.

A lot of anthocyanes are found in fruits of blackberry, wild ash, blackberry, egg-plant, dark-colored sorts of plum, vine, mulberry and red cabbage. However, the red color of tomatoes is caused by carotene pigments; red color of cayenne – by capsicine pigments, the violet colouring of red beet plants is caused by betaidine pigments that are different to that of anthocyanes by nature.

To speed up removing of radionuclides incorporated into an organism and deposited in certain tissues or organs is considered to be topical, but extremely difficult task. According to present knowledge some forms of anthocyanes posses such properties.

There are evidences that different teas and extracts prepared from commonly known medicinal herbages may also speed up removing of radionuclides incorporated into an organism. Thus, green tea and even ordinary black tea promote removing of not only relatively easy soluble ^{137}Cs but also ^{90}Sr. Such affinity of tea and some other plants species is considered to be connected with content of various complex forming substances that are flavonoid by nature. Among them flavones, catechins, anthocyanes, rutins, quercetins, hesperidins, etc., as well as tannins substances. All of them belong to a large class of phenolic compounds that have well known affinity to bind ions of heavy metals and to form stable complexes. Although speeding up of radionuclide removing from an organism sometimes is explained by ordinary dissolution of radionuclides and their „washing out” from an organism.

It is suggested that mentioned above ferrocine and alginates may speed up radionuclide removing not only from a gastro-intestine tract but also radionuclides incorporated into some tissues and organs. Thus, ferrocyanide of iron was successfully used to speed up ^{137}Cs removing from an organism of 250 patients (10–20 g per day for adults and 5–10 g for children) after a nuclear accident in Goiania (Brazil) in 1987, when 0.69 TBq ^{137}Cs radiotherapy source was dismantled in a residential garden and the contents sold to a junk yard merchant.

Generally, in radiation medicine practice the special synthetic complex forming agents that have specific binding ability for specific radionuclides are used. Such complex compounds bind specific radionuclides in tissues, increase their solubility, speed up their transfer and promote their secretion from an organism by natural ways. They are called radiodecorporators or radiodecorporants. The most known of them are pentacine, cyncacine and tetacine. Thus, pentacine (calcium of trysodium pentanat) promotes the removal from an organism such incorporated isotopes as plutonium, cerium, yttrium, lead and zinc. Unfortunately, pentacine does not affect the rate of caesium and strontium secretion from an organism. It is suggested that for this reason, pentacine does not affect potassium and calcium content when some absorbents and complex forming agents are used including natural ones.

Estimating the importance of certain foodstuff, especially of plant origin to reduce radionuclide uptake and accumulation in a human organism, it is worth emphasizing that food products seem to be effective only when human nutrition is well balanced with carbohydrates, fats and proteins. It shows that the absorption of most radionuclides in a gastro-intestine tract substantially depends on the way by which they enter the stomach: in an empty stomach or with a food. For example, after 12 hours of starvation the absorption of ^{90}S increases by factor 2–3. Proteins, by themselves contain a lot of substances that have radiation protection properties. Apart of this, protein balanced diet decreases the sorption rate of radionuclides in a stomach as well as promotes their secretion from blood, muscles, liver, kidneys, spleen, lung and other organs. On the contrary, the protein starvation enhances ^{137}Cs accumulation in an organism. It is also proved that low content of proteins in a diet increases the loss rate of radionuclides from tissues, i.e. the biological half-life ($T_{1/2b}$). In turn, internal doses of irradiation may substantially increase.

11.6. The role of forest in protection of the environment against radioactive contamination

In chapter 9 we’ve already mentioned that radionuclide releases to the environment (especially forests) are currently a cause of increasing concern. At the same time forest ecosystems are given a low remediation priority due to the high ecosystem complexity (long rotation period, multilayered structure of forest vegetation and forest floor, existence of different plant species, biodiversity of flora and fauna, complex interaction between plants and animals) and their relatively low immediate contribution to a human radiation dose. However, forests are an efficient reservoir for pollutants and a long-term impact of contaminated forests can be significant. In 1990, for example, forest workers in Russia were estimated to receive a dose up to three times higher than other people living in the same area. It is known that the residence time of some stable elements in forests approaches several thousand years. A significant portion of radioactivity released into natural environments ends up in forests. The higher organic content and the stability of the forest floor soil increase the soil-to-plant transfer of radionuclides with the result that lichens, mosses and mushrooms often express high concentrations of radionuclides. Being incorporated into forest products such as construction materials, paper, fuel and food by-products such as mushrooms, berries and grasses consumed by humans and animals, radionuclides can contribute significantly to the human radiation dose.

Having an extraordinary large surface of tree overstorey as well as shrubs (woody plants) and herbs (grasses) understorey canopy, forest ecosystems play an important role in the protection of the environment from radioactive contamination. The presence of large and high tracts of forest, tree clumps or even single standing trees on the way of horizontal air flows provide some kind of radioactive cloud filtration during fall-outs of radioactive particles on leaves surface, pine-needles, trunks, branches of trees and bushes. Since artificial radionuclides generally enter the environment from the atmosphere, the contamination level of forest ecosystems is often much higher (tenths times) in comparison with an opened area. Forests retain the radioactive substances (i.e. act as a buffer) that prevents further mass transfer of radionuclides.

Vertical migration of radiocaesium in forest soils is slow, and most of the Chernobyl deposition of radiocaesium is still, more than three decades after the accident, in the upper organic-rich layer of the forest soil horizon. It is in this layer that the most important processes of nutrient uptake by plant roots or by fungal mycelium occur, as well as recycling of radiocaesium. In the decomposing organic layer, fungi have the highest biomass, are the most important source of enzymes necessary to degrade litter and are very important for the recycling of nutrients and thus radionuclides in forest soils. As shown by M. Vinichuk et al., (2003) the highest ^{137}Cs activity concentrations were found in the upper layers of the soil profile. The ^{137}Cs activity concentrations were usually higher in the fruit bodies compared with the mycelium, with ratios ranging from 0.1 to 66 and a mean of 9.9. The percentage of the total inventory of ^{137}Cs in the soil found in the fungal mycelium ranged from 0.1 to 50%, with a mean value of 15%.

Thus, relatively large quantities of radioactive substances released from the Unit 4 of the Chernobyl NPP to the atmosphere (in the end of April–beginning May 1986) were to some extend absorbed by the forest around the plant (over 40 % of the territory is covered by forest where dominating trees are pine. In such a way forest prevented radioactive substances from being transferred by means of wind on much longer distance.

The initial interception and retaining of radioactive fall-outs by forest vegetation depends on a number of factors: the height of trees, tree closeness, the vegetation biomass per area unit, the character of plant surface, tree species, the degree of radioactive particles dispersion, and, finally, the season of the year, weather conditions during fall-outs, especially precipitations, the wind, its speed, the direction, etc.

To count the initial interception and retaining of radioactive fall-outs by the forest canopy the coefficient of initial interception and retaining of radionuclides (C_{IR}) is introduced. The C_{IR} is defined as the amount of radionuclide intercepted and retained by plants divided by the amount of radionuclide deposited per area unit (both, e.g. in kBq m^{-2}). The C_{IR} is expressed in percents.

Table 48 shows the C_{IR} for ^{90}Sr by ligneous plants. The C_{IR} values vary widely, that is due to listed above factors. In some cases, for example, in the case of closely standing trees in coniferous forests in temperate climate or in tropical rain forests the radionuclides released into the atmosphere may be completely intercepted by forest canopy.

Table 48. The coefficients of initial interception and retaining of radionuclides (C_{IR}) by forest canopy (R. Alexakhin, M. Narishkin, 1977)

Object	Fall-outs	C_{IR}, %
Pine undergrowth in the age of 6–9 years	Hydrosols	90–100
Pine forest in the age of 60 years	Aerosols with particles size up to 50 mkm	80–100
Pine forest in the age of 25 years	The same up to 100 mkm	70–90
Pine forest in the age of 30 years	Soil particles lifted by the wind from soil surface	40–60
Birch forest in the age of 40 years in winter	The same	20–25
Birch forest in the age of 35–40 years in summer	Fall-outs from global nuclear weapons testing	20–60
Pine forest in the age of 50–60 years	The same	50–90
Tropical forest	The same	100

In the following periods owing to the surface run-off, leaves fall over 90% of the radionuclides were mainly deposited in forest litter, i.e. in the organic layer that is a composite compartment that transforms newly formed organic matter into decomposed and humified substances. In such a way the forest continues to protect the environment from the distribution of radioactive substances. Practically there is no surface run-off and downward migration of radionuclides with water within soil profile in forest ecosystems. Radionuclides entered forest soils due to leaching process are bound with various organic compounds. The major part of radioactivity deposited in the forest retains within forest ecosystems for many decades due to the specificity of radionuclide turnover in forest biocenosis discussed in chapter 9. Forest ecosystems prevent practically any discharge of dusty particles to the surroundings, including airborne radioactive particles.

The natural decontamination of contaminated forests occurs extremely slow. The net export of, for example, ^{137}Cs from forest ecosystems is determined to be less than 1% per year (A. Tikhomirov et al., 1993).

It must be stressed that the accumulation of great amounts of radionuclides in forest ecosystems serves a source of radioactive contamination of forest flora and fauna, including wood. And it may cause possible radiation-induced damages of some of the radiosensitive animal species and plants. Moreover, most of tree species, especially coniferous, are highly radiosensitive.

Thus, the forest is considered to be a powerful biochemical barrier protecting surroundings from being contaminated by radionuclides. For this reason, the construction of nuclear power plants as well as other enterprises of nuclear energy in opened areas is always protected (shielded) by the thick and dense rows of artificial wood-shrub planting. Thus, high and quickly-growing tree seedlings are used. The radius of such buffer zone must be about 30–60 km to provide the interception, the retention and the following stabilization of possible radioactive fallout.

11.7 Strategies of radiation protection of forest ecosystems

Regarding the protection of forest biocenosis from radioactive contamination the mechanical removal of forest litter is considered to be the only measure that can be an effective mean among very limited methods. The forest litter comprises up to 90 % of total inventory of radioactivity deposited in forest ecosystems. However, many foresters believe that complete removing of forest litter may cause drying up of the forest environment and its death. Practically, this measure is considered to be only applicable in the case of forest preparation for entire cutting. As we already mentioned in previous chapter, the potassium fertilization had also effect on ^{137}Cs uptake by plants and fungi growing in a forest ecosystem in central Sweden (Rosén et al., 2011). ^{137}Cs levels in plants and fruit bodies of fungi growing on K-fertilized plots 17 years after application of the K fertilizer were significantly lower than in corresponding species growing in a non-fertilized control area.

Some forest-based industries such as pulp production that often recycle chemicals are shown to be a potential radiation protection problem due to the enhancement of radionuclides in liquors, sludges and ashes. However, harvesting trees for pulp production is considered to be a viable strategy for decontaminating forests.

Among other strategies that are developed for combating forest contamination include the restriction of access and the prevention of forest fires. Thus, in chapter 5 we've already mentioned the pine-tree forest known as "Red forest", in which trees received doses up to 100 Gy that killed all of them. An area of about 375 ha was severely contaminated and remedial measures (in 1987) were undertaken to reduce the land contamination and to prevent the dispersion of radionuclides through forest fires. The upper 10–15 cm layer of soil was removed and dead trees were cut down. This waste was placed in trenches and covered with a layer of sand. A total volume of about 100,000 m^3 was buried, reducing the soil contamination by, at least, factor 10. These measures combined with other fire prevention strategies significantly reduce the probability of the dispersion of radionuclides during forest fire.

Changes in the forest management and use can also be effective in reducing dose. For forest ecosystems removal of falling leaves, needles and litter is considered to be the only applicable in the first month after an accident. Early felling of trees is an option based on the assumption that the concentrations of radionuclides in wood in some forests will increase with time. Delay of trees felling according to the rate of physical decay and the removal of radionuclides from the system is another option. The removal of trees, the soil improvement and the replanting of trees require careful consideration, since the resulting biomass may require treatment or disposal.

The prohibition or the restriction of food collection and the control of hunting can protect those who habitually consume them in large quantities.

Dust suppression measures such as reforestation and sowing of grasses are also undertaken on a large scale to prevent the spread of existing soil contamination.

The chemical treatment of soil to minimize radionuclide uptake by plants may be a viable option. The processing of contaminated timber into less contaminated products can be effective provided that measures are taken to monitor by-products.

Thus, the problem of radiation protection of various components of the environment against radionuclide transfer may be solved at all stages of their migration within trophic chains. It is the main element of rehabilitation system of contaminated by radionuclides biocenosis. The practical implementation of such radioprotective measures should be realized not only by radiobiologists and radioecologists, but also by many other specialists, who are aware in the field of radioecology as well as other sciences – agronomists, specialists in land-reclamation, hydrogeologists, specialists in forestry, technologists of food processing industry, hygienists and many others. The problem of radiation protection of the environment against radioactive contamination, and, accordingly, the reduction of radiation damage of living organisms and, finally, humans may be effectively resolved under the conditions of complex approaches.

Control points to chapter 11:

1. The essence of anthropocentric and eccentric conception.
2. The necessity and the importance of non-human species protection.
3. Land-reclamation measures on the territories contaminated by radionuclides.
4. Erosion control measures on the territories contaminated by radionuclides.
5. Phytodezactivation of soils.
6. The contamination of water bodies.
7. Radiation protection of the aquatic environment.
8. The reduction of radionuclide uptake and the accumulation by humans.
9. The role of forest in radiation protection of the environment and radiation protection of forest.

12. USING OF IONIZING RADIATION IN AGRICULTURE, FOOD INDUSTRY AND MEDICINE

The development of general radiobiology as well as its branches gives wide opportunities to use ionizing radiation in various fields of human activity such as medicine, agriculture, microbiology, pharmacy, food industry, etc. Practical use of ionizing radiation requires the development of special measures and principles to create a new irradiation technique. Indeed such complex development of science, technology and technique originated a new branch of radiobiology – *applied radiobiology*. It combines the results of fundamental researches of the radiobiological phenomena that are the basis of certain technological processes having the best technical and economical indexes. It includes the development and the creation of devices and options for irradiation of living objects at the certain stages of these technologies providing radiation safety of a man. Radiation-biological technologies have appeared at the interfaces between technological sciences and applied radiobiology.

Radiation-biological technology is a technology that means the application of the irradiation of living organisms at a certain stage of this technology.

Many of these technologies are widely used in the national economy, especially in the area of agriculture and, foremost, in the plant-growing.

Ionizing radiation doses used in radiation-biological technologies vary from a few tens of grays (centigrays) that are applied for the growth stimulation and the development of vegetative plants and animals to a few millions used for irradiation of course fodder containing cellulose for the improvement of its nutrient values (Fig. 86). Therefore, for irradiation of different objects there is a necessity of ionizing radiation sources that have different power and technological capabilities.

12.1. Radiation technique used in radiation-biological technologies

Low-powered X-rays photography apparatuses and rather expensive radium preparations were the unique sources of ionizing radiation for a long time. It restricted the wide application of radiation in the national economy.

