Formation of Radiation Doses of Ukraine's Population in Areas Contaminated by Radionuclides After the Accident at the Chernobyl Nuclear Power Plant

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Abstract The paper describes the set of the indicators that led to the growing technogenic impact on natural ecosystems and biota due to the rapid increase of natural and artificial radionuclides in the environment. The study states that there is a need to create system to assess reliability of ecological systems and biota taking into account content of artificial pollutants as far as living conditions and peculiarities of radiation doses formation of population of contaminated areas of Ukraine changed drastically and contamination level of many foods exceeds acceptable levels even 35 years after the Chernobyl catastrophy. The biological objects have an extremely high reliability which far exceeds reliability of any technical system that can be shown through the definition of biosystems reliability are described. The new sensitivity indicator is offered—the factor of radiocapacity to assess the impact on the state of the plant ecosystem to radiation exposure. A new radioecological concept is described in the paper along with the specific mathematical modelling methods. The study presents the development and application of methodology to assess state of ecological systems of different types and levels during radiation damage based on the use of mathematical chamber models and reliability theory as well as the consideration and determination of negative impact of radionuclides on the state of ecological systems. Development of reliability model of radionuclide transport and substantiate application of proposed method to study distribution and redistribution

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of radionuclides in the environment and in assessing dose loads on biota, humans and environmental safety on the basis of developed modified mathematical chamber models of agroecosystems is described. Was shown that modern radioecology lacks methods and models suitable for assessing and forecasting of local ecosystems state for specific settlements of Ukraine. Therefore, was offered a method of operative creation of environmental safety model for some settlements with binding to concrete conditions of any settlement. Such model will allow to minimize scope and detail of monitoring and to predict critical situations in ecosystem under study. Chamber models of real ecosystems affected by the Chernobyl accident were developed and analyzed.

Keywords Radionuclides · Radiocapacity factor · Chamber models · Environmental safety · Ecological control

1 Introduction

Determining of distribution and redistribution ways of the main dose-forming radionuclide ^{137}Cs in the environment and ecological control of territories is an important task. As far as it determines state and dynamics of Chernobyl contamination of natural ecosystems. The radioecological situation that developed after the accident at the Chernobyl Nuclear Power Plant (ChNPP) radically changed living conditions and peculiarities of radiation doses formation of population of contaminated areas of Ukraine. Contamination level of many foods exceeds acceptable levels even 35 years after the Chernobyl disaster.

The aim of the chapter—development and application of methodology to assess state of ecological systems of different types and levels during radiation damage based on the use of mathematical chamber models and reliability theory; consideration and determination of negative impact of radionuclides on the state of ecological systems; development of reliability model of radionuclide transport and substantiate application of proposed method to study distribution and redistribution of radionuclides in the environment and in assessing dose loads on biota, humans and environmental safety on the basis of developed modified mathematical chamber models of agroecosystems.

The research methods—factual materials and literature data; own field research, dosimetric and radiation measurements of objects in selected ecological systems; mathematical modeling of the studied ecosystems.

2 Chamber Model Development of Radionuclides Migration in the Ecosystem

One of the most important and prior tasks of our time is to ensure population' livelihood, especially residents of areas located near nuclear power plants, their protection from radiation and nuclear accidents.

Radiation and environmental situation became especially acute after the Chornobyl catastrophe. The accident at the fourth unit of ChNPP led to need for comprehensive analysis and clarification of distribution, composition and amount of radioactive products emissions in time and space. Analysis of radiation consequences of such scale led not only to use of existing methods at that time, but also to development of new approaches to protect the population, as described in [1–13].

Estimation results of the total release of radioactive substances into the environment after the accident at the fourth unit of ChNPP are known. Knowing, determined the Specific activity of fission products was defined knowing changes dynamics in the temperature of nuclear fuel over time. Those radionuclides were released into the environment after the accident [14–18]. Peculiarity of the Chornobyl catastrophe is unevenness, contamination "spotting" of huge areas and living organisms.

