MODEL OF EXTERNAL EXPOSURE OF POPULATION LIVING IN THE AREAS SUBJECTED TO RADIOACTIVE CONTAMINATION

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Abstract

In the paper, we formulated the general approach to assessment of external doses to population living in contaminated areas (the model equation and the set of parameters). The model parameters were assessed on the basis of results of monitoring in the environment, phantom experiments, and social and demographic information obtained on the contaminated areas. Verification of model assessments performed by comparison with measurement results of individual external doses in inhabitants within the thermoluminescent dosimetry method have shown that differences in dose assessments within both methods does not exceed 1.5 times at a confidence level of 95%. In the paper, we present the results illustrating specific features of external dose formation in population living in the areas of Russia subjected to radioactive contamination due to nuclear tests at the Semipalatinsk test site, radioactive releases from the Mayak enterprise, and the Chernobyl accident.

1. FORMULATION OF THE MODEL OF EXTERNAL EXPOSURE

External exposure is one of the most significant possible ways of population exposure due to broad-scale releases of radioactive substances into the environment. In any situation of human external exposure, the following three blocks of data are necessary for assessment of the effective dose:

— parameters of external gamma radiation field;

— parameters of human behaviour in this field;

— conversion factors from parameters of the gamma radiation field to the effective dose in a person.

The basic model for human exposure in case of radioactive contamination of the environment is the model for exposure above an open plot of virgin soil, and the absorbed dose in the air at the height of 1 m above the surface is used as the parameter for the radiation field. In this case, its value is influenced, besides the surface activity of deposited radionuclides, only by such natural factors as the initial deepening of radionuclides in soil, their radioactive decay, vertical migration of long-lived radionuclides, and the presence of snow cover.

The parameters of radiation field are different in case of population exposure in the anthropogenic environment. In the model, this fact is taken into account by means of location factors f_j defined as the ratio of the dose rate in the air in point j inside a settlement and in its vicinity, attributed to gamma radiation of radioactive depositions, to the similar value above a plot of virgin soil.

Human behaviour in the radiation field is described by means of occupancy factors p_{ij} which are the part of the time spent by representatives of the i-th population group in the j-th point of the settlement.

The third block of data necessary for assessment of the effective external dose is represented by the conversion factors that relate the actually measured values (the absorbed dose in the air) with the criterion of radiation impact – the effective dose–being assessed.

On this basis, we write the model equation for assessment of the effective external dose rate E_i for representatives of the i-th population group in the following way:

$$E_i(t) = d(t) \cdot k_E \cdot k_S \cdot \sum_j f_j \cdot p_{ij} \ ,$$

$$d(t) = r(t) \cdot \sum_k A^k \cdot g_0^k \cdot \exp(-\lambda^k \cdot t) \ ,$$

where: $d(t)$ is the absorbed dose rate in the air at the height of 1 m above the open plot of virgin soil;

k_E is the transfer factor from the absorbed dose in the air to the effective dose;

k_S is the factor of influence of snow cover on the value of the effective dose;

f_j is the location factor;

p_{ij} is the occupancy factor;

A^k is the surface activity of the k-th radionuclide as of the date of termination of radioactive deposition;

g_0^k is the specific rate of the absorbed dose in the air from gamma radiation of the k-th radionuclide in the geometry of a plane isotropic source located at the air-soil interface;

$r(t)$ is the function that describes the influence of radionuclides migration in soil on the absorbed dose rate in the air, equal to the ratio of the dose rate at the time moment t above soil with the observed distribution of radionuclides in soil to the dose rate from a thin source with the same surface activity located at the air-soil interface;

λ^k is the constant of radioactive decay for the k-th radionuclide;

t is the time elapsed since the moment of termination of the radioactive depositions.

Numeric values of the parameters listed above were determined on the basis of long-term dosimetric investigations in the most contaminated regions of Russia, by performing phantom experiments, and on the basis of population polls [1, 2]. Verification of model assessments on the basis of measurement results for individual doses in inhabitants within the method of thermoluminescent dosimetry has shown that dose assessments obtained according to the model calculations did not differ from experimental results with the error up to factor 1.5 times at a confidence level of 95% [3]. The model was taken as the basis for official documents on assessment of current [4] and reconstruction of accumulated external doses to population living in the areas contaminated as a result of the Chernobyl accident [5]. Below we present the results illustrating the specific features of external dose formation in population after different radiation accidents that took place on the territory of the former USSR.