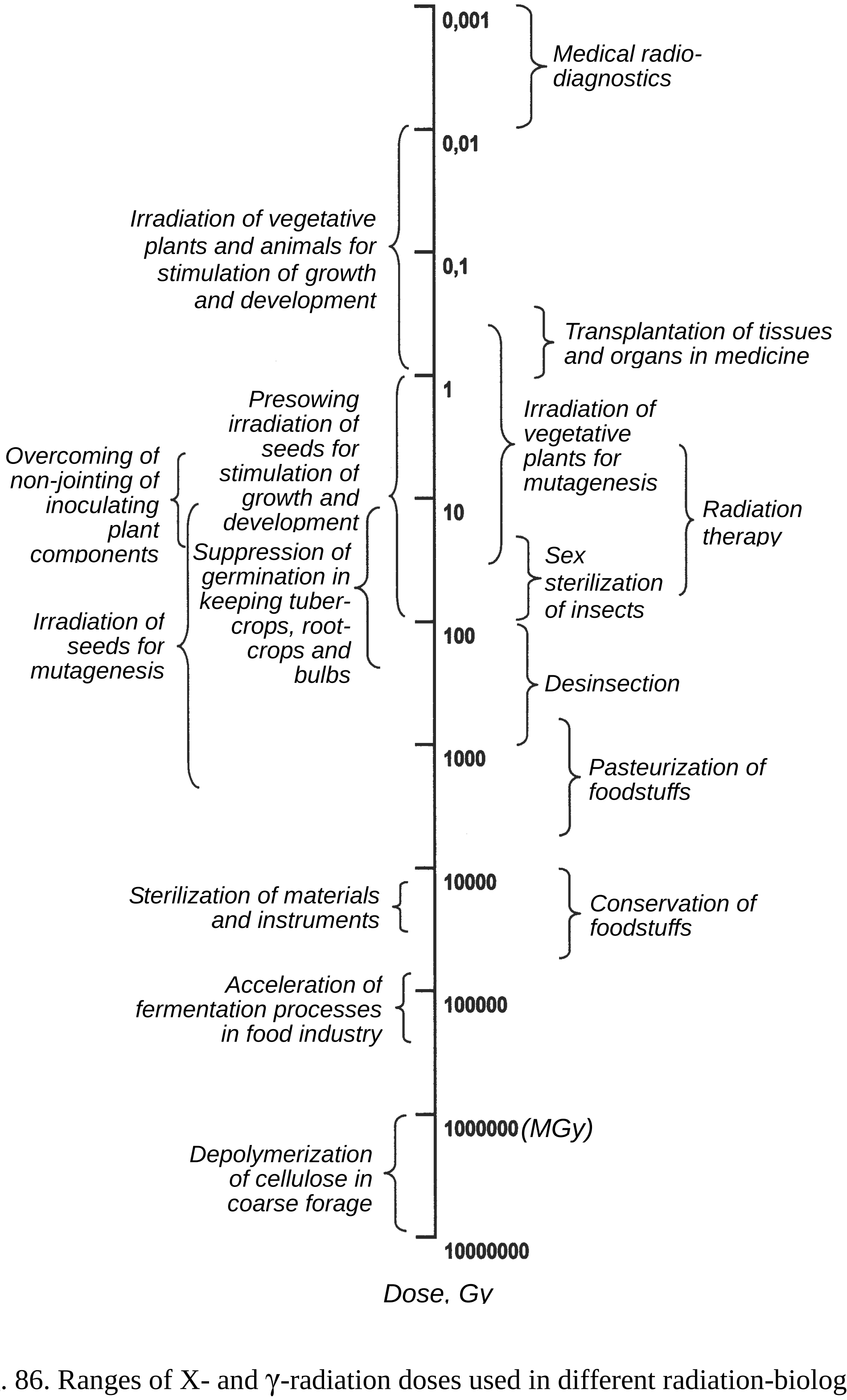

Fig. 86. Ranges of X- and γ-radiation doses used in different radiation-biological technologies.

From the beginning of 1950th the mass production of artificial radioactive isotopes began. It stipulated the introduction of relatively inexpensive sources of radiation of high energies. X-, γ-radiation, β-, electron and neutron radiation sources are still used in applied radiobiology. However, γ-rays of artificial radioactive isotopes of ^{60}Co and ^{137}Cs sources as well as electron radiation of accelerators are most widely used nowadays.

The wide application of the first one is due to the following advantages: prolonged half-life (5.3 and 30 years accordingly), high penetrating ability, the absence of induced radioactivity in irradiated objects, the possibility to create sources of wide range of specific activity from several to thousands Curie per gramme (up to 10^{14} Bq g^{-1}) as well as the appropriate properties of sources from the point of view of the technology allowing its long-term use in autonomous installations of different types with a minimum energy consumption rate.

The use of such installations exposes various biological objects at small and high doses of X-radiation. The irradiation by nuclear reactors (so-called radiation contours of reactors) or it's partly or the fully worked out heat producing elements (fuel elements) are used even more frequently, since reactor block contains a nuclear fuel.

The sources of radiation used both in the national economy and in other areas of its application have to meet following main requirements: to provide a certain absorbed dose within the limits of needed exactness; homogenous distribution of applied dose within the volume of irradiated subject; the absence of reactions causing induced radioactivity; to provide radiation safety and to compensate cost price of technology (comparable cost of used materials, low energy consuming rate).

The following serial installations produced in Russia – „Issledovatel'", experimentally-industrial and industrial installations "Sterilizator", "Stebel", "Genetic", industrial installations "Kolos", "Stimuljator", "Universal", "Gamma-panorama" meet the case.

12.2. The application of ionizing radiation in agriculture

Agriculture became one of the main users of radiobiology achievements to solve its practical problems. The use of ionizing radiation in the plant-growing and stock-raising is a powerful factor of intensification of agro-industrial production.

12.2.1. Radiation-biological technologies in plant-growing

Over 40 different radiation-biological technologies are introduced in the plant-growing worldwide.

Irradiation of crop seeds before sowing to increase productivity. Biologists pay much attention to the effect of radiation stimulation as means of agricultural crops yield increase. Nowadays irradiation of crop seeds before sowing is considered to be a radiation-biological technology that promotes economic efficiency of crops production due to speeding up of plants growth and development, shortening of vegetation period, the increase of yield and sometimes the improvement of its quality.

There is the number of experimental studies showing the effect of stimulating doses on crops productivity. Such great number of publications is generalized in tens and hundreds of literature surveys and monographs. Detailed methodical references and practical recommendations on the irradiation of agricultural plant seeds before sowing by γ-radiation are worked out. Special mobile installations for seeds irradiation in the field conditions are manufactured, e.g. mentioned above "Kolos", "Stimuljator". Mass scientific and practical tests of mentioned technology have been performed in many different countries. The method was introduced in the large scales in Moldova, Latvia, Kirghizia, Kazakhstan and many regions of Russia. During 60–70s the method was widely tested in Ukraine.

Table 49 shows γ-radiation-induced oriented doses that increase agricultural crops yield when seeds are irradiated before sowing. From 30 to 40% of yield increase may be achieved.

Table 49. Irradiation of crop seeds before sowing and crop yield increase, average data

Crops	Stimulating dose, Gy	Yield increase, % to the control
Maize corn	5–10	110–115
Maize silo	5	110–130
Wheat	5–8	109–111
Barley	10–30	107–115
Buckwheat	5–7	115
Sunflower	10	100–120
Pea	3	115–140
Lupine	10	118–127
Rye	5–10	112–114
Clover	5–10	130

Cotton plant	10	110–120
Cabbage	20	113–120
Tomato	5–10	110–115
Garden radish	10	115–130
Carrot	25–40	125–135
Cucumber	3	110–140
Sugar beet	10–20	115–120
Red beet	10–15	120–130
Rice	5–20	110–112
Kidney bean	7.5–10	110
Flax	7.5–10	112
Soy-bean	7.5	112–117

By affecting metabolism processes, irradiation of seeds can result in an increase of plant compounds that characterize the quality of the plant products, e.g. protein content in corn of cereal and leguminous crops, sugar content in sugar beet, fat content in sunflower seeds and flax, carbohydrates and vitamin content in vegetables. Growth stimulation increases the fiber length and the strength in flax and hemps, i.e. indexes that characterize products quality of these industrial plants.

The slight (up to one week) speeding up of plants ripening is also observed; it may be important for some vegetables. Early ripening of vegetable products can give a substantial economic effect.

Irradiation of propagation vegetative organs of plants and seedlings before planting to speed up plant growth and its productivity. Ionizing radiation stimulates plant growth and its development when vegetative plants or some of their organs are irradiated. To stimulate plant growth and its development usually much lower doses are required in comparison with doses for seeds irradiation, e.g. from one tenth to several units of Gray.

The vegetative propagated potato plant is well studied. The maximum stimulation effect of potato plant (irradiation of tubers) is observed at a dosage between 0.5 and 5 Gy; the yield increases on 18–25% and starch content increases from 15 to 16%.

Irradiation of cuttings before planting and inoculation are considered to be perspective. There are many works showing radiation-induced stimulating effect of vine, goose berries as well as black and red currants cuttings at a dose of 2–5 Gy. It stimulates root formation with the following enhancing root and shoots growth and their development, increases photosynthesis and respiration intensity and finally results in the yield increase by factor 1.5 and higher. Irradiation of mentioned berry plant cuttings as well as many fruit-trees, e.g. apple-trees, pears, plums, apricots and others improves jointing of graft to stock.

Irradiation of mint rhizomes and sweet roots before planting by doses of 5–10 Gy caused higher amount of bud awakening, the increase of shoot formation and of green forage. Irradiation of strawberry tendrils at a dosage of 5–15 Gy increases berries yield by factor 1.2–1.3. Irradiation of onion bulbs and garlic at a dose of 0.5–3 Gy increases the yield of leaf on 6–30%. Similar yield increase and ripening speeding up was obtained for seedlings of tomato, vegetable pepper, egg-plant and cabbage.

Application of irradiation of plant propagation vegetative organs and seedlings before planting is limited mainly due to technological reasons. The irradiation of potato tubers seemed to be achievable on a large scale.

Irradiation of seeds and plants to select new varieties. The discovery of radiation mutagenesis gave the possibility to select new forms of living organisms by using ionizing radiation. Thus, radiation mutagenesis is the most widely used method in plant selection.

Selection of a new sort by using ionizing radiation has two stages: irradiation of plants to obtain the maximum number of mutations as an initial material for selection; to raise a new sort using generally accepted approaches and methods, its testing, propagation and introduction in practice. The first stage of a selection process, which is related to radiobiology, is specific. It requires such irradiation dose of seeds, vegetative and generative plant organs, which induce maximum outcome of new plant forms – mass irradiation of initial material.

As we mentioned in chapter 5, the amount of mutations arising from ionizing radiation is straight proportional to the dose applied. However, plant's survival and their ability to produce seeds is inversely proportional to the dose. Therefore, it is important to choose such dose rate that provides high output of mutations and high enough number of survived reproductive plants. Radiation doses causing death of 70, 80 or even 90% in a population of living plants are denoted as LD_{70}, LD_{80} and LD_{90}. It means that 30, 20 or 10% of irradiated plants survive and are able to produce seeds. Well known Swedish geneticist and radiobiologist A. Gustafson named such dose a *"critical dose"*. It means that even small increase of dose rate results in death of a whole plant population.

Russian radiobiologist E. Preobrazhenskaja, whose name was mentioned earlier, generalized her own and known already data about seed's radioresistance of 63 families, 262 genera, 506 species and 218 interspecific plant forms in the book "Radioresistance of Plant Seeds" (1971). The book even today remains one of the basic references for researchers in the field of radiation mutagenesis industry. Critical doses for seeds of some of the crops are shown in Table 50. Data for seeds of some shrubs and fruit-trees spesies as well as arboreal species are presented in Table 51.

Table 50. Critical doses (LD_{70}) of γ- or X-radiation for seeds of some crops

Genus and species	Dose, Gy	Genus and species	Dose, Gy
Beans	50–125	Oat	150–300
Rutabaga	2500	Cucumber	500
Mustard	1000–2000	Tomato	200
Pea	75–250	Millet	300–400
Buckwheat	250	Wheat	150–250
Melon	200	Durum wheat	200
Rye	100–200	Garden radish	1500–2000
Cabbage	800–1000	Rice	300
Potato	250–500	Castor bean	1000
Kidney	100–200	Rape	1000–1500
Clover	2000	Sorghum	300
Maize	100–200	Timothy	100
Flax	400–1000	Turnip	700–1500
Lupines	500	Onion	100–150
Alfalfa	1000–1500	Spinach	200
Carrot	300	Barley	200–350

For the radiation mutagenesis other types of ionizing radiation, e.g. neutrons are used. The relative biological efficiency (RBE) of neutrons for different types of plants varies within the limits from 3 to 10, although it can reach the value of 20. It is suggested that neutrons act selectively in the cell genome and are considered to act gently in the division apparatus and cytoplasm.

It has to be stressed that ionizing radiation does not induce any new types of mutations in comparison with mutations that occur in nature. It only multiplies the amount of mutations that facilitates the selection process. An increased amount of radiation-induced mutations increases the appearance of various types of mutations that are very rare in nature.

The irradiation of pollen may give advantages in comparison with the irradiation of seeds. The pollen grain contains one cell with generative nucleus whereas seed's embryo consists of thousands of cells. Radiation-induced mutations in pollen grain are transferred to all cells formed from the plant zygote. It follows that a plant becomes affected by mutagenesis in the first generation after being impregnated with irradiated pollen; it means shortening of selection process, at least, for one year.

Table 51. Critical doses (LD_{70}) of γ- or X-radiation for some species of cultural and wild arboreal plants

Genus and species	Dose, Gy	Genus and species	Dose, Gy
Fruit crops and grape			
Gooseberry	50	Almond	60–150
Quince	100	Sea-buckthorn	200
Grape	150–200	Peach	60–150
Cherry	75	Plum	60–150
Pomegranate	100	Currant	50
Pear	50	Mulberry	100–200
Lemon	200–300	Apple	40–100
Arboreal and shrub species			
Birch	50–10	Laurel	30
Alder	50	Linden	150
Honey-locust	200	Larch	10–50
Black walnut	60–150	Fir	15
Oak	50	Pine	15–20
Horse chestnut	150	Rose	100
Cedar	10–50	Spruce common	5–10
Cypress	50	Spruce siberian	50–100
Maple	200	Ash	450

Obtaining new varieties of plants is also possible by irradiation of tubers, root crops, bulbs, seedlings and other vegetative reproductive organs.

The ionizing radiation in plant selection is most widely used in radiation-biological technology in agriculture and nowadays such technology continues to develop. Thus, according to the International Agency Atomic Energy (IAEA), 225 new sorts of crops have been obtained and introduced by using radiation-induced mutagenesis (data in 1980). In 1990 its number exceeded 1500 and reached nearly 3000 in 2000.

In Ukraine obtaining of new crop varieties by using ionizing radiation is successful. Ukrainian scientists have raised such well-known early ripe, high-yield and resistant to low temperatures and disease sorts of crops as buckwheat Aelita, Lada, Galleja, Podoljanka; low alkaloid variety of lupine Kyivskiy mutant, Mutant 486; variety of mint Zimostiyka 1; variety of tobacco Bezpasunkovy, etc.

Overcoming of tissues incompatibility and stimulation of its accretion at vegetative inoculations of plants. It is well known that by means of inoculation, i.e. transplantation of a plant part to another one some rather complicated problems may be solved. It is possible to save properties and economically useful signs of plants that are not able to undergo vegetative propagation. However, tissue accretion at intersort and especially at interspecies inoculations is rather complicated or does not take place at all. The main reason of weak tissue accretion is biological incompatibility caused by the remote biological affinity.

The theoretical principles and practical possibilities of biological incompatibility inhibition in plants were developed by Ukrainian radiobiologists D. Grodzinsky and A. Bulakh in 1970th. It was shown that γ-irradiation of graft or stock before the inoculation causes suppression of the immune systems of plants and increases quality of tissue accretion resulting in higher yield of inoculated seedlings. Particularly, radiobiological technology of grape preparation in a grafting viticulture is based on the mentioned above method. What is the essence of this phenomenon?