Biological objects have an extremely high reliability which far exceeds reliability of any technical system. This follows primarily from the time of biological systems existence. It is much longer than time of trouble-free existence of technical systems. We can offer following as a definition of biosystems reliability: reliability is a fundamental property of biological objects, which determines their effective existence and functioning in randomly varying environmental conditions and over time [19, 20]. Measure of reliability is probability of systems failure, which can vary from 0 to 1.

It is proposed to use a sensitive indicator—the factor of radiocapacity to assess the impact on the state of the plant ecosystem of radiation exposure. This factor idea is basis of new radioecological concept. It should be noted that radio capacity of ecosystems is defined as limit of radionuclide deposition in ecosystem and its elements, above which there is suppression and death of ecosystem biota.

Chamber models of different types are used to describe ecological processes occurring in ecosystems. Method of chamber models is the simplest and adequate mathematical method for describing radioecological processes in ecosystems of different complexity [21–23].

Method of structuring ecological systems consists of four consecutive procedures: (1) development of chamber radioecological model of corresponding defined ecological system; (2) determination of its configuration (serial, combined or parallel); (3) determination of parameters and rates of radionuclide transition; (4) reliability calculation of structural elements and the ecological system as a whole by models.

Let's consider a simplified ecosystem "environment – biota" to analyze parameters used in radioecology (Fig. 1).

Method of chamber models in the simplest two-chamber form is used: "environment"—"biota" based on the application of the software product MAPLE-5 for theoretical analysis. Chambers contain stock of radionuclides $Y(x)$ and $Z(x)$ with

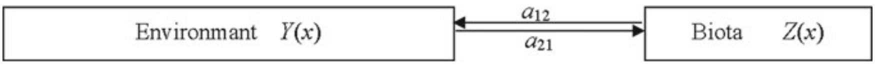

Fig. 1 Block scheme of two chambers ecosystem model

time—x; a_{12} is absorption rate of radionuclides, and a_{21} is rate of their outflow from biota into the environment. System of two differential equations is formed under given initial conditions: $Y(0) = 1$, $Z(0) = 0$. That is at the beginning of radioecological process the entire stock of radionuclides (let it be—^{137}Cs) is in the chamber "environment" for simplicity. Initial content of radionuclides in environment is taken as 1. Parameters a_{12} and a_{21} set rate of radionuclides transition from chamber to chamber and determine what proportion of the stock passes per unit time:

$$\frac{dy(x)}{dx} = a_{21}z(x) - a_{12}y(x); \ \frac{dz(x)}{dx} = a_{12}z(x) - a_{21}y(x). \tag{1}$$

Initial conditions: $Y(0) = Y0$, $Z(0) = 0$. Solution is:

$$y(x) = \frac{a_{21}}{a_{12} + a_{21}} + \frac{a_{12}e^{(-(a_{12}+a_{21})x)}}{a_{12} + a_{21}}, \ z(x) = \frac{\frac{a_{12}e^{(-(a_{12}+a_{21})x)}a_{21}}{a_{12}+a_{21}} + \frac{a_{12}a_{21}}{a_{12}+a_{21}}}{a_{21}}. \tag{2}$$

Let's analyze formulas that determine dynamics of radionuclide supply in each chambers. Assume that radionuclides content in the chambers reached its equilibrium at $X = \infty$. Then for such time the exponent is equal to zero. For radionuclides stock that will be in the chamber "environment" (F_S) and in the "biota" chamber (F_b):

$$F_S = \frac{a_{21}}{a_{12} + a_{21}}, \ F_b = \frac{a_{12}}{a_{12} + a_{21}}. \tag{3}$$

Value determining proportion of radionuclides is called the radiocapacity factor. The radioonuclides are deposited in particular chamber (component) of the ecosystem.

Developed models and theory of ecosystems radiocapacity made it possible to introduce radiocapacity factor to determine state of the ecosystem's biota. Factor of ecological and radiation capacity of particular element oflandscape F_j or ecosystem is determined as follows:

$$F_j = \frac{\sum a_{ij}}{(\sum a_{ij} + \sum a_{ji})}, \tag{4}$$

where $\sum a_{ij}$—sum of contaminats transfer rate from different components of the ecosystem to particular element of landscape or ecosystem—j, according to chamber models, and $\sum a_{ji}$—the sum of velocities of pollutants from the studied chamber—j—to other components of ecosystem associated with them.