2. SPECIFIC FEATURES OF EXTERNAL DOSES FORMATION IN POPULATION DURING DIFFERENT RADIATION ACCIDENTS

Fig. 1 presents the calculation results that reflect dynamics of accumulation of effective external dose on the trace of radioactive depositions after a surface nuclear explosion and after the Chernobyl accident. In the first case, the initial data were activities of 41 radionuclides in the non-fractionated mixture of products of instant ^{239}Pl fission by neutrons of fission spectrum, normalised to the ^{137}Cs activity release as of the moment "x + 3 hours". The effective dose rate was calculated for $t > 3$ hours from the explosion moment, which corresponds to the minimum time period of approach of the radioactive cloud to the boundaries of the Altay Kray. The value of the effective dose was obtained by integrating the dependence of the effective dose rate within the given time limits. In the second case, the initial data were activities of 15 radionuclides in the proportion determined for the far zone (over 100 km from the Chernobyl NPP) of the north-east Chernobyl trace [6]. Calculation of the effective dose was performed beginning from 48 hours after the moment of the accident, i. e., the time of beginning of main radioactive depositions on the territory of the Bryansk region. The dynamics of accumulation of the effective external dose in settlements of the Altay Kray located approximately at the distance of 150 km from the test site is such that about 60% of the dose during 50 years was formed during the first week after the radioactive depositions (without consideration for future changes in configuration of the source), and during the first year the dose was formed almost completely. In contrast to this case, in the settlements of the Bryansk region also located at the distance of 150 km from the Chernobyl accident, only 25% of the effective dose value during 50 years was formed during the first year after the accident.

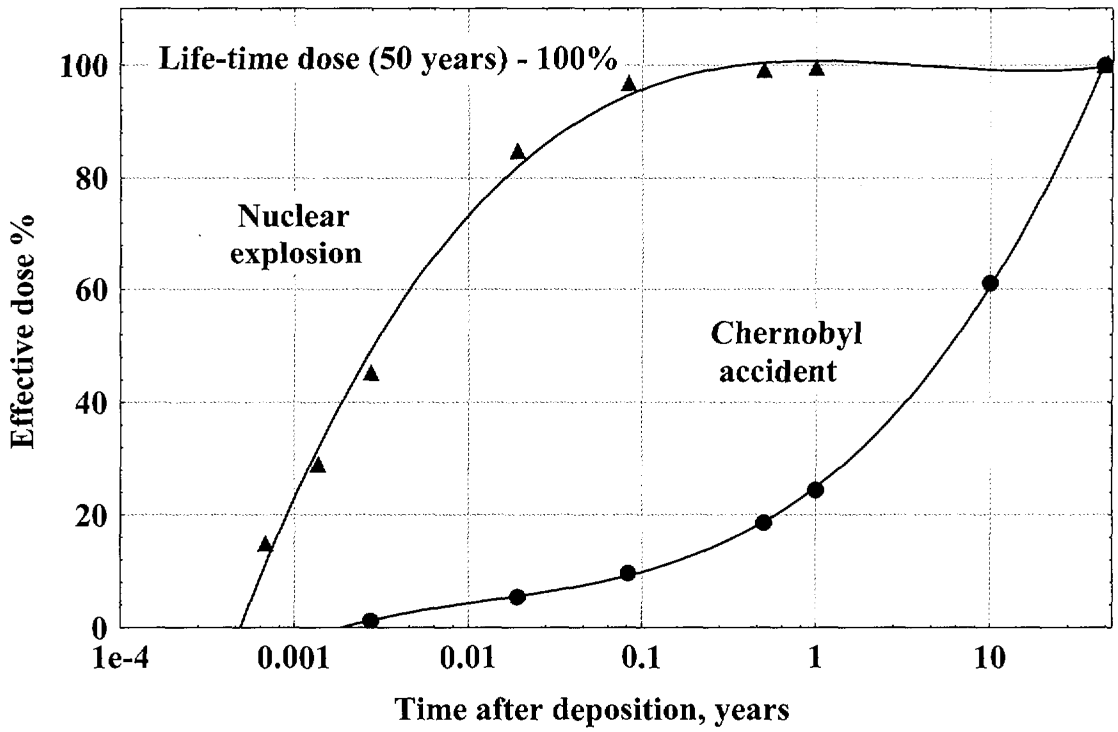


FIG. 1. The dynamics of accumulation of the effective external dose after nuclear explosion and after the Chernobyl accident.

The long-term dynamics of the gamma radiation dose rate is primarily connected with migration of the long-lived ^{137}Cs radionuclide in the environment. During 1987-1999, in the most contaminated south-west part of the Bryansk region, over 300 samples of virgin soil were taken to the depth of 20 cm. Each core was separated in layers 2-5 cm thick with subsequent determination of ^{137}Cs content within the gamma-spectrometry method. After that, the determined distribution of ^{137}Cs activity in the upper soil layer was used to calculate the dose rate in the air at the height of 1 m above the soil surface [7]. The results of pre-Chernobyl investigations of caesium migration [8, 9] indicated that the function of influence of caesium deepening in soil on the decrease of absorbed dose rate in the air can be represented in the two-exponential form with a short (~ some years) and a long (~ some tens years) periods. The short time of investigations after the Chernobyl accident did not permit to assess correctly the value of the long period. Therefore, we included in the analysis the results of investigations of caesium migration during 24 and 30 years [10]. The joint analysis of the results permitted to assess the parameters of the $r(t)$ function with lesser error, at least for the "age" of radioactive depositions up to 30 years (see Fig. 2).