The phylloxera insect (root louse) is known to be rather serious pest of some sorts of European grape. It affects leaves, shoots, tendrils, but, mainly, an underground part, i.e. root system of vine grape. Inoculation of European assortment with phylloxeraresistant American subgrafts is the way of pest control. However, due to low compatibility of domestic species with American ones the output of standard nursery transplants makes only 20–35% and some of the combinations do not accretioned at all. Under the irradiation of subgrafts either at a dose of 15–30 Gy or grafts at a dose of 5 Gy both components increase the output of inoculations (including those with low compatibility) by factor 2–3.

In addition, the irradiation of grafts helps to avoid the important and time consuming “operation” – so-called “blinding” of grafts which is the removal of superfluous buds (eye). Developing such buds compete for the nutrients, inhibit callus formation resulted in weak accretion with a stock. Therefore, ordinary technology requires removing of superfluous buds, usually, by hand, which is time consuming. Up to 90% of “blinding” may be achieved by irradiation of grafts by γ-rays at a dose of 25 Gy (by manual or mechanical method gives up to 70% of “blinding”). A dose of 50 Gy can give 100% effect.

Irradiation of inoculated components appeared to be effective at vegetative inoculation of fruit-trees. It facilitates the selection of vegetative hybrids of plants even those having low compatibility or incompatible. The method is applicable to select hybrids between biologically distinctive sorts and species as well as to select hybrids between different genera, e.g. such combinations as apple-tree-pear, plum-apricot, apricot-peach, raspberry-blackberry.

Prevention of tubers, root crops and bulbs from germination at storage. The weight and the quality losses of different types of plant products, e.g. potatoes, root crops, bulbs during the storage is due to lasting of metabolism and germination. By using irradiation of such types of plant products it is possible to delay or even completely inhibit metabolism and germination of meristem tissues in growth zone and to extend storage terms. Thus, irradiation of tubers by γ-radiation at a dose from 50 to 150 Gy allows prolonging storage term of potatoes depending on a sort and terms of storage to year and more during of spring-summer rise in temperature. Such storage period in the conditions of uncooled store-house at a temperature of 6–8°C may be prolonged by factor 2–2.5.

Similar situation is observed at root crops storage. The irradiation by the same doses allows extending their storage terms. The irradiation of sugar beet root crops is rather effective. Ordinary storage of sugar beet root crops in heaps before processing results in sugar content decrease due to the lasting of respiration processes for a few months of storage by factor 1.5–2 and more. The irradiation of root crops by γ-rays before the storage in heaps reduces their weight and sugar losses considerably.

The irradiation of onion and garlic after the harvest at a dose of 10–100 Gy prolongs their storage term up to two years. The temperature and humidity conditions have to meet requirements to prevent rotting and pest damage (Fig. 87).

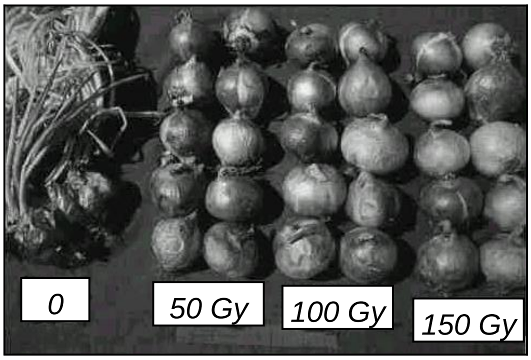

Fig. 87. The appearance of irradiated by γ-radiation and not irradiated (control) onion in the spring. Onion irradiated in autumn.

Naturally, subjected to such high doses vegetables can not be used for planting and have to be consumed only as food, fodder or for technological processing.

A typical multipurpose installation is designed specifically to provide radiation and biological technologies for irradiation of potatoes, roots, onions, fruits and other products (Fig. 88**)**.

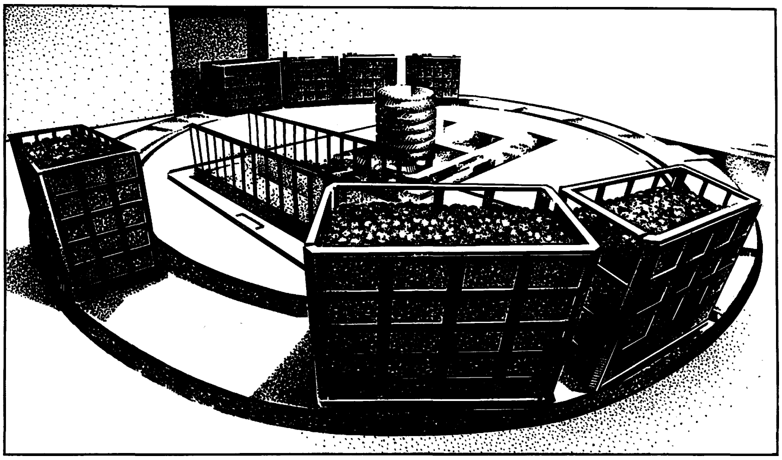

Fig. 88. A multipurpose gamma-ray machine for irradiation of potatoes, vegetables, fruits and other products (the source of irradiation is in the centre, containers with products move around it in a circle.)

Storage term prolongation of berries, fruit and vegetables. Great losses in farming as well as horticulture products are observed due to the infection caused by various microorganisms during storage term. The traditional methods of storage term prolongation of berries, fruit and vegetables are heating, cooling or various treatments with chemical reagents. All of them, however, affect the quality of products. Using ionizing radiation in doses that inhibit or suppress microflora development actually is a process of cold pasteurization. Such treatment can kill many or even all microorganisms allowing in such a way to prolong storage term at the ambient air temperature.

Most convincing data are obtained for strawberry at γ-rays and electron irradiation. Irradiation of strawberry at dose of 2–3 kGy, i.e. semilethal for most types of microorganisms, extends its storage at 4–5°C by factor 2.5–3 (Fig. 89) and by factor 2 at 15–18°C. Treated in such a way berries may be transported on large distances. Treatment by irradiation for prolongation of storage terms is practically applicable treatment for the increase of storage terms of tomatoes, currant, raspberry, grape, apricots, peaches, cherry, plum, apples, pears, bananas.

It was found that γ-irradiation of pears and lemons as well as tomatoes at dose of 3 kGy retard their ripening on 10–15 days and bananas at dose of 0.25–0.5 kGy – on 8–26 days. Similar effect was observed when green and ripe oranges were irradiated at doses of 0.14–2.8 kGy. Storage term prolongation is very important. It allows transportion of these products on large distances, e.g. from Africa to Ukraine. It is suggested that irradiation of unripe fruits inhibits metabolism as well as the production of phytogormone ethylene that is involved in ripening processes.

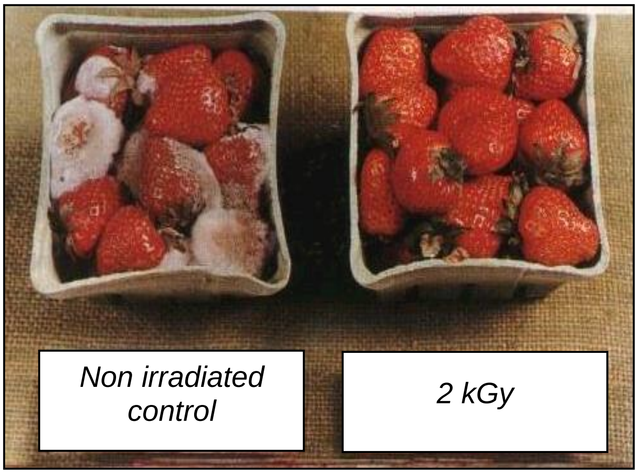

Fig. 89. Appearance of irradiated by γ-radiation and not irradiated strawberry after 15 days of storage at 4°C.

Pest sterilization with ionizing radiation. Radiation-biological technology of pest sterilization is based on a different radiosensibility of gametes and somatic cells. By means of experiments it is possible to choose such dose that does not affect most of the physiological functions of pest, including the ability for coupling. But it causes irreversible changes in gametes. Being irradiated, male sperm, for example, preserves the ability for eggs impregnation, but zygote development is held up; it means that exposed males become sterile.

The vital capacity of insects, as a separate species, is determined by their exceptional fecundity rate. Some of known species whose lifetime is measured by a few months, may produce tens thousand of eggs. For this reason the appearance of sterile males in the pest population reduces its growth rates and number. Repeated release of sterile males in the pest population during a few years may kill all pest population on a limited territory.

In comparison with other methods (e.g. chemical), pest sterilization with the use of ionizing radiation technology has several advantages. One of them is that the pest sterilization is directed towards special species of pests, while the application of insecticides affects many of insects including useful ones. Apart of this, pest sterilization with the use of ionizing radiation technology is safe for animals and humans, as well as for the whole environment.

The pest sterilization biotechnology distinguishes of three major stages. The firs and the main step of technology is pests' breeding on special insect plants. The second stage is irradiation of insects. It requires studying of radiosensitivity of specific pest species. For this, insects are transferred to special chambers with the low temperature (4–8°C) or subjected to a special gas which inhibits their physiological activity, including mobility. Treated in such way insects are transferred to special containers equipped with the source of ionizing radiation and subjected to X-rays. Sometimes insects are irradiated during natural immobile stage of their development, i.e. pupa. The third stage of technology is the release of exposed to radiation insects in the environment using airplanes and helicopters.

Until now over 50 programs of pest control using technology of radiation sterilization have been carried out worldwide. Some examples of successful application of mentioned technologies are well known. Pest sterilization with ionizing radiation is very effective when applied in island remote regions where insect migration from other places is limited. Thus, pest sterilization with ionizing radiation technology was used successfully against the Mediterranean fruit fly in Costa Rica. For this an insect plant producing about 10 million of insects per week was built on the Hawaiian Islands. The population was reduced by factor 130 during the first year due to the release of sterile flies. On the Rotha Island located in south part of the Pacific Ocean the release of sterile flies (once per week for 35 weeks (257 million of exposed insects) killed all pest population. The effective application of such technology against fruit and melon flies on Japanese islands is also reported.

The pest sterilization technology is also applicable on the continent. The reduction of Mediterranean fruit fly population is reported in the USA (California) and in Mexico. Reduction of rose cotton worm is reported in California and apple worm in Canada (British Colombia). Pest control of migratory populations of those insects is achieved through the special quarantine barriers, i.e. the periodical (once per 2–3 weeks) output of sterile insects. Such pest control appears to be much more economically profitable in comparison with application of insecticides.

Radiation-induced disinfestations of plant products. Such pests as granary weevil, corn weevil, rice weevil, surinam flour-eater, grain worm, flour engraver may destroy about 15% of the worldwide harvest during storage. The quality losses may be even greater, since insects eat away mainly a part of grain enriched with a protein.

Usually, pest control is achievable through the application of chemical method, i.e. using insecticides and some other drastic chemical pest-killers. Such approach is considered to be an effective but its application is limited due to high toxicity for humans and the environment. The method of radiation-induced disinfestations of plant products has been developed during last decades. The method considers the use of γ-rays or electron irradiation of corn before its loading in an elevator. This method is used in many countries.

The starting point of technology is the determination of dose level, which has to be lethal for pests. As we mentioned in chapter 6, the lethal doses for most of the insect species vary from 100 to 500 Gy. Doses recommended for disinfestations are in this range.

At the same time irradiation dose depends on the individual specific radiosensitivity and the stage of pest development at the moment of irradiation. Thus, for the pupa and imago stage of granary weevil and corn weevil a lethal dose is 200 Gy and for eggs and larvae stage is only 55 Gy. Obviously, those factors have to be considered when separate corn lots are irradiated, since it may speed up corn treatment.

There are serial industrial installations, i.e. grain radiodisinfection chambers (РДЗ-200 and РДЗ-400) in Ukraine. The electron accelerator with energy of 1.4 MeV is a source of ionizing radiation. The chamber of the second type having production capacity up to 400 tones of corn per one hour is put into operation on Odessa port elevator in 1980. The experience showed that radiation disinfestations is an effective measure for pest control when corn is loaded for storage or when transported from abroad. The radiation-induced disinfestations are also used for preservation of dried vegetables, fruits, mushrooms, medicinal herbage.

Amendment of medicinal plants quality. Plants synthesize a lot of various substances of secondary origin, some of which show strong biological effect on an animal organism. These are various alkaloids, glycosides, terpenoides, flavonoides. The only alkaloids is known to be about 10,000. Cocaines, morphines, atropines, strychnines, nicotines, quinines and theobromines are among other things of that nature. They are widely used in medicine as medications and in agriculture as insecticides. However, physiologycal role of many of these substances in plants is not known. It is suggested that they are some kinds of metabolism wastes, that's why they got the name "secondary" substances.

When high doses of ionizing irradiation are applied to seeds or vegetative shoots of plants, synthesis of these secondary substances, especially those having phenol and chinone nature is activated. Such mechanism of ionizing radiation action sometimes is referred to as radiotoxins hypothesis. Thus, γ-irradiation of datura seeds at doses of 50–100 Gy results in the increase of tropane alkaloids within a plant, e.g. atropine, scopolamine, hiosciamine. Irradiation of seeds and shoots of periwinkle rose (catarantus) increases very important alkaloids content in plant leaves. These alkaloids are used as an initial material for the production of oncostatic preparations known as vinblasnine and vincristine. Irradiation of foxglove and strophant increases the amount of glycosides of digitoxine and digoxine that are used for treatment of heart sickness.

Obviously, using high irradiation doses may inhibit plant growth and reduce a gross release of these biologically active substances. However, the application of experimentally designed doses of ionizing radiation for relatively high release of secondary substances at negligible inhibition of growth rate may be achieved.

12.2.2. Radiation-biological technologies in animal-breeding

The radiation-biological technologies are also found to be applicable in animal-breeding. However, the scales of its use in this area of agricultural production are much limited in comparison with plant-growing. There are many reasons for that, but the main and foremost is that stock-raising objects are less "technological" for these purposes.

The most practically applicable are ***stimulating doses*** of radiation used in the poultry farming. It was shown that eggs irradiation before the incubation or within the period of incubation at doses of 0.03–0.05 Gy reduces incubation term, increases hatchability, and enhances their postembryonic development and growth. Chickens that grow from exposed eggs lay eggs earlier. Irradiation of chickens at doses of 0.2–1 Gy enhances their growth, development and eggs laying. Irradiation of one-day age suckling pigs at doses of 0.1–0.25 Gy increases their size and mass. Irradiation of rainbow trout sperm at doses of 0.25–0.5 Gy increases caviar fecundation on 35–40%. The list of similar examples can be continued but most of them are considered to be experimental by nature. The irradiation at small doses in the poultry farming was used in production.

The application of ***radiation mutagenesis method*** in the stock-raising is also limited. The only Russian scientists were able to breed of mink species having an original silvery fur color. There is also evidence of successful method application by the Australian scientists in the poultry farming.

Nevertheless, let us consider some of radiation-biological technologies in more detail.

The radiation-induced sterilization of insects as spreaders of agricultural animal's thickness. The method was successfully applied against flesh flies on Kurasao Island in the USA. The fly spreads disease among wild and domestic animals making a lot of harm in western hemisphere. Later, flesh-flies were completely killed in the USA and Mexico. The long-term program of tsetse fly control initiated by IAEA is fulfilled on the Africa continent. The tsetse fly spreads trypanosomes that parasitize in blood of mammals and cause severe disease in animals known as "Nagana sickness" (often lethal) and sickness in humans called "sleeping-sickness". Three species of tsetse fly are killed in Nigeria and Zanzibar.

Biotechnology of fodder preservation, disinfection and improvement its quality. Ionizing radiation may be used to improve coarse fodder quality for agricultural animals feeding. The radiobiology technology is used for canning of fresh fodder, disinfection of cereal and combined fodder as well as for radiochemical modification of coarse forage.

Thus, γ-rays irradiation of green forage at doses of 10–40 kGy is used to make a silo and to preserve fodder during winter period.