Therefore, based on theoretical studies we can assess the reliability of the ecosystem component as an element of the system of transport of radionuclides through the chambers by formula (4) using of radionuclide exchange rates between chambers αij and α_{ji}.

Thus, determining reliability of ecological systems involves development chamber radioecological model of ecological system with determining its configuration [24–26], setting parameters, radionuclides transition rates and calculating reliability of structural elements and ecological system as a whole.

Comparing Eqs. (1, 2 and 3), you can get the expression:

$$\frac{a_{12}}{a_{21}} = \frac{F_b}{F_s} = \frac{1 - F_s}{F_b} = Z. \tag{5}$$

Thus, absorption and outflow rates ratio of radionuclide is proportional to the biomass of the biota and the accumulation coefficient in the system "environment"—"biota". It is defined as parameter Z This means that greater biota biomass and accumulation coefficient of ^{137}Cs by the biota leads to higher ratio of absorption and outflow of ^{137}Cs rates, and hence the required substances from the environment into biota biomass. Relationship between radio capacity parameter and absorption and outflow rates is clearly visible here.

3 Modeling of Radionuclides Migration for Some Settlement of Ukraine

Modern radioecology lacks methods and models suitable for assessing and forecasting of local ecosystems state for specific settlements of Ukraine. Therefore, specification of existing generalized approaches and models is urgent and important task of modern ecology. It is necessary to have method of operative creation of environmental safety model for some settlements with binding to concrete conditions of any settlement [27, 28]. Such model presence will allow to minimize scope and detail of monitoring and to predict critical situations in ecosystem under study. This makes possible to set limits on environmental capacity to limit excessive anthropogenic pressure in the study area.

Chamber models of real ecosystems affected by the Chernobyl accident were developed and analyzed: for the village Haluziia (Manevytskyi district, Volynska oblast), contaminated by ^{137}Cs, and Kotsiubynchyky (Chortkivskyi district, Ternopilska oblast) contaminated by ^{90}Sr [29, 30].

Use of chamber models is typical for modeling of radionuclides migration in selected areas. In this case, any element of the ecosystem, agrocenosis (or part of it), where the accumulation of radionuclides can be considered as camera.

Agrocenosis is considered as a set of homogeneous chambers, between which there is a transfer of radionuclides characterized by some functions k_{ji},q_j within this approach. These functions describe intensity of radioactive substances flow between the chambers.

Apparatus of ordinary differential equations is used in mathematical description of substances transfer in chamber models:

$$\frac{dq_i(t)}{dt} = \sum_{j=1}^{n} k_{ji} q_j - \sum_{i=1}^{n} k_{il} q_i - \lambda q_i, \tag{6}$$

where $q_i(t)$—radionuclide content in the chamber i; k_{ji} and k_{il}—transition coefficients between cameras; $k_{ji}q_j$—the amount of substance coming per unit time from chamber j to chamber i; $k_{il}q_i$—the amount of substance leaving per unit time from chamber i to chamber l; λ—constant of radioactive decay.

Modified chamber models of typical settlements were created and the process of radionuclide migration (^{137}Cs and ^{90}Sr) by trophic chains (chambers) was modeled as a result of research: soil → fodder plants → cow → milk → man. Parameters were established and features of this phenomenon were investigated. Methods and approach for control, forecast and management of radioecological safety for local ecosystems of settlements of Ukraine were obtained.

Transition rate of total proportion of radionuclides from chamber to chamber per unit time (year) was used instead of the parameters of radionuclide transition rate from unit weight to chamber to chamber in this modification of chamber models. This method helps to generalize characteristics of ecosystems and obtain integrated characteristics of process of radionuclide transfer in ecosystem. Mathematical model of radioecological processes of typical local ecosystems with estimation of dose loadings formation for population for long term is developed and constructed. This model is suitable for modeling almost any type of local ecosystems specific to territory of Ukraine and can be used to assess ecological status of any agroecosystems. It was shown for the first time that formation of high dose loads in population can be carried out relatively quickly or can have character of slow accumulation, depending on the established parameters of the chamber models according to the calculations on the models. This means fundamentally different dynamics of dose loads formation which can actually occur in different local ecosystems of Ukraine [31].