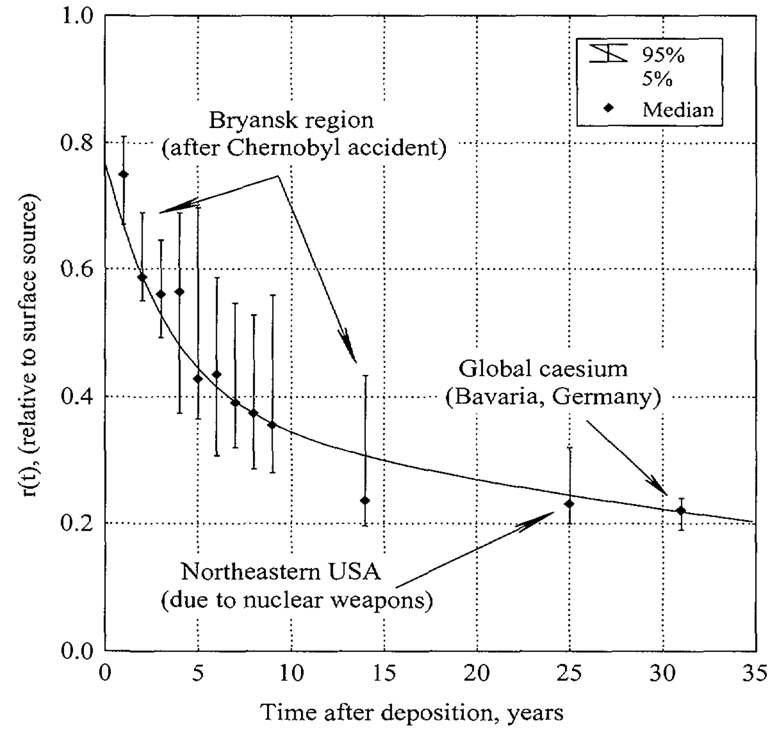


FIG. 2.Long-term dynamics of the absorbed dose rate in air from ^{137}Cs gamma radiation over virgin land.

The analysis of over 5000 individual external doses measured within the method of thermoluminescent dosimetry in inhabitants of the Bryansk region has shown that the distribution of individual doses can be approximated by a lognormal law [11]. Moreover, if we plot the distribution of ratios of individual doses to the average value of the dose in the settlement, then the parameters of such distribution will be very close for all settlements, and the lognormal distribution with the geometric mean ~ 0.9 and geometric standard deviation ~ 1.5 can be assumed typical for the areas contaminated as a result of the Chernobyl accident. Fig. 3 presents the results for comparison of distributions of individual doses obtained on the basis of measurements within the thermoluminescent dosimetry (565 measurements) in three villages of the Bryansk region in summer 1993, and within stochastic simulation. It is directly seen that both distributions actually have the same parameters, thus confirming the adequate character of the model structure and numeric values of its parameters.

The conditions of external exposure to population living in the drainage area of the Techa river significantly differ from those on other contaminated areas of Russia, because here the main source of radiation is a small part of the river water-meadow. The territory of settlements proper was subjected to considerably lesser radioactive contamination. Thus, for example, in village Muslyumovo, the average value of the ^{137}Cs surface activity in soils of river water-meadow is approximately by 60 times higher than the similar value for soil plots in the settlement proper or in its vicinity outside the river water-meadow. In contrast to the "Chernobyl" variant of the model, in this case the parameters of the gamma radiation field that we used were the results of direct measurements of dose rates in the air at the height of 1 m above the surface both in the Techa river water-meadow and in settlements proper obtained during investigations of radiation situation in the region in the middle of the nineties [12].

To find out the character and duration of contacts of the population with the river water-meadow, we performed on site observations by the river in the village Muslyumovo [13]. Processing the observations results permitted to assess both the average values and scatter for values of duration's of staying in the river water-meadow for representatives of different population groups. As an example, Fig. 4 presents the results for assessments of individual external doses distribution in two population groups in the village Muslyumovo obtained within the method of stochastic simulation. Representatives of the first population group correspond to adult inhabitants of the village with the average value of duration of staying in the river water-meadow (about 1.5 hours per day in summer). The duration of staying of another, critical population group (herdsmen) in the river water-meadow in summer can reach 10 hours per day. Both distributions of individual doses, as in the Chernobyl case, correspond to the lognormal law. However, these distributions have greater positive asymmetry, which is quantitatively confirmed by the greater value of the geometric standard deviation (~ 2). The presented results indicate that in a part of representatives of the critical population group the external dose even taken separately can exceed the dose limit set for population, 1 mSv.