The irradiation of potatoes at doses exceeding recommended ones for germination suppression (5–15 kGy) may be applied to prevent fodder potatoes from being rotted during the storage term. To prolong the storage term and to prevent mould and bacterial insemination of grains (oats, barley, maize) stored at elevated humidity the irradiation by doses of 1–3 kGy is recommended.

Salmonellosis is the infectious intestinal sickness caused by the salmonella bacteria. It is known to be very dangerous for people and animals. The salmonella bacterium enters an animal organism together with the infected forage and transfers with meat, milk, eggs and other animal products to a man. The ordinary methods used against salmonella bacterium are ineffective or economically unprofitable. Chemical preparations used for the disease treatment are dangerous for people and animal health. The thermal treatment results in considerable losses of nutrients and vitamins. The special radiation-biological technology of fodder disinfection to protect fodder against bacteria is designed.

The lethal doses of γ-irradiation of 4–5 kGy are required to protect against all salmonella bacteria strains. Using these doses disinfects completely flour sterns and mixed fodders, meat-bones and fish flour intended for feeding of pigs, chickens and other animals.

Irradiation by very high doses from 1 to 10 MGy is required to increase the feeding value of coarse forages containing cellulose, e.g. straw of cereal crops, cores of maize heads, grape squizings, branches, pine-needles and even woody flour. Irradiation promotes radiochemical depolymerization of celluloses and pectines as well delignification, i.e. the extraction of lignin from the forage. Treated in such a way fodder undergoes better fermentation followed better use of cellulose by the scar microorganisms of ruminant animals.

Home and foreign experience revealed advantages of radiobiological technology of fodder disinfection in comparison with other methods, i.e. preservation, disinfection and quality improvement. The radiation technology allows saving value of feeding fodder, since traditional methods of fodder treatment, e.g. high temperature cause reducing of proteins, vitamins and other nutrients content.

Prolongation of storage terms of animal products. Ionizing radiation is used in many countries to prolong the storage terms of animal products, e.g. meat and meat products. This method is especially applicable for animal products that are transported for long distances. The experience obtained evidences that irradiation of meat by γ-rays or electrons at doses of 1–5 kGy allows substantial extending of storage terms at a storage temperature 0–4°C.

Thus, irradiation of mutton and beef at doses of 4 kGy does not require their freezing or storage at inert gas when transported in a hot climate of Australia and New Zealand for long distances. English scientists found out that irradiation of fresh beef at doses of 1–5 kGy allows prolonging the storage term by factor of 2–8 at a store temperature 2–8°C.

The treatment of poultry and eggs with ionizing radiation showed to be economically profitable. The Canadian scientists found out that the dose of 5 kGy prolongs storage term of fresh chicken carcasses at 4°C from 6 to 16 days, and at 0°C up to three months.

Disinfection of some types of animal products. A lot of harm for agriculture, as well as for national economy, in the whole, is caused by such infectious animal disease as plague of carnivorous, ringworm, Siberian ulcer, listeriosis. Very often infectious animal products such as wool, fur, skin as well as bristle serve as a source of animal and human infection. The chemical methods of raw material disinfection are rather time and work consuming. Some of them are related to the use of moist treatments causing quality worsening of products. The use of ionizing radiation for disinfection of down and feather materials are perspective.

Industrial gamma installation for disinfection of sheep skins and wool (one of the main objects of agriculture and export articles of this country) is operated in Australia during some decades. The raw material is exposed to X-rays in bales with a volume of about 1 m^3 at dose of 20 kGy. The radiation causes death of microorganisms that are spreaders of the listed sickness. Such sterilization appears to be substantially more effective and less costly in comparison with chemical treatments.

Studies of Russian radiobiologists showed high efficiency of radiation disinfection of mink fur, polar fox, fox and rabbit. It is found out that γ-rays doses of about 20–25 kGy cause complete disinfections of products without any worsening of its quality.

Mentioned above radiation technology of animal products disinfection substantially raises the productivity of treatment due to its speeding up. Radiation technology allows treating animal products after being packed in comparison with the chemical method that requires moistening of material and adding of poisonous substances.

12.3. The application of ionizing radiation in food industry

Generally, the radiobiological technologies in food industry such as radiation-induced pasteurization and preservation are similar to those used in agriculture.

It has to be emphasized that very often questions concerning possible influence of irradiation on foodstuffs quality arise. It is speculated that irradiation of foodstuffs may occasionally cause changes of various radiochemical processes and even become harmful for a man. Comprehensive studies were performed to set the maximum values of irradiation doses when foodstuffs are irradiated. Such irradiation doses are considered to be safe and do not cause any change of quality. The International standard comprises principals that limit the use of ionizing irradiation of corn, its processing products and foodstuffs. For these purposes the use of electron stream and γ-rays at doses up to 1 kGy is recommended. To prevent the appearance of radiation-induced radioactivity the energy of electrons is limited to 10 MeV (the energy of γ-radiation is one order of magnitude less). In Ukraine the productive corn irradiation for disinfection purposes is settled to be in the limit of 1 kGy, and energy of electrons up to 4 MeV.

But the dose limit of 1 kGy became out of date and is actually groundless. According to the World Health Organization (WHO) report published in 1981, the γ-rays and electron irradiation of some food products at doses of 10 kGy with energies up to 10 MeV is safe for humans. Concerning irradiation of other plant products, including forages, the energy of radiation is limited up to 10 MeV, since higher energy of γ-radiation may cause radiation-induced radioactivity.

Nowadays many plant and animal products as well as various foodstuffs for various purposes are irradiated in the worldwide – from the USA and France to Bangladesh and Thailand.

Preservation of plant products and fruits. Irradiation doses of 10 kGy and higher kill most of the microorganism species and therefore may be recommended for preservation of plant products. Both fresh vegetables and fruits as well as their processing products such as juice of vegetables and fruits may be subjected to radiation treatment. The ability of X-rays to penetrate deeply into the environment is a unique and the most important feature of ionizing radiation. Preservation of products by means of ionizing radiation does not require e.g. sterility and may be applied to already packed products.

Saving of vitamins as the main component of fruits and vegetables is one of the main advantages of radiation-induced preservation of fruits and vegetables. Ordinary preservation heating methods lead to the destruction of vitamins. Although the color and taste of preserved products may also be affected, since high doses of ionizing radiation induce oxidization of some pigments and other radiochemical reactions.

Some specific types of plant products, e.g. tea, tobacco, makhorka, dried fruitage; spicy plants, medicinal plants, etc. are dry stored. During the period of growth, gathering, drying of raw material and its sorting, listed above plant products may be infected by various types of microorganisms, some of which may cause quality worsening and the loss when stored, and some may be dangerous for a man. The application of γ-irradiation at doses of 5–10 kGy leads to complete disinfection of the product. Such products are hermetically sealed up in polyethylene or polypropylene packages or other container. Packed in such a way material than is irradiated by X-radiation. Treated by this method material may be stored for long time without any losses of its properties and quality.

Such technology sometimes referred as radiation-induced disinfection but it is considered to be the variety of the radiation-induced preservation**.**

Preservation of animal's products. The special technologies for radiation-induced preservation of chickens are developed. Chickens are hermetically packed in tin or glass or sealed up in polyethylene packages and exposed to the X-rays at doses of 5–15 kGy. It allows avoiding heat treatment and therefore worsening of product quality.

A similar technology may be applied to milk and milk products exposed to the X-rays after being packed.

Similarly to radiation treatment of fodder the irradiation of meat and meat products is required to control salmonellosis infection. Technologies for meat and meat products treatment by X-rays require application of lethal for bacteria doses that are set within the limits of 4–5 kGy. According to many studies these doses are thought to be optimal, since they do not affect the protein and vitamins state of the products.

All mentioned above allows considering radiation treatment of meat products to be preferable in comparison with traditional low temperature (freezing) or high temperature (preservation) treatments. The economic efficiency of radiation technology is one of the main advantages.

12.4. The application of ionizing radiation in medicine

It is assumed that medicine was the first area of ionizing radiation application. There is also strong evidence that W. Röentgen was the first who proposed to use discovered by him X-rays for diagnosis of bone breaks (Fig. 90).

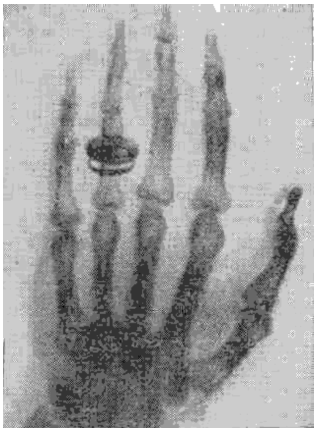

Fig. 90. Roentgenogram of anatomist Koulliker's hand made by W. Röentgen in January of 1896. The picture was made only a few months later after the discovery of X-rays. This is the first roentgenogram that began the application of X-rays in medicine (E. Hall, 1970).

Such idea was quickly realized by traumatologists. Later X-rays were used in other areas of medicine. In 23 days after X-rays discovery an American doctor G. Dzhillman and physicist D. Grubbe made successful attempt to use radiation for treatment of inoperable breast cancer. Until today the ionizing radiation is still in use and remains one of the basic methods for diagnosis and disease treatment, including veterinary medicine. However, there are two more trends of practical application of ionizing radiation in medicine, i.e. medical instruments and materials sterilization, and transplantation of organs and tissues.

Application of ionizing radiation for disease diagnosis. Nowadays X-raying became one of the most powerful and widely used instruments for various disease diagnoses. The majority of population of the most civilized countries takes X-raying at less once per year. The main aim of such investigation, however, is not diagnostics but sooner therapeutic purpose allowing early reveals of disease or even susceptibility to illnesses.

The principle of X-raying is based on the affinity of X-radiation to penetrate through an organism and to be taken up differently by different tissues and organs. Using a photosensitive material, for example, film, is possible to get the roentgenogram, i.e. an image showing a broken or damaged bone, morphological changes of various organs, ulcers, tumors or presence in an organism of strange bodies.

Until today the roentgenogram on a film material is the main way to obtain X-photography image. However, at the end of the last century the situation began to change. Nowadays the X-radiation of many roentgen apparatuses passing through the human body falls on photosensitive crystals instead of photography film. Such crystals convert X-radiation into electric impulses that, in turn, produce an image visible on the computer display. Obtained in such a way image may be stored on a CD, operatively transferred on any distance and treated in many ways using various electronic devices and appropriate software.

The method of *X-radiation computer tomography* is widely used during last decades. Special scanning device allows obtaining rather clear organ image at a certain body depth, resembling “thin microscopic section”. Any abnormalities may be easily seen on the image obtained (Fig. 91). Many-dimensional (volumetric) computer pictures showing details of internal structure of organs may be obtained by composing cut-layers. The device named X-radiation photography computer tomography (gr. *tomos* means a layer) allows viewing any body point at any point of view at a minimum dosage of irradiation. Depending on the purpose the γ-radiation, electrons as well as neutrons of different energies may be used. The device is called γ-, or electron, or neutron computer tomography accordingly.

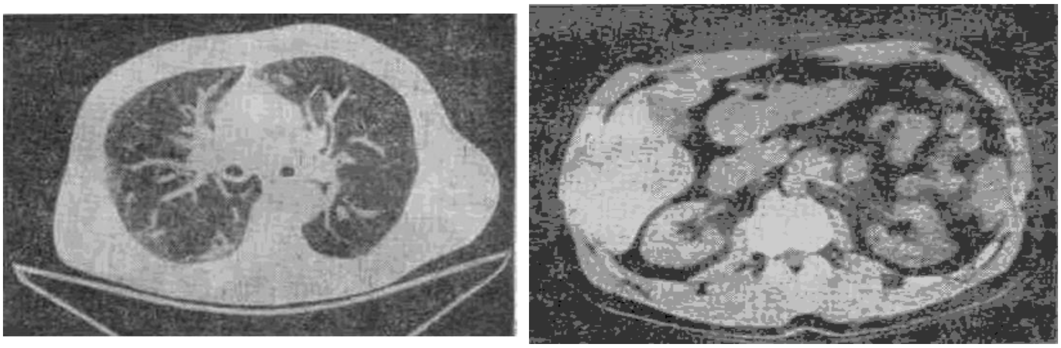

Fig. 91. Computer tomography scanning image of a human body microscopic section at the pelvis level. The liver is visible.

The specific area of X-raying is a mammagraphy method (lat. *mamma* – means a breast). The method allows revealing of breast cancer in women by using special low energy X-radiation photography devices that identify soft tissues. The mammagraphy method is considered to be the second method for disease diagnosis after X-raying that is widely used nowadays.

The discovery of radioactive isotopes opened a new trend in medicine known as radioisotope diagnostics. One of the first methods developed in this area was the estimation of thyroid gland state and functions. For this the special radioactive iodine preparations are injected into an organism. The level of iodine uptake by a thyroid gland evidencing possible alterations of it functions. The iodine is a specific element that needed for the production thyroxin enzyme.

Low as well as elevated function of thyroid gland may result in the formation of areas having altered structure, which, in turn, can eventually develop a tumour formation. By using γ-scanning the picture of the gland, so-called scintigramma is obtained. It shows the distribution of isotope within an organ and tumor. Such image allows making decision about treatment method of surgery if required. It is hardly possible to overestimate the importance of this method for diagnosis of many disease of thyroid gland. The great number of population living in contaminated area, have been affected due to radioactive iodine injection in an atmosphere after the Chernobyl catastrophe.

The structure and functions of other organs, e.g. liver, kidneys, lungs, brain, and bones may be investigated in the same way. Thus, radioactive arsenic isotope ^{74}As, that accumulates preferably in damaged brain matter is used for investigation of brain tumor. ^{74}As emits positrons that undergo annihilation the electrons of brain matters and produce γ-rays. The γ-radiation is easily registered by ordinary detectors that give a picture of isotope distribution in brain. To reveal tumor or stones in kidneys the radioactive isotopes of mercury, e.g. ^{197}Hg or ^{203}Hg, are used. Such isotopes are injected into an organism as special preparations. The state of liver and its functions may be investigated with a colloid solution of radioactive isotope ^{198}Au (dye-stuff is a Bengal pink marked by ^{131}I). Lungs are investigated when the patient inhales a gas mixture with a tracer or radioactive aerosol with, for example, ^{11}C. Generally, any metabolic activity may be investigated by applying proper substances and relevant radioactive tracer.

Following the general principles of radiation protection (justification, optimization and dose limits) only small amounts of short-lived radionuclides having short residence time are recommended to use for radioisotope diagnosis.

The method of radioimmunoassay (RIA) differs slightly from other radioisotope methods. The method is very sensitive and allows measuring small amounts of hormones, e.g. in blood of a patient. If a substance penetrates into an organism that recognizes it as foreign (antigen), an organism responds by the formation of antibodies in the globulin fractions of blood (gammaglobulin of various classes). Antibody should be regarded as a defensive weapon created by an organism for protection against "undesirable guests" (mostly pathogenic organisms). The ability of an antibody to discriminate between its "own" antigen and many other substances of widely diverse structure that are found in biological fluids (blood, urine, etc.) is the basis of its application as an analytical tool. An antibody is also able to bind selectively a group which is only a constituent part of an antigen. The principle of (RIA) is based on the reaction between radioactively labeled free antigens with antibody. If the equilibrium is disturbed by the addition of unknown or standard amount of non-labeled antigen, then the competition converts a certain part of the labeled antigen from the bound state into a free state. The higher the amount of non-labeled antigen added, the lower the amount of bound and free labeled antigen obtained. In other words, the concentration of antigen in a sample is determined by the comparison of the inhibition degree (retardation) of binding of the labeled antigen caused by the presence of sample with that caused by standard.

The advantage of this method is that radioactive substance does not enter an organism but is added to the patient sample, e.g. blood, urine or saliva.