In radioecology there are two main closely related problems: radionuclides migration and their accumulation in various elements of the ecosystem. There are variety of radiological situations associated with radionuclides incorporation into agriculture. Therefore, radionuclides accumulation by plants from the soil determines initial scale of radionuclides inclusion into trophic chains in system: radioactive emissions—soil—agricultural plants—farm animals—humans. Radionuclides supply to plants depends on number of factors: physicochemical properties of radionuclides, species characteristics of plants, soil properties and its mechanical treatment, climatic factors, reclamation system, fertilizer application, etc. Radionuclides transition from diet to bodies of animals is determined by radionuclides physicochemical properties and as species characteristics and age of animals.

Numerous studies showed that significant dose loads in humans are formed due to the large values of the transition coefficients in the system "soil – plants" in studied areas. Main reasons for this phenomenon are peat and swamp soils, which dominate in these areas, high degree of moisture and waterlogging of soil, acidic soils, low levels of minerals in territories. This contributes to high cpntamination level of grass and hay, forest products—mushrooms and berries. Use of contaminated forage grasses leads to radionuclides migration in system "grass - farm animals". In this case, level of radionuclides in milk and meat is increased significantly.

The concept of transition coefficient (TC) is used when it comes to the migration of radionuclides by trophic chains. It reflects radionuclides proportion that fall from one element of ecosystem to another. The coefficient shows how many times greater (or less) can be activity of particular radionuclide in elements of ecosystem compared to environment.

For the system "soil – plant" TC is ratio of radionuclide activity per 1 kg of air-dry biomass of plant to its content per 1 m^2 of soil where these plants are grown.

Preliminary estimates showed that there are following main directions for entry of radionuclides to humans for studied areas: through pastures (which are fodder base for dairy and beef cattle); through forest products (mushrooms, wild berries); garden plot (garden).

Obtained results on assessment of distribution and redistribution of radionuclides in the agroecosystem showed significant dynamics of dose loads formation in humans.

Therefore, it can be argued that radiocapacity parameters can be measure of each element of ecosystem and ecosystem as a whole. Higher reliability of radiocapacity factor and (or) probability of radionuclide retention in each of ecosystem elements lead to higher reliability of constituent elements of ecosystem. It is possible to adequately assess reliability of entire ecosystem through its ability to ensure distribution and redistribution of radionuclide, reflecting its steady state using these parameters of reliability of ecosystem elements and knowing structure of particular ecosystem.

Structured block diagram of chamber model is given in Fig. 2. Parameters indicated in the diagram (from a_{12} to a_{510}) mean rates of radionuclide transfer between ecosystem chambers and have dimension: share of radionuclides transferred between the chambers in one year. Methods and model parameters of calculation of transition between cameras are content of specially designed and protected declaration package for utility model [32].

The selected for study settlements are typical. So, the block diagrams of chamber models for them are similar in structure. The model takes into account all main streams of radionuclides ^{137}Cs and ^{90}Sr (no other radionuclides were found in these villages).

It was possible to find and form a high degree of similarity in the block diagrams of chamber models in the studied areas as a result of research. It is important that these villages are characterized by rather low levels of radionuclide soil contamination from 1–2 Ki/km^2 for ^{137}Cs (Haluziia village) and for ^{90}Sr—from 1.2 to 1.3 Ki/km^2 (Kotsiubynchyky village).