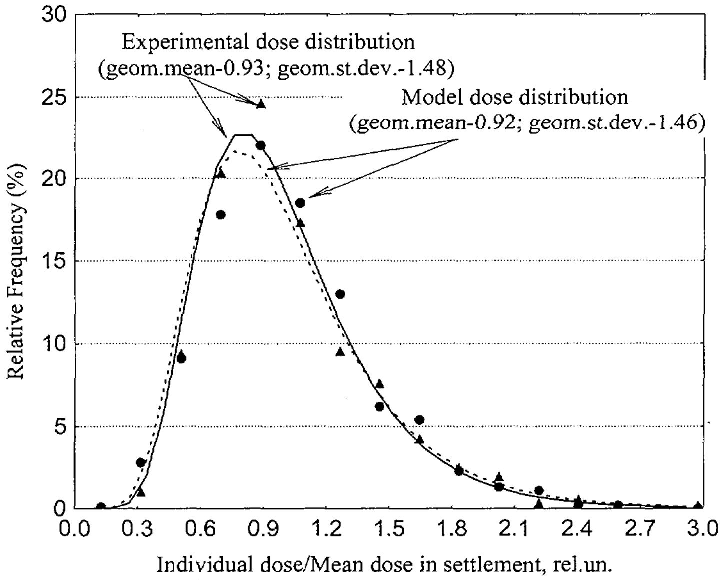
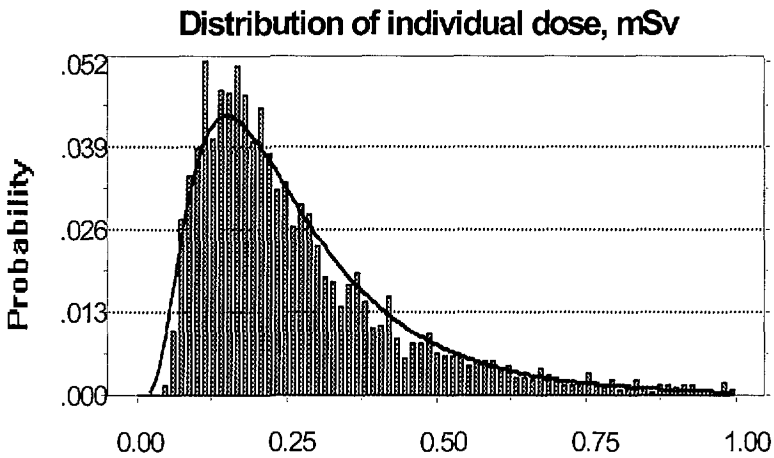


FIG. 3. Frequency distributions of monthly effective doses measured in summer 1993 with TL-dosimeters in three villages of the Bryansk region and calculated by stochastic model.



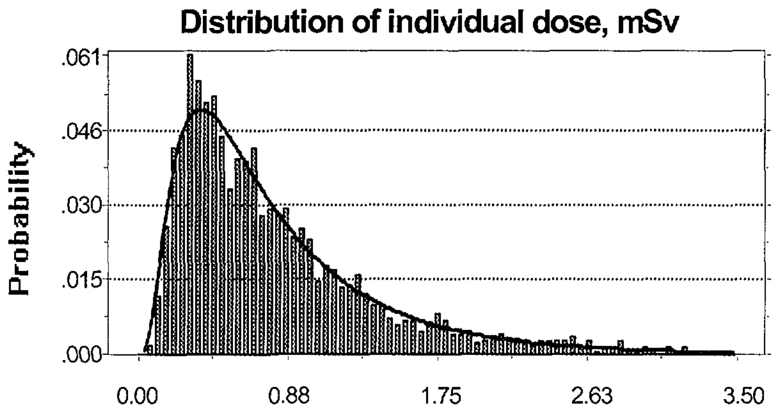


FIG. 4. Individual external doses distribution in two population groups in the village Muslyumovo. The upper figure correspond to adult inhabitants of the village with the average value of duration of staying in the river water-meadow, the lower figure correspond to critical population group.

The methodology for external dose assessment described above was used as the official procedure for determination of current and accumulated doses in inhabitants who live in the areas subjected to radioactive contamination due to the Chernobyl accident. To conclude, we present in Fig. 5 the calculation results for the collective effective external and internal doses (excluding the thyroid dose) in inhabitants of 18 regions of Russia accumulated during 15 years after the accident. The total collective dose in 36 millions inhabitants