Application of ionizing radiation for sickness treatment. Ionizing radiation for sickness treatment is mainly used for radiation therapy of localized malignant sickness. About 70% of patients require radiation therapy that may be used along or applied in combination with other, mainly surgical and chemical methods of sickness treatment.

A tumour grows due to uncontrolled cell division. Radiation therapy is based on Bergonie and Tribondeau law according to which the dividing (germinate) cells are markedly affected by radiation, while non-dividing (interstitial) cells are undamaged.

The main problem of radiation therapy application is, so to say „delivery" of lethal for tumour cells dose insuring minimum harm to normal cells surrounding tumour ones. It may be achieved by many different approaches; however, the main one considers determining exact tumour localization followed by irradiation of selected tissue volume with special rotary X-, γ- or other types of radiation. The beam of rays focuses on the center of tumor (Fig. 92).

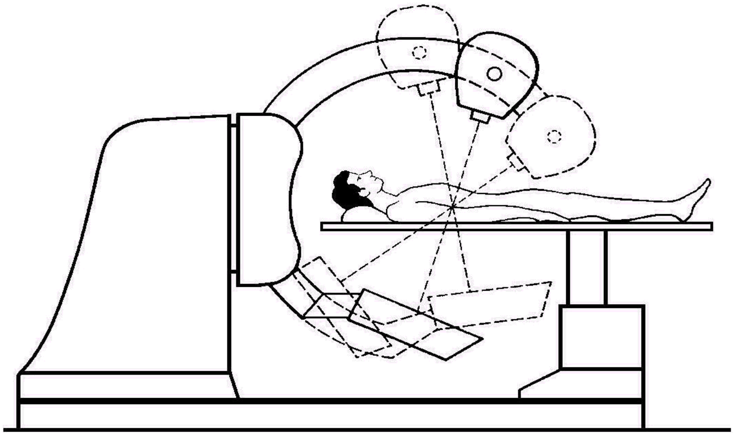

Fig. 92. The scheme of γ-therapeutic installation for human tumor treatment: the source of irradiation, e.g. ^{60}Co or ^{137}Cs in a leaden container with the narrow opening moves on a circle in different planes, focusing rays beam on a tumor.

Apart of described above, another method of radiation therapy is used, when the source of irradiation is incorporated directly in a tumor. Such source, e.g. needle, short wire or grains which contain the radioactive substances providing necessary dose rate is incorporated in a tumor by means of surgery for the period of from 3 to 10 days. Incorporated radioactive sources with short-lived radioisotopes, e.g. ^{125}I having life-time period of 60 days remain in the patient body as long as they disappear by itself, i.e. disintegrate and resolve. There is no need in second surgery.

Radioactive isotopes that localize in a certain organ or tissue are also used for radiation therapy of tumours. Thus, iodine isotopes are used not only for diagnosis of thyroid gland sickness but also for the treatment of some thyroid sickness, e.g. knotted goiter and tumours. Such sickness develops due to hyperfunction of thyroid gland. The application of iodine isotopes for thyroid tumour treatment requires much higher dose rate in comparison with that used for diagnostic. The dose required is in a range of from 0.3 to 0.5 Gy per gland.

The α-particles of plutonium isotope ^{238}Pu are considered to be useful as autonomous energy source in cardiostimulator, i.e. a small size device that provide normal systole rhythm. Usually such devices are implemented into a human body by means of surgery together with the energy source. A plutonium energy source provides cardiostimulator function for 10–25 years while an electric battery requires replacement every 2–3 years.

Nowadays radiation therapy is exclusively effective technology used against cancer. It evidences high recover rate in comparison with surgical methods used for treatment of such forms of malignant disease as breast cancer, cervix of the uterus, prostate, larynges, gall-bladder, tongue, palate and many others. Radiation treatment of skin cancer by means of soft X-rays that does not penetrate deeply in tissue is highly effective. Up to 95% patients recover after the treatment.

Radiation sterilization of materials and instruments in medicine. Plastics and polymeric materials and instruments are used widely in medicine. It caused the application of radiation-induced sterilization in this field. The traditional sterilization methods that are based on the use of autoclave at high temperature and pressure are unsuitable due to low heat-resistance of most types of modern materials. Besides, high temperature treatment of plastic material may cause some toxic by-products. In many cases the radiation-induced sterilization seems to be the only way to solve the problem. There is one more advantage of radiation-induced sterilization, i.e. the possibility to sterilize hermetically packed medical instruments and materials. Radiation-induced sterilization is technologically simple, economically effective and requires controlling the only one parameter, i.e. dose rate.

Radiation-induced sterilization is based on the ionizing radiation affinity to kill microorganisms at a certain dose. Theoretically, the dose rate applied for sterilizing purpose is determined by the contamination of exposed material and radioresistance of microorganisms. For practical purposes sterilizing dose of from 25 to 30 kGy for low LET (usually γ-) radiation is recommended in many countries. In former Soviet Union the lowest dose of 25 kGy was recommended for medical industry. Such dose is considered to be lethal for all microorganisms.

Nowadays radiation-biological technology is used for sterilization of many types of medical products. Firs of all, radiation-induced sterilization is used for instruments and materials made from polymers: syringes for injections, systems of blood taking and transfusions, catheters, cardiac valves, artificial blood vessels, items of prosthetic appliance, items used for artificial blood circulation, artificial kidneys and many other materials. Radiation-induced sterilization is used for treatment of stitch and bandaging materials (catgut, bandages, cotton wool, tampons, etc). Many of mentioned medical items can be sterilized by ordinary methods.

Apart of listed advantages radiation-induced sterilization saves original properties and functional features of medical preparations. For this reason the nomenclature of materials that can be treated with radiation-induced sterilization eventually increases.

Application of ionizing radiation for transplantation of organs and tissues. The biological tissues for transplantation, e.g. blood, blood vessels, bones, cartilages and some others are very specific group of medicine materials and require sterilization. Neither thermal nor chemical methods of sterilization are suitable in this case, since they cause damage of living tissues. Dose used for sterilization of materials and instruments is not suitable due to possible denaturation of high-polymerized substances of a cell.

It was decided to use the combination of thermal treatment and radiation sterilization. Thus, blood sterilization is achieved by combination of irradiation at dose of 7.5 kGy and heating up to 60ºC. Such combination allows obtaining sterile preparation without any changes of its original natural biological properties. Elevated temperature acts as a radiosensibilizing agent but not as a sterilizing one.

Ionizing radiation affects biosynthesis control of proteins in a cell. Such distortions of cell metabolic activities are related to the reveal of some radiobiological effects at cell level, i.e. suppression of immune-biological recognition (immunity) that protects an organism from penetration of foreign proteins. Mitigation of intercellular recognition that is responsible for suppression of immune-biological recognition may be achieved by irradiation. Thus, overcoming of tissues and organs incompatibility at transplantation is based on the mitigation of intercellular recognition. Such methodology is practically applicable, when kidney, liver and other tissues and organs are transplanted.

Wide application of examined radiation-biological technologies in agriculture and in other industries of Ukraine lacks for special installations.

Control points to chapter 12:

1. The concept of radiobiological technology.
2. Irradiation of crop seeds before sowing to increase its germination, development and productivity.
3. Irradiation of crop seeds and plants to obtain new varieties.
4. The concept of a “critical dose”.
5. Biological essence of radiation biotechnology to overcome tissue incompatibility and to stimulate its accretion at vegetative inoculations of plants.
6. Radiation technology of prevention of tubers, root crops and bulbs against germination at storage.
7. Storage terms prolongation of berries, fruits and vegetables using ionizing radiation.
8. Radiation preservation of plant products, fruits and animal products.
9. Advantages of the radiation preservation of products in comparison with traditional methods.
10. Biotechnology of radiation pest control.
11. Radiation disinfestations of plant and animal products.
12. Application of radiation technologies for forages treatment.
13. Application of ionizing radiation in food-processing industry.
14. Radiobiological technologies in medicine.
15. The essence of radiation therapy of tumor treatment in humans.
16. Advantages of radiation-induced sterilization of materials in medicine in comparison with traditional methods.

13. ISOTOPIC INDICATORS METHOD IN BIOLOGY AND ECOLOGY

Using method of isotopic indicators, or, as it is also called, the method of labeled atoms is one of the ways to make practical use of the achievements of nuclear physics in various fields of science and goods production. Such method is widely used in biology, medicine, and ecology.

13.1. Tagged atoms

The tagged atoms are isotopes (a radioactive isotope) that have the mass, differing from the mass of the atoms of the main isotope of the element. This can be used as a mark (indicator) in studying the various processes involving distribution, displacement and transformation of substances in complex systems, including in living organisms.

As a label, the isotopic indicator usually uses radioactive isotopes. However, in some cases (will be discussed later); stable isotopes may be also used. When using radioactive isotopes, the biological effect of their ionizing radiation may be of particular importance. Therefore, the method of isotopic indicators is based on two main suggestions:

- ➢ the chemical properties of different isotopes of one element are practically the same, so that their behavior in the investigated processes does not differ from the behavior of other atoms of the same element;
- ➢ radioactive isotopes in quantities that are used as tagged (labeled atoms) do not cause biological effects on living organisms during the period of research.

It is believed that the method of isotopic indicators does not directly related to the radiobiology. And generally speaking, that is true. However, the fact is that this method, like the science of radiobiology as well, appeared due to the discovery of the radioactivity phenomena, radioactive isotopes, which are much more often than stable, are used as a label. The Hungarian radiochemist György Hevesi, together with the German chemist F. Panet developed the radioactive tracers to study chemical processes such as in the metabolism of animals. For this discovery they were awarded the Nobel Prize in Chemistry in 1943. Moreover, the method was first applied in biological experiments.

The prehistory of this discovery, so to speak, the first use of isotope indicators in practice is interesting and instructive.

In 1911, a 26-year-old student from Hungary, G. Hevesi, was working with radioactive materials in Manchester, UK. Because of poverty he lived in a student dormitory and had everyday meals in a students' dining room. Over time, he began to suspect that someone, among those who prepared food were conscienceless persons, since they used uneaten remains, which, sometimes, judging by the taste, were quite old. To test the hypothesis he added to his uneaten dishes a small amount of radioactive material. A day later, when a similar dish was served, he took a sample and, using a Geiger counter, confirmed his guess – the food was radioactive.


G. Hevesi
(1885–1966)

It is unknown how this story ended up for the cook, but two years later the scientific community learned about a new, unique method of research.

Since then, the science of how the ionizing radiation affects living organisms and the doctrine of the use of radioactive isotopes in biological research go in parallel. It is no coincidence that many authors, when considering the problem of the practical use of the achievements of nuclear physics and radiobiology, along with radiation and biological technologies as an independent direction or separate approach, differentiate the use of the method of isotopic indicators in research and applied work in the field of medicine, biology, and agricultural sciences. That is why it is appropriate to include a section on this method in the radiobiology manual. Moreover, the radiobiology as a discipline in higher educational institutions of the agrarian profile came precisely in the same time as the course "The Use of Isotopes in Agriculture". This happened in the middle of the last century. Due to this course, one of the authors of the textbook became a radiobiologist.

Of course, the use of the method of isotopic indicators is not limited to the interests of radiobiology and even biology in general. It is difficult to name the direction in the natural sciences and the branch of the national economy, in which it would not be used today. This is the medical and pharmaceutical industry, chemistry and chemical industry, metallurgy, material science, physics, geology, archaeology. The method gained considerable popularity in soil science, physiology of plants, plant cultivation when evaluating the physical properties of soil and its reserves of moisture and nutrients, studying the interactions of soil and fertilizers, processes of nutrients assimilation by plants from the soil and fertilizers, the foliar uptake of nutrients by plants, physiologically active substances to explore how such substances affect the plant organism when using pesticides, studying the metabolic processes, particular photosynthesis. The method makes it possible to study the most important properties of field and fruit crops – growth and development, the peculiarities of individual processes of exchange, resistance to various unfavorable environmental factors, and the formation of its productivity.

The method of isotopic indicators allows to investigate the biochemical and physiological processes occurring in the body of animals and humans, the role of certain substances in the metabolism, analyzes fodder and food on the content of toxic substances, small quantities of which are difficult or even impossible to determine by other methods.

By applying labeled atoms it makes possible to examine the migration of animals in the range from the movement of certain industrial fish species in the oceans to the assessment of fish stocks in local waters, the migration of birds and their migration paths, the behavior of bee and ants, pest insects of agricultural crops and organisms transmitting animal and human diseases.

The sensitivity of the isotope indicator method, especially the use of radioactive isotopes, is extremely high. It is many times greater than the sensitivity of chemical and physical methods. So, if the latter allow one molecule to be found among 10^6–10^7 molecules of matter, then the molecule of the radioactive isotope can be determined among 10^{20} molecules. Thanks to the method of labeled atoms we were able to solve many problems that were fundamentally impossible to solve by using other approaches. Due to the extremely high sensitivity of modern radiometric equipment, a week after the accident at the Fukushima NPP, which took place on March 11, 2011, radioactive cesium "of Japanese origin" was discovered over Ukraine.

13.2. Radioactive and stable isotopes

The following radioactive isotopes are most commonly used in biological and environmental studies (in parentheses, the type of radiation and half-life is $T_{0.5}$: ^{3}H (β-, 12.26 years), ^{14}C (β-, 5730 years, ^{18}F (γ-, 109, 8 minutes), ^{22}Na (γ-, 2.64 years), ^{32}P (β-, 14.3 days), ^{35}S (β-, 87 days), ^{42}K (β-, γ-, 12.5 hours), ^{45}Ca

(β-, 152 days), ^{59}Fe (β-, γ-, 45.1 days), ^{58}C0 (β-γ-, 70.8 days), ^{65}Zn (γ-, β-, 250 days), ^{86}Rb (β -, γ-, 19.5 days), ^{89}Sr (β-, 50.5 days), ^{125}I (γ-, 60 days) and ^{131}I (γ-, 8 days), ^{134}Cs (γ-, β-, 2, 06), etc. Among the well-known man-made 1880 radioactive isotopes, it is possible to choose one nearly for any element that can be used for specific studies. At the same time in order to reduce the risk of radioactive contamination of the environment, if possible, the isotopes with a relatively small half-life period ($T_{0,5}$) should be used. So, instead of ^{90}Sr ($T_{0.5}$ = 29 years), the ^{89}Sr should be used, and instead of ^{137}Cs ($T_{0,5}$ = 30 years) – ^{134}Cs.

However, in some cases, the use of radioactive isotopes is problematic.

1. Short isotope $T_{0.5}$, which does not allow research. Thus, among artificial radioactive nitrogen isotopes, the longest half-life has ^{13}N ($T_{0.5}$) only 10 minutes. This means that in an hour, that is, after 6 half-life periods, the isotope will be problematic to detect in the environment.

2. Lack of facilities (specially equipped laboratories) for working with radioactive substances.

In such a case, the stable isotopes such as: ^{2}H, ^{13}C, ^{15}N, ^{18}O etc. can be used. For the most part ^{15}N isotope is one of the most important nutrient elements.

In some cases it is impossible to use a certain isotope of any kind. In such a case its chemical analogue can be used. Thus, $T_{0,5}$ artificial potassium isotope ^{42}K makes 12,5 hours. So, for long-term studies on the behavior of this element such isotope does not fit. In this situation the solution is to use its closest chemical analog ^{86}Rb with a longer half-life period of $T_{0.5}$, which usually occurs in the nature as an isomorphic admixture in potassium. It is assumed that inert rubidium (showing similar effect on living organisms, in any case at very low quantities, unlike another close chemical analogue of sodium) behaves similarly to potassium.