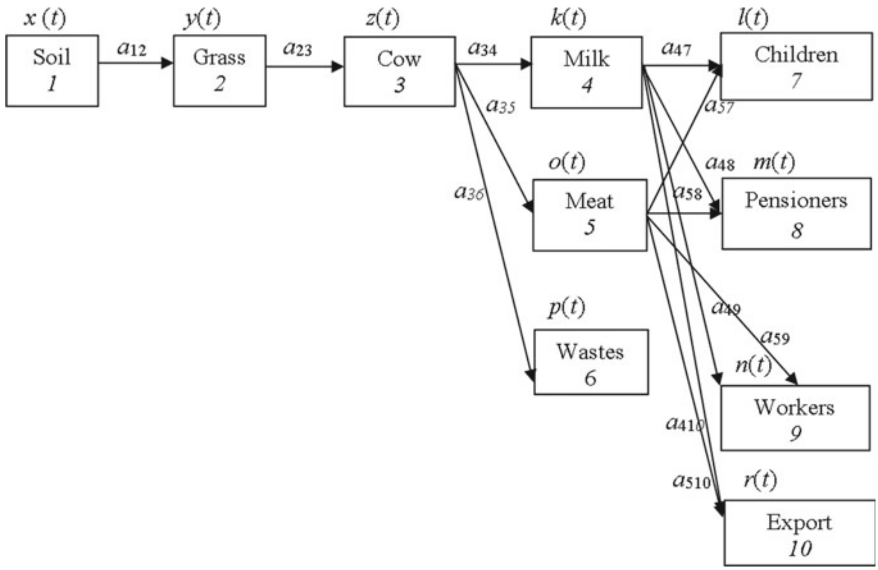

Fig. 2 Structured block scheme of Haluziia village (Manevytskyi district, Volynska oblast)

Calculated data on radionuclides fluxes by chambers of the studied ecosystems were obtained according to the developed model. Significant dose loads in different categories of population are formed due to constant consumption of milk from cows grazing on contaminated pastures. Formation of dose from use of milk for inhabitants of Haluziia village is up to 40–60% and 70% of the total dose for Kotsiubynchyky village. Average level of daily milk consumption for inhabitants of the studied settlements is from 0 to 3 l (^{137}Cs milk contamination levels are from 40 to 1000 Bq/l; for Kotsiubynchyky village ^{90}Sr is from 2 to 30 Bq/l) according to expeditionary research. Current standard for permissible levels of milk contamination is up to 20 Bq/l for ^{90}Sr, and 100 Bq/l for ^{137}Cs (permissible levels of ^{137}Cs and ^{90}Sr radionuclides in food and drinking water).

It is inserted those significant levels of milk contamination are formed in areas not immediately after the accident but increase over time according to simulation data. It explains that significant levels of 137Cs milk contamination were identified in Haluziia village in 1993 and in the Kotsiubynchyky village ^{90}Sr in 1998.

Graphs of expected dose dynamics were constructed for selected social groups—workers, pensioners, children (the division into groups was made because according to expeditionary research in these villages the amount of milk consumption in different population groups differs) based on the simulation data. Figure 3 and 4 show dynamics of dose loads formation in different social groups due to use of the main dose-forming product—milk.

The upper curve of Fig. 3 shows radionuclides accumulation and hence dose of milk consumption in Haluziia village for group of workers, the middle—children, and the bottom—pensioners. This course of curves is due to diet, in particular, due

Fig. 3 Dynamics of dose loads formation of from milk consumption for different social groups of the population Haluziia village: 1—workers; 2—children; 3—pensioners

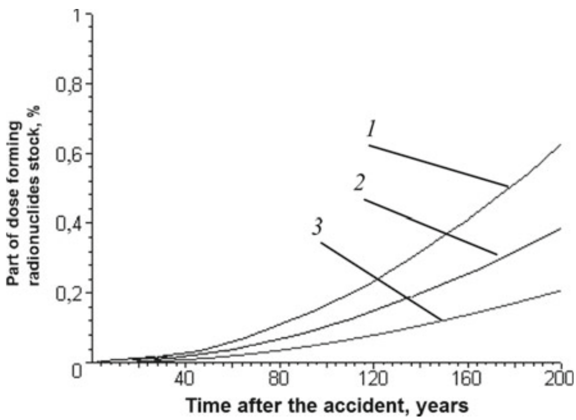

Fig. 4 Dynamics of dose loads formation of from milk consumption for different social groups of the population Kotsiubynchyky village: 1—workers; 2—children; 3—pensioners

to significant amount of milk consumption by workers and children. The graphs show that the villagers are characterized by a rapid and then slower accumulation of collective dose.