Methods of chemical and physical analysis, as a rule, give only general information about the number of elements per unit mass of the organ, tissue, any specimen. The method of isotopic indicators allows us to trace the path of a particular element introduced by one way or another in the organism. It allows observing its flow, transport, assimilation, accumulation in specific organs, and transformation in the course of metabolism. Therefore, nowadays, the method of isotope indicators becomes one of the major in biological research.

13.3. Labeled compounds

The so-called isotope raw material – a substance consisting of a pure isotope – is obtained through successive complex operations called "isotope separation", by using special devices – isotopic separators. The stable isotopes are usually obtained by using such technique. The radioactive isotopes are either obtained by irradiation of non-radioactive substances in atomic reactors and accelerators of charged particles (similarly to ^{60}Co for irradiation installations and devices, as briefly described in the previous section), or by chemical separation from a mixture of nuclear fuel waste (in analogy with ^{137}Cs).

Labeled compounds are chemicals in which the atoms of one element, sometimes several ones, have an isotopic composition that is different from the natural one. The labeled compounds are obtained using three basic methods: chemical synthesis, isotope exchange (sometimes they are called under the general name – the chemical pathway) and biological synthesis (biological pathway).

Chemical synthesis, as a rule, is carried out by using conventional methods of preparative chemistry. However, instead of the usual element, the desired isotope is included at a certain stage of synthesis in the composition of the reaction components.

Isotope exchange is a chemical process that involves the redistribution of isotopes of an element between the reactants. In this exchange one isotope of an element is replaced by another in the molecule of a substance without changing their elemental composition. For example:

$$^{22}\mathrm{NaCl} + \mathrm{KOH} = {}^{22}\mathrm{NaOH} + \mathrm{KCl}$$

Labeled macromolecular compounds of biological origin, such as nucleic acids and individual nucleotides, proteins and some amino acids, cyclic compounds, hormones, vitamins and others are usually obtained by cultivating various organisms in environments containing the isotope or by entering an isotope into the organism by any other method with subsequent preparation of these compounds. This procedure, however, is applied to compounds, for which chemical synthesis is complicated or impossible at all, and which do not always enter the isotope exchange reaction.

This method does not always allow obtaining a labeled compound with a sufficiently high amount of an isotope (high specific radioactivity); however, rather often this is the only pathway to obtain a labeled compound of biological origin.

In some cases, the researcher may receive the labeled compounds in the ordinary radiological laboratory. So, when studying the physiology of mineral nutrients assimilation by plants it is often necessary to have labeled fertilizers or individual labeled salts. The basic requirements for their quality, as against any labeled compound, are: the isotope indicator must be in the same chemical form as the study element in the composition of fertilizers; it must be uniformly distributed throughout the fertilizers mass; the quantity of added isotope indicator should be sufficient to determine the its amount by available measuring devices, but not to cause biases in biological processes.

There are two main pathways of obtaining labeled fertilizers. The first one involves the entering of the label into fertilizer in the process of its manufacturing. For example, a solution containing radioactive calcium phosphate $Ca_3(^{32}PO_4)_2$, that is the non-radioactive salt and is the main component of naturally occurring phosphates (phosphorite and apatite), is added to sulfuric acid, which is treated with ordinary simple superphosphate, or phosphoric acid when double superphosphate is produced.

Labeled nitrogen and potassium fertilizers can be obtained in a similar way during its production process. Depending on the chemical basis of the fertilizer, different compounds are exist, e.g. $(^{15}NH_4)_2SO_4$, $^{15}NH_4Cl$, $^{86}RbCl$, $^{86}Rb_2SO_4$, or their varieties depending on the place of the added label in the molecule – $^{15}NH_4NO_3$, $NH_4{}^{15}NO_3$, $^{15}NH_4{}^{15}NO_3$. Such method of getting labeled fertilizers is considered as probably the best, since the inclusion of the isotope in the technological process of fertilizer production makes it possible to achieve a uniform distribution of the label compound within its mass. Such approach is quite expensive, since it requires the creation of a special technological line in the factory or its reproduction under conditions of an experimental laboratory.

The second method is much simpler and, therefore, it is used more often in experiments. The labeled compound can be obtained by mixing of a solution of radioactive salt with an aqueous suspension of the fertilizer under laboratory conditions. After that, the suspension is dried to the initial moisture content of the fertilizer. This method is not perfect, but quite suitable, provided that a uniform distribution of the label is achieved throughout the mass of fertilizer. If the fertilizer is represented by simple salt (for example, ammonium nitrate, potassium chloride) and mixed with the same labeled salt, it is possible to obtain labeled fertilizers that are more or less the same quality as those produced by the first method.

According to similar schemes, the label may be incorporated into other substances that are used as a nutrient substrate, individual components of the diet or other components of the trophic chains.

The technology for the production of labeled liquid solutions and environments is even simpler. The procedure is as follows: the part of the substance, that must have a specific label, is replaced by a similar substance containing the isotope. For example, a portion of the labeled salt that is a part of its composition is added to the liquid nutrient mixture.

13.4. Indicative dose

A very important step in the production of a labeled compound is the choice of the indicator dose – the quantitative content in the substance of the radioactive isotope. On the one hand, it should be high enough to ensure accuracy in assessing the participation in the metabolism of the test element, and on the other hand, it should be low enough to avoid irradiation. It should be kept in mind that not only the inhibitory dose of radiation, but also the stimulating dose can alter the real picture of the behavior of the entering and transformation of the labeled substance. The possible impact of radiation on the experimenter and the radioactive contamination of the environment should be avoided. This is especially important when field experiments, both with plants and animals are involved.

Several important things, such as the purpose of the experiment, the conditions for its implementation, the specificity of the isotope and the compound in which it is included, the duration of the label entering into system, the radiosensitivity of the object of research, the capabilities of the measuring instruments, etc. should be considered.

In experiments with plants, the prognostic intervals of indicative doses, as a rule, is in the range of 10^3–10^4 Bq/l (kg) of nutrient solution, medium or soil. The indicative doses for studies with mammals (considering their higher radiosensitivity and metabolic rate, etc), as a rule, are approximately one order lower.

The upper limit of the indicator doses in order to increase the sensitivity of the method for short-term experiments lasting for hours-days is shifted towards higher activity. In the case of experiments lasting months-years, for example, when studying the biomass increase of plants during the vegetative period or migration pathways of animals, the upper limit on the contrary is shifted towards the lower activity.

When radioactive isotopes are used for diagnostic purposes – the identification of some human diseases, the indicator doses are established in each particular case, but rarely when they exceed 10^4 Bq/l. In this case of particular importance of the labeled substance there are such properties, as its rate of elimination from the body (its half-life elimination) and the half-life of the isotope. It is clear that the smaller these values, the lower the dose of radiation should be received by the patient.

In general, estimating the indicator dose by calculation is not an easy task and can only be done approximately. Therefore, it is necessary to conducting preliminary control experiments that can help to determine the required amount of radioactive isotope in each case, and which will provide optimal conditions for conducting research both in terms of obtaining reliable data and guaranteeing radiation safety of the experimenter and probability of radioactive contamination of the environment.

When working with stable isotopes, the procedure of selecting the indicator dose is greatly simplified. The sensitivity of the quantitative determination of the isotope seems to be the main thing to keep in mind.

13.5. The main ways of using isotopic indicators in plant research

Generally, the method of isotopic indicators in plant biology allows solving two problems: the study of transport and the distribution of certain elements and substances within the plant and the study of their role in the metabolism. In animal biology these issues, however, are considered to be the most important. Meanwhile, such methods, even if formulated in the most general terms, cover virtually all possible ways of using the method in the context of experimental biology: transport, transformation, utilization, deposition of nutrients and certain substances when its enter the plants through the roots and leaves; study of the spatial distribution of individual elements and substances in the plant; studying the influence of various types of plant nutrients on the exchange of certain substances; the study of the participation of individual compounds in the exchange processes; estimation of the substances movement rate within the plant and many others.

It should be emphasized that the labeled substance after being entered into a plant is involved in a metabolic processes and various chemical transformations of such substances may take place. Undoubtedly, the kinetics of the entering and distribution of such a substance largely depends on the form in which it is entered into the plant. When such substances are included in a metabolic exchange various interactions and transformations can occur, as a result of which the substances are "overwritten", that is, the label – the radioactive isotope may fall into a completely different form of compounds. In order to identify the chemical form and the composition of the compound to which labeled element is included, there is a need to combine the method of isotopic indicators with other physiological, biochemical, cytochemical methods and approaches of preparative separation technique and analysis of a substance mixture.

13.5.1. Investigation of transport and distribution of plant elements

Each method is a logical chain of specific techniques that need to be carried out when setting up and conducting an experiment. For example, we can consider the classical scheme of conducting an experiment on the study of the distribution of a labeled element in a plant, which was proposed by one of the classics of the method V.V. Rachinsky (Fig. 93).

The experiment begins by growing the plant in a soil, sand or water culture to a certain age or phase of development, according to the formulated aim. After this stage /period is achieved, a solution of the labeled compound with a specific activity or concentration is prepared. Often, a labeled element is incorporated into the plant as a part of any compound that entered the plant through the root system. If a plant is grown on soil or sand culture, it can be done by watering of the substrate with a solution containing the labeled substance or by supplying the substance through the drainage tube. In the case of soil culture, more even distribution of the solution may be achieved by making evenly distributed through vertical holes. An evenly distributed labeled compound in a water culture is easier to achieve. Sometimes the labeled compound is incorporated into the substrate even before sowing the plants. In this case, the even distribution of solution within a vessel is easy to attain.

The isotope may be entered into a plant by two methods: by spraying using the sprayer or by wetting the surface of the leaves. If leaves are used for analyses, the radioactive substances should be removed from the surface by washing them with water and solutions of unlabeled salts, in the form of which a label was incorporated.

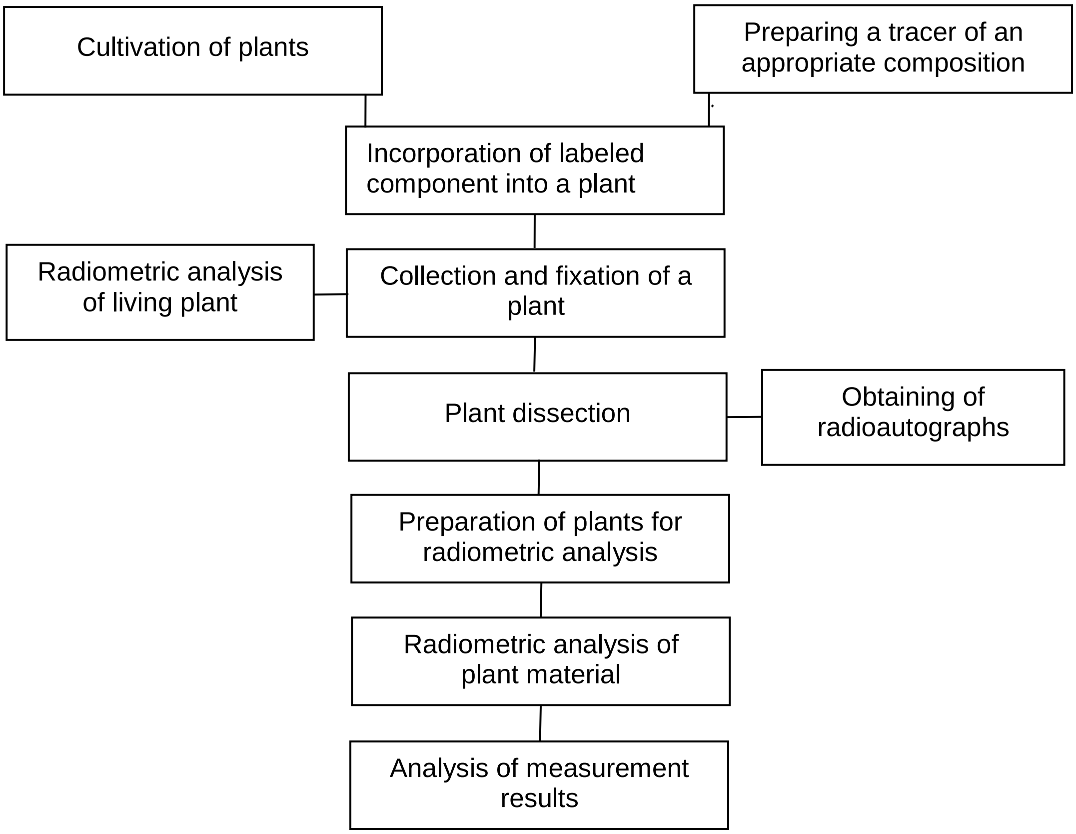

Fig. 93. The design of experiment for studying the distribution of a radioactive element in a plant.

There are other ways of entering a label into a plant. One of such method is to inject a solution of an isotope into a conducting system of plant by using a medical syringe. In some cases a solution of an isotope may be absorbed by a “strip” of a leaf up which solution is drawn by capillary action. The “strip” is obtained by cutting off the lateral parts of the plate, and a “strip” remaining with an average vein ("a wick"), are immersed in a test tube with an isotope; absorption of the solution with an isotope takes place through a cut of a petiole or stump of the lateral stem; application of a solution with an isotope to a growth point of a plant (the apex).

When working with radioactive isotopes for which the above scheme is developed, the method involves life-time study of transport and distribution of the labeled compound in the plant. For this purpose, remote detectors of radioactivity are used on the basis of small-sized gas–discharge counters connected to the radiometric apparatus. By using such devices it is possible to register the exact time when the labeled substance is entering the organ, to estimate the speed of its movement within the stem and leaf, and on the level of radioactivity will determine the location point of the label.

It is clear that in this way it is only possible to approximate the nature of the isotope movement within the plant, and even more to quantify its distribution. When used skillfully, the method can provide valuable and sometimes very unique information. This method is most effectively used in experiments with large plants – sunflower, corn, grapes, fruit crops. In this case, the plant can be fixed with several sensors and with a fairly high accuracy within its ontogenesis it makes possible to study the processes of transport and accumulation of the labeled compound in different organs.

To obtain a more complete picture of the distribution of a labeled element within a plant or within a specific plant part, the method of radioautography (will be discussed later) can be used. However, the most accurate quantitative picture of movement and localization the labeled element within the plant can be obtained by using radiometric analysis of individual parts and organs of the plant. To do this, the whole plant or specific plant part/organ are fixed (in fact they are killed) at certain stages of development. This is a very responsible operation, which should be performed as fast as possible to prevent the re-distribution of the label after the completion of the experiment, i.e. the cease of the metabolism.

The best fixation method is the immersion of plants or their specific organs / tissues into liquid nitrogen at a temperature of –196°C that provides almost instantaneous ceasing of metabolism. The thermal fixation is used, i.e. plant is warming up in a thermostat at a temperature of 105°C following immersion in ethyl alcohol, formalin, a mixture of alcohol with acetic acid and other media. Although all these methods are less effective compared with the first one and what is more important that, the distribution pattern of the labeled compound may vary. To minimize these shortcomings, the plants are dissected into separate organs, milled and dried as soon as possible in the thermostat. Afterwards the specimen is ground to a powder-like state and radioactivity is measured. Knowledge of the radioactivity of the labeled compound administrated into the plant makes it possible, when comparing, to calculate its amount per organ or per unit weight of the plant.

13.5.2. Study of the role of certain substances in the metabolism of plants

By using approaches outlined above it is possible to greatly expand the range issues to be solved if the involvement of the labeled compound in the process of metabolism is taken into consideration. By isolating specific substances from certain organs of plants by methods of preparative biochemistry and by determining their level of radioactivity of an isotope, it is possible to trace the metabolic transformations of one or another compound. By using radioactive isotopes in a way described above the unique knowledge about the pathways and exchange of phosphate, calcium, sulfur in a plant, the physiological role of many trace elements, fundamental data on the transformation of certain substances were obtained.

The use of the method of isotopic indicators made it possible to study the role of carbon in photosynthesis more profoundly. The only use of a labeled carbon dioxide $^{14}CO_2$ made it possible to look into the mystery of green leaf, which converts such simple substance together with water into numerous diverse complex organic compounds. This path of biosynthesis is studied extensively by the prominent American biochemist and physiologist of plants, for which he received the Nobel Prize, known as the Reductive Carbon or Pentosophosphate pathway (Calvin Cycle).

V.V. Rachinsky gives the classical scheme of an experiment on the study of the chemical transformation of carbon in photosynthesis as a typical example of solving the problem of this type (Fig. 94).

According to such scheme the prepared for the experiment the plant, together with the vessel, is placed in a chamber with labeled carbon dioxide for a certain period of time. The labeled carbon dioxide is usually obtained by addition of 30% chloric acid in a test tube with slightly wetted labeled barium carbonate ($Ba^{14}CO_3$). A small camera can also be constricted for a separate leaf. Of course, the camera should be airtight (impermeable). In short-term studies on photosynthesis, leaves, that cut off from the plant and, petioles which are immersed in test tubes with water and nutrient solution can be used. In some cases the leaves can be immersed directly in the solution with labeled carbonate. After exposure, plants are fixed and a group separation (fractionation) of carbon-containing substances should be done. The last make it possible to separate, for example, amino acids, organic acids, proteins, carbohydrates, lipids and other compounds. The next step is partitioning of obtained substances into individual chemical compounds and determination of their radioactivity by using methods of analytical biochemistry – chromatography, electrophoresis and others.

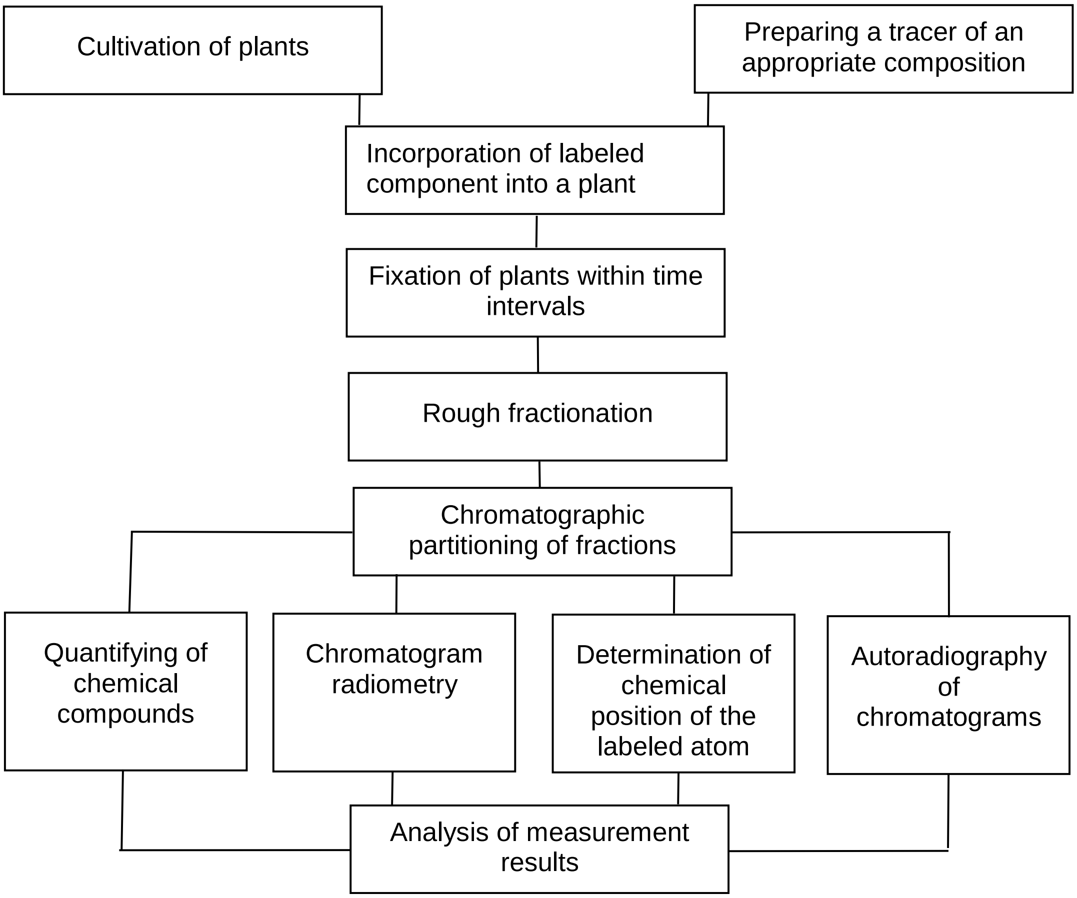

Fig. 94. The design of experiment for studying the pathways of carbon during photosynthesis.

If paper or thin-layer chromatograms are obtained, electrophoregrams can be made from the radioautograph (photo reprints), which literally reflects the picture of the distribution of the radioactive labeled element in the composition of various compounds, that is, in which compounds carbon is included. Its radiometric analysis enables to quantify the carbon distribution dynamics. Such approaches allowed to study and describe the pathways of fixation and transformation of carbon during photosynthesis. Such techniques also allow solving issues related to the study of the role of metabolism and more complex compounds: amino acids, enzymes, physiologically active substances, and even nucleic acids.

13.6. Radioactive isotopes in vegetation and field studies

In order to study how nutrients enter the plant and move within it, the conventional approaches of vegetative experiments conducting are also used. At the same time it is always necessary to take some precautionary measures aiming to prevent the spread of radioactive contamination, which, in the case of vegetative experiment, and even more in the field experiment, is much more difficult to perform than in the laboratory.

In Fig. 95, as an example, the scheme of a two-component vegetative vessel is shown, which is used to study the supply of nutrients to various organs of peanut plants. Root plants are placed in a 15-liter vessel, and plant's fruiting organs that grow up in the soil are placed in a separate cup. Each plant zone can receive nutrients individually. Under such conditions, it is easy to trace the pathways of any labeled element introduced into the plant in a certain way, including through the above-growing plant's part, its absorption, movement and distribution within the roots, leaves and fruits. By using such experiments with radioactive isotopes the higher efficiency of plant nutrition through leaves has been proved, compared with other types of nutrition elements such as phosphorus, potassium, sulfur, which were readily absorbed through the leaves and moved on to other organs in the phloem. At the same time it was found that calcium, magnesium, iron and copper are readily absorbed by the leaves, but move from them slowly and only at short distances.

The design of such an installation virtually eliminates the probability of the release of radioactive substances into the environment.

The characteristics of absorption of plant nutrients from fertilizers using the method of isotopic indicators can be well studied in field experiments, i.e. in conditions that are rather similar to those we have in the nature. The biggest obstacle in this case, is to add labeled fertilizers to the soil. In experiments with annual plants labeled fertilizer, as usually, can be applied before sowing (planting) thoroughly mixed with the soil. In experiments with perennials plants or when applying labeled fertilizers under the vegetative period for annual plants, for example, during the formation of productive organs, two methods of application – superficial and deep placement can be recommended.

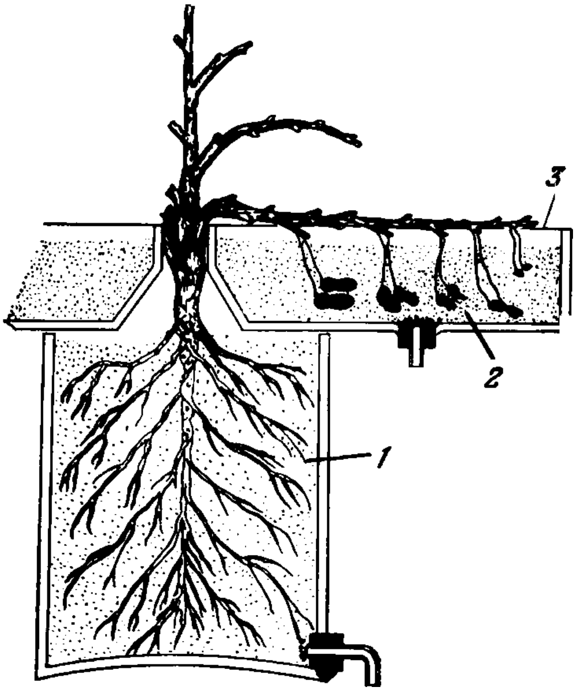

Fig. 95. The design of a vegetative vessel for the study of the absorption of radioactive isotopes separately from the roots and fruits of peanuts (R.V. Beldzo et al., 1997): 1 – a vessel with a nutrient medium for the roots, 2 – a vessel with a nutrient medium for fruits, 3 – a metal net which prevents the contact of above-ground organs with labeled nutrient media for fruits.

Methods of applying labeled fertilizers in the field under grape plants, described by American researcher A. Ulrich, are considered to be a typical one. According to this method when fertilizers are applied superficially around the grapevine a square or round bed or a hole with a side size of 120 cm in diameter should be arranged. First, 40 liters of water are added to the bed, and then 20 liters of water dissolved in labeled fertilizer are added in the same way. After the solution soaks into the soil, another 100 liters of water are added to get it more evenly distributed within the zone of the root system.

At deep placement of labeled fertilizers the holes are drilled with a diameter of 4 cm and a depth of 40 cm in each corner of a square bed or well (if the hole is round, the labeled fertilizers are placed in the places of intersection with a circle of two mutually perpendicular diameters). The entire dose of fertilizer is dissolved in 600 ml of water and distributed equally in four holes around the vine tree. Immediately after that, 150 liters of water should be poured to each vine tree.

The described methods are appropriate for applying labeled fertilizers to fruit crops, vegetative annual plants, and others, when species specificity, phase of development or age etc are taken into account. Sometimes, for the deep application of labeled fertilizers under vegetative plants special probes that operate on the principle of a syringe are used. Such a probe should be thin enough and sharpened at the end of the steel tube to avoid the damage of the root system. The diameter of such tube is usually about 10 mm and the thickness, which ensures fertilizer to be delivered to the required depth. The tube is equipped with a piston or other mechanism for injection of the solution.

As we already mentioned, when conducting field experiments with radioactive isotopes it is very important to observe radiation safety measures to prevent contamination of the site. For this reason it is advised to use the short- and medium long half-lived isotopes and smallest their amounts when conducting field experiments.

On the other hand, field or greenhouse experiments with isotopes contrary to laboratory studies, make it possible to experiment with dozens, hundreds or thousands of plants, placing labeled compounds in different stages of their development, conducting sampling and assessing radioactivity throughout the growing season. In such a case one can study the characteristics of the dynamics of assimilation, distribution and accumulation of specific compounds in different organs in the course of ontogenesis and to determine the influence of a variety of factors on these processes, including the effects of ionizing radiation.

By conducting greenhouse and field studies with labeled compounds the effectiveness of using different nutrients of fertilizers, depending on their form, method of application, type of soil, species characteristics of plants was evaluated. Such approaches also allowed to establish the actual mobility rates of individual nutrients, physiologically active substances and other compounds depending on the pathways by which they entered the plant and to figure out the characteristics of nutrients absorption by plants when they are taken up from different types of fertilizers.

Of course, the transformations of various substances in the process of metabolism, which were described earlier, may be also studied in greenhouse and field studies by using radioactive isotopes. As we already noted, the results obtained in such experiments are supposed to be more trustworthy.

13.7. Radioautography

An important advantage of radioactive isotopes, compared to stable ones, is their ability to leave a footprint on photographic materials, similarly to the visible light. Namely such quality helped A. Becquerel to discover the phenomenon of natural radioactivity of uranium. Such ability is also widely used to study the localization of labeled compounds in specific organs using the method of radioautography.

Radioautography, or autodiagnosis, is a method of studying the distribution of radioactive substances in the investigated object, by superimposing on this subject photographic materials that are sensitive to ionizing radiation. The radioactive substances incorporated in the object, in fact as if they are "taking pictures themselves", giving actually the name of the method.

The point of the photographic method of radioactivity detection is that ionizing radiation, when passing through a photo-emulsion, interacts with silver halides microcrystals – "grains" that are part of photo-emulsion composition. In this case, silver ions are restored to neutral atoms, resulting in the so-called "hidden" image. The dark spots are appeared on the layer of photo-emulsion on the points where ionizing radiation appeared after its detection and fixation. Areas that received higher number of particles or quanta will be darker than those that received less.

A negative image is formed on ordinary photographic materials due to action of ionizing radiation similarly to a light photography. If a positive imprint is obtained on the basis of negative image the brightest spots will be seen that correspond to the highest intensity of radiation, less light – lower, and dark – the radiation is absence. Thus, the intensity of radiation and, accordingly, the amount of radioactive substance contained in any section of investigated object can be recognized depending on the degree of illumination of photographic materials.

Radioautograph, or autoradiogram, is a photographic image of the radioactive substances distribution within the investigated object, obtained by the method of radioautography.

The method of radioautography has many benefits that make it a unique one for spatial-quantitative analysis, which is widely used in many areas of the natural sciences, including applied ones, and especially in biology and medicine.

The main advantages of the method of radioautography are:

- ➢ the possibility of obtaining a spatial picture of the distribution of a radioactive substance, including a specially introduced radioactive isotope, in the specimen of a study;
- ➢ the high sensitivity of the method based on the properties of specific photographic materials to record individual particles and quanta and to make it possible to detect such small amounts of radioactive substances in the specimen which can not be detected by using ordinary radioactivity counters;

- the possibility to quantify the accumulated substances in different parts of the investigated object;
- the possibility to estimate / to quantify the radioactivity in very small specimen, which may be as small as the size of small silver halide crystals (ten hundredths of a micrometer);
- the possibility to obtain a document that captures all the results of the experiment – the radioautograph.

As a "recording" medium in a radioautography the photographic emulsions are usually used. Although any photographic material in which the ionizing particles or quanta determine the color or chroma (brightness) and which has a high enough sensitivity to the radiation change may be used. However, many studies have shown that the most convenient material is photographic emulsion. Such emulsions have a number of advantages compared to other similar materials, which make them irreplaceable. The main benefit is its capability to continuously record the radioactive decays of atoms so that it allows estimating the total number of decays during the period when the incorporated compound is acting. This becomes possible because the photographic emulsions keep their physical properties constant for weeks and months. This allows in turn dramatically reduce the amount of radioactive substance that is incorporated into a living organism, which in some cases is crucial. Another essential advantage of an emulsion is its ability to locate radioactive decays in space and make it possible to calculate the number of decays. One can not ignore that the emulsion is relatively cheap and easily available material, and physical properties can be easily adjusted by changing the size of silver halides microcrystals (grains).

There are two main types of radioautographs – macroradioautography and microradioautography. The use of both types is based on the principle of contact radioautography – the method according to which the object of study is in direct contact with the photomaterial, while e.g. nuclear physics usually uses the track radioautography.

13.7.1. Macroradioautography

Macroradioautography deals with large objects – whole plants, individual organs – leaves, flowers, fruits cuttings etc. In this case, a photographic film or photographic plate is applied to an even surface of the specimen and pressed with a press. After an exposure and development, the radioautograph is analyzed by means of passing light and comparing the density of the photographic material when it is getting dark.

To obtain a radioautogram a substance containing the radioactive isotope is incorporated in a plant, usually through the root system, together with the nutrient medium. To obtain a macroradioautograph the cuttings of individual leaves or other organs or the whole plant (after some time (hours-days), depending on the aim of study) are put on a filter paper, straighten in a way similar to when making a herbarium and covered with a filter paper. The prepared in such a way object is placed between two equal metal plates and placed in a press in a drying oven at a temperature of 80−85°C. After the object become completely dry it is covered by a film or photographic plate. This operation is performed in a photographic room equipped with a weak dark red or a special yellow-green light on. The object covered again with a soft cloth and placed again under a press in a light-proof chamber or a special cassette. Be assured that the maximum possible contact is provided between the photo-emulsion and the plant (object).