Situation for residents of Kotsiubynchyky village (Fig. 4) is characterized by different dynamics of collective dose accumulation. The model demonstrates that no significant doses of ^{90}Sr should be expected, but over time these doses increase 20 years after the accident. Here you can expect very slow accumulation of dose first and then increase it in all segments of population. At the same time maximum collective doses can be expected for workers; pensioners can be next in dose level, and the lowest doses can be expected for children.

It should be noted that in general the dose for Kotsiubynchyky village is almost twice smaller than for the Haluziia village because due to lower contamination levels.

The difference between these typical agroecosystems in terms of radioecological processes and collective dose accumulation parameters is clearly related to different radionuclides, climatic factors, and differences in food consumption.

We believe that these phenomena reflect fundamental features of collective dose formation for Ukraine's population in relation to agroecosystems with significant contribution of forest component (for example, Haluziia) and for the case of agroecosystems where there is no forest component of collective dose accumulation.

4 Discussion

Therefore, modified method of chamber models was developed and applied. The method uses the parameters of radionuclides transition rate between ecosystem chambers not transition rate per unit weight or volume. This approach allows general systematic assessment of state of radionuclide fluxes and predict their dynamics.

System type of radiological study of settlements was created. It covers the main links: soils, hay, farm animals, milk, forest products and people. Chamber models of real ecosystems affected by the Chernobyl accident were developed and analyzed. The models take into account all major streams of radionuclides ^{137}Cs and ^{90}Sr.

It was determined that in settlements of the Haluziia village type significant dose loads were formed not immediately after the accident but only in 1992–1994 according to the simulation results. 30 years after the catastrophe we can observe high collective radiation dose of ^{137}Cs—from 40 to 80 person\Sv. These areas are characterized by a significant accumulation of the collective dose for the population for 30–40 years after accident, due to the use of 1% of the stock of radionuclides 137Cs in this ecosystem.

Insignificant radiation doses are formed in the first decades after the ChNPP accident: 20 years later, the collective dose is 0.3–0.5 people for such settlements as Kotsiubynchyky village where contamination by ^{90}Sr is dominated. Accumulation of certain dose on 40th year after the accident is expected to be insignificant, no more than 0.1% of the stock of radionuclide ^{90}Sr in this ecosystem. But over time, we can expect fairly rapid accumulation of the collective dose. As a result of researches the regularity of continuous increase of a collective dose in villages with strontium pollution is revealed. This means that ecosystems of this type can become dangerous over time.

It was established and verified that a significant part of the collective dose is not formed locally in these villages but is transfered to other territories through export of milk and meat according to modeling and field research of regional sanitary-epidemiological stations. This phenomenon of collective dose exports outside villages is common characteristic for the whole territory of Ukraine. The results show that environmental safety of area can be achieved only with use of system of protective countermeasures.

The proposed modified chamber model is suitable for modeling of almost any type of local ecosystems specific to the territory of Ukraine. It can be used to assess, control and forecast their ecological status for both radionuclide contamination and other pollutants of agroecosystems.

5 Conclusions

Agroecosystem is an important source of radionuclides transition from the environment to humans. Greater the factor of agroecosystem radiocapacity makes it more "reliable" in the sense of radionuclides flow reducing to humans.

It is possible to calculate the reliability of this agroecosystem and assess contribution of different components of the agroecosystem due to rates of migration, distribution and redistribution of ^{137}Cs radionuclides in components of agroecosystem and magnitude of cesium transition to all groups.

Depending on the amount of radionuclides falling on the territory it is possible to take countermeasures. Their effectiveness depends on many factors (for example, soil type, humidity, precipitation, etc.), and their benefits can be evaluated.

Application of reliability models and theories to investigate ecological processes in different types of ecosystems is useful and heuristic. It allows assessing basic characteristics and fundamental properties of ecosystems by tracking behavior of ^{137}Cs.

Proposed method of reliability assessment can be used to assess level of pollution and transitions of other pollutants in ecosystems of different types.

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