Exposure time depends on many factors but is basically determined by the amount of radioactive substance entering the plant and as estimated experimentally may vary and usually takes weeks or a few months. After the development of a film, a macroradioautogram that characterizes the distribution of the incorporated radioactive isotope in the plant is obtained (Fig. 96). If necessary, a positive imprint on photographic paper or other material can be obtained from the negative image.

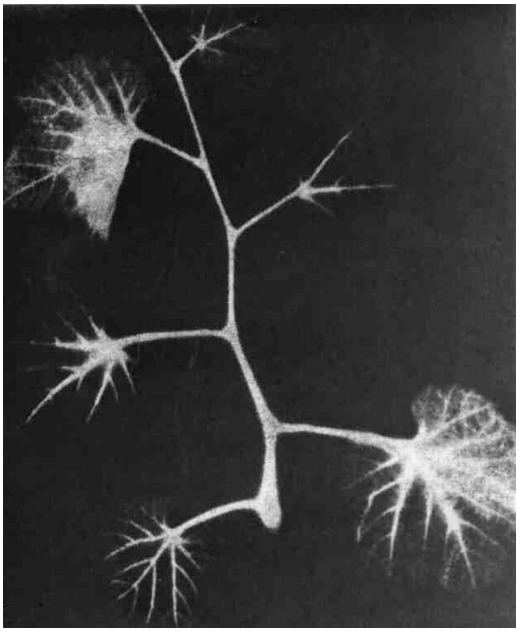

Fig. 96. Macroradioautogram of ^{32}P distribution in a grape plant when phosphate fertilizer is applied to the soil (negative image) (V.I. Kilianchuk et al., 1979).

In some cases it is necessary to get a macroradioautograph from a fresh, still “wet/growing” plant e.g. when working with short-lived isotopes. In this case, the specimen is laid with a waterproof lining made of a polymeric film and then placed on the surface of the photographic material. Otherwise the film can be wrapped. The important thing here is to prevent the plant moisture from being entered the photo-emulsion, especially in the place of its contact with the plant. This is because even a small amount of moisture can cause the diffusion of silver halides from the photographic layer and distort the picture of the radioautograph.

13.7.2. Microradioautography

The objects of microdiagnostics are the microscopic preparations – plant cuttings, smears, pressed preparations, etc. In this case, the molten liquid photo-emulsion is directly applied to the specimen and a solid layer adhering to the specimen when it is sealed is formed. After exposure and development, the radioautograph displaying the object is formed. Afterwards the radioautograph is examined under an optical or electronic microscope in the reflected or passing light, depending on the transparency of the object. The analysis is used to calculate traces in a photo-emulsion that formed by ionizing particles on the background of various tissue and cell structures.

The resolution of microradioautography is noticeably larger than that of macroradioautography. If macroradioautography may be obtained by using large microcrystals – grains of 0.2–0.5 microns in size (ordinary or X-ray films) as photographic materials, the microradioautography requires special fine-grained nuclear photo-emulsions with grains size of 0.01–0.02 μm.

The microradioautographs approach also requires fixed preparations of individual organs or tissues and cells of a plant in which the radioactive isotope is entered accordingly to generally accepted or special methods of cytology, histochemistry. The microradioautography is obtained by the application a photo-emulsion on a dried specimen, its exhibition and development. The dark spots (dots clusters) can be detected by using the microscope (Fig. 97). The size of such spots may be determined by means the size of the silver grains. The possibilities of radioautography method have not been utilized yet to its full potential. Obviously, the development of new photo materials, techniques and digital photography, new devices in combination with the new methodical approaches of analytical chemistry and biochemistry, cytology and histology will also expand the application radioautography method.

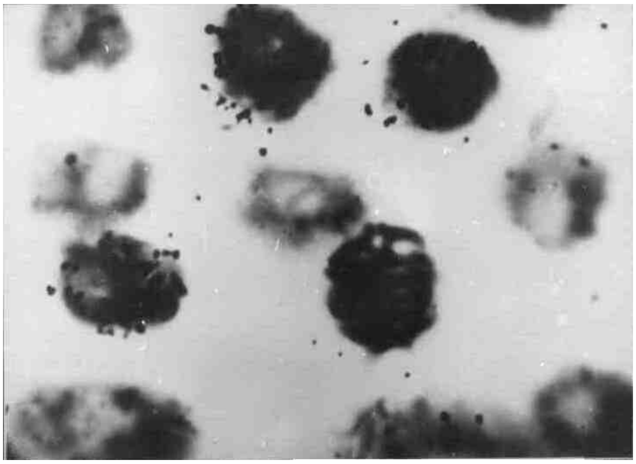

Fig. 97. Microradioautograph of labeled nuclei cells in the meristem of peas root when plants were growing in a nutrient medium with ^{3}H-thymidine; positive image, a magnitude 1350 times.

Generally, the method of radioautography allows not only to locate the labeled compound in a plant, tissue or cell, but also to estimate its quantity, since the amount of grains of the recovered silver emulsion is directly proportional to the intensity of incorporated radiation. A quantitative analysis of macroradioautographs may be done by using the ordinary methods of photometry. To analyze the microradioautograph i.e. the counting of the number of grains per unit area or per specific cell, may be done by using the macroradioautographs. In such a case the automated quantitative cytometric techniques are successfully used.

13.8. The application of stable isotopes

The use of the method of stable isotope tracers in biological and environmental studies as well as in many other areas is more limited in comparison with the method of radioactive isotopes due to its much lower sensitivity. However, the method of stable isotopes tracers can be used in the number of other areas, where the radioactive isotopes are used as indicators, although, as a rule, with lower accuracy.

The initial stages of techniques that use stable isotopes are practically the same as radioactive ones. The difference between those two methods is appearing only on the final stages of the quantitative analysis of the specimen. Such analysis is carried out by using special devices – mass spectrometers, intended for separation of atoms and molecules based on the difference in their mass.

A mass spectrometer generates multiple ions from the specimen under investigation, separates them according to their specific mass-to-charge ratio, and records the relative abundance of each ion type.

Among mentioned earlier stable isotopes the isotope of nitrogen ^{15}N is the one most widely used in biological studies. There are several general directions where this isotope is used:

- studying the rate of absorption of both free nitrogen and nitrogen, which is a part of various nitrogenous compounds, including fertilizers by plants;
- studying how atmospheric nitrogen is fixed in different species of plants;
- studying the rate of nitrogen compounds exchange.

^{15}N is widely used in the field of agrochemistry, soil science, physiology of plant nutrition, agroecology. By means of ^{15}N as a tracer the transformation of soil nitrogen and nitrogen of mineral fertilizers applied to soil, the mobilization and immobilization of soil nitrogen and the role of specific types of soil microorganisms in the processes of soil nitrogen transformation has been successfully studied. The use of ^{15}N as a tracer in experiments with plant nutrition and plant metabolism resulted in discovery of the nature of initial processes of nitrogen assimilation by plants, that allowed finding out the importance of interactions between nitrogen uptake, photosynthesis on the one hand and the supply of other mineral elements to plants on the other hand.

Using of ^{15}N isotope as a tracer when studying the nitrogen behavior in the nature has a number of advantages compared with commonly used chemical, biochemical, agrochemical methods. Still, at the moment, the use of ^{15}N method is unjustly limited. A well-known American specialist in the field of using this isotope R. McVickar believes that the main reason for this is the difficulty in determining the content of ^{15}N in any object, since there is a need to measure the ratio of molecular mass-to-charge ^{15}N and ^{14}N. Such measurements are expensive, complicated and require mentioned above mass spectrometers (Fig. 98**)**.

Is there any benefit of using stable isotops, particulary the isotop ^{15}N, compared with radioactive ones?

Fig. 98. Benchtop GC Time-of-Flight Mass Spectrometer Pegasus BT https://uk.leco-europe.com/product/pegasus_bt/

Yes, there is a benefit to using ^{15}N. It is well known that natural nitrogen consists of two stable isotopes: ^{14}N (99.63%) and ^{15}N (0.37%). Since living organisms do not show high selectivity with respect to assimilation of both isotopes, ^{15}N can be used as a tracer in compounds containing relatively high amount of this isotope – up to 60%. The degree of labeled compound enrichment with the isotope ^{15}N is characterized by the magnitude which is the difference (in the so-called "atomic percentages") between the ^{15}N content in such labeled compound and its content in the natural mixture of nitrogen isotopes. This value is called an excess of an atomic percentage of ^{15}N. So, if the content of ^{15}N in a labeled compound is 0.48%, then the “surplus” of atomic percent will be 0.48–0.37 = 0.11.

Mass spectrometry is an extremely accurate method that analyzes a mixture of isotopes in a gaseous state. For this, the test material is burned according to the well-known Kjeldahl method, which allows quantifying the nitrogen contained in organic and inorganic compounds. The ammonia produced from ammonium sulfate is then oxidized in vacuum by hypobromite (BrO^-) to free nitrogen. The lowest detectable value of atomic percent surplus in the sample is 0.01–0.02, which corresponds to approximately 0.1–0.2 mcg of ^{15}N in 1 ml of nitrogen under normal conditions. This is quite high precision.

Still, the sensitivity of isotopic indicators method, when stable isotopes are used, is far away from the sensitivity of the radioactive isotopes method. If the accuracy of the isotope content in the samples when stable isotopes are used is 10^{-4}–10^{-6}%, the radioactive isotopes method allows determining the isotope radiation when its content in the sample is in a range 10^{-11}–10^{-19}%, depending on the type of isotope. That is why the radioactive isotopes method is preferable when high accuracy of an element in the specimen is important. Unfortunately, in the case of nitrogen, such alternative does not exist.

Nevertheless, the short-lived ($T_{0.5}$ 10 min) radioactive isotope ^{13}N may be used in short-term experiments. One of the authors of this book in a short-term experiment (≈ 30 min.) showed that the rate of nitrogen movement within the plant stem, registered with the radioactive isotope, is twice as high as it is suggested earlier to be based on experiments with a stable isotope.

Surely, the experimental level of many biological disciplines has changed drastically over the past decades due to the widespread application of the isotopic indicators method. The use of such approach allowed to make a great advance in biological science and to gain the knowledge needed to get the understanding of the basic laws of life.

The labeled atom approaches have long been an effective tool for solving many important issues in radiobiology. The distortions of metabolic processes in radiation damage and radiation sickness, kinetics of cell’s pattern in the irradiated critical organs, mechanisms of various radio-modifying agents action, the course of post-radiation restoration processes and many others have been studied by using labeled atoms method.

It has to be noted, that even today many possible aspects of isotopic indicators method application are neither achieved nor even defined yet. Combination of such approach with other appropriate techniques and methods make them applicable in many other areas of research. So, the nuclear physics assured biologists and environmentalists with a unique and remarkable tool.

Control points to chapter 13:

1. The concept of labeled atoms. Stable and radioactive isotopes.
2. Two basic concepts on which the method of isotopic indicators is based.
3. Methods of obtaining of labeled compounds.
4. Concept of indicator dose.
5. The main pathways of using the method of labeled atoms in studies with plants.
6. The essence of radioautography method application and its advantages in comparison with application of the method of isotopic indicators.
7. The main reasons why the method of radioactive isotopes cannot be applied.
8. Application of ^{15}N isotope for the study of nitrogen exchange in plants.
9. Application of the method of isotopic indicators in ecology.

CONCLUSION

With the development of human civilizations the wide use of atomic energy in various branches of national economy, the application of ionizing radiation and radioactive isotopes in practice of domestic and world-wide agroindustrial production as well as in agricultural science increases. However, rapid development of atomic energy that is accompanied by the increase of mining and processing of uranium raw materials, operation of nuclear power plants, radiochemical processing of irradiated fuel, storage and disposal of radioactive wastes, nuclear explosives leads to increase of radiation background. The release of radionuclides into the environment under normal and accident-related operations of nuclear power facilities inevitably results in the formation of additional (above background) radiation doses. Therefore, the comprehensive estimation of the consequences of radioactive release into the environment is of primary importance.

However, special attention requires one of the main problems of radiobiology: prophylaxis and therapy of radiation damage of living organisms. These additional doses may be internal and to lesser extent external. It is considered that internal radiation in different radiological situations makes up considerable part of the total additional dose. The mechanisms by which the radioactive elements are incorporated into the biological system are basically the similar to those by which the plants and animals obtain their nutrients from the atmosphere, soil, water and foodstuffs. Therefore, the system of countermeasures that may decrease the intensity of radionuclide transfer via food chains and may reduce internal doses by limiting transfer of radioactive substances into a human body also requires a special attention. Breaking of the food chain at early stages is considered to be the most effective measure and must be fulfilled by the agriculturists of various specialties, i.e. agronomists, soil- chemists, soil scientists, specialists on plant pest control, horticulturists, vegetable- growers, veterinaries, cattle-breeders and others. Since agricultural products comprise the basic nutrition of the majority of the population, the behaviour of radionuclides in agricultural ecosystems are of primary importance.

At the same time there is a need to underline that responsibility for radiation safety of the country population is actually laid on the producers of plant and animal products, i.e. the workers of agricultural production. The scale and severity of the Chernobyl accident in 1986 that resulted in radioactive contamination of huge territories in Ukraine had not been foreseen and took most national authorities responsible for public health and emergency preparedness by surprise. Insufficient competence was also shown by most of the specialists of agriculture dealing with an accident of such scale and provided little help in decision-making concerning the choice and adoption of protective measures. There is no wonder, since the problem of radiobiological and radioecological education in the country at that time was not given appropriate attention and the level of radioecological knowledge among population in the whole and specialists was extremely unsatisfactory. Some steps were undertaken in this direction only after the accident. Thus, starting from 1987/88 academic year, the courses of radiobiology and radioecology during a few following years were introduced in many higher institutes and universities as well as on faculties of agrobiological specialties. To facilitate these efforts the Ukrainian textbook "Agricultural Radiobiology" was written by authors in 2003. However, some years ago courses of radiobiology and radioecology given in English were included into curricula of some universities that requires appropriate textbook.

Nowadays any well-educated person must know about the effect of ionizing radiation on a living organism; the ways of radioactive substances transfer to a human body and, finally, how to mitigate the possible consequences of radiation.

Therefore, this book may be useful not only for the future specialists of agriculture, but also for many other readers of different interests.

For lectures in radiobiology and radioecology the practical skills are required. Thus, following the curricula for radiobiology and radioecology the practical skills in dosimetry and radiometry are obligatory. Such practical training promotes acquisition of necessary practical skills connected with the estimation of radiation situation, determination of activity in environmental samples and agricultural products. This part of the discipline is only partly outlined in the theoretical course that is based on present book. As we mentioned above, radiobiology, in contrast to any other disciplines that are studied in agrarian and other institutes and universities, is close connected with many other natural sciences. The reading of radiobiology course requires knowledge of many other subjects, such as elementary bases of nuclear physics and physical chemistry, knowledge of biology, biochemistry and physiology, geneticists and selection, agricultural chemistry and soil sciences, i.e. pedology, agriculture and plant- growing, animal's feeding and hygiene, their medical treatment, technologies of processing of plant and animal products. Therefore, students become proficient with such disciplines that are thought to be better prepared for reading of radiobiology and radioecology courses. Authors suggest that the aim of this book is formulated in preface of the book, i.e. to provide the future specialists of agriculture as well other related fields with basic knowledge of general and agricultural radiobiology and radioecology. For this, the book provides reference list for those who want to increase their knowledge of such interesting and topical sciences as radiobiology and radioecology.

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CONTENT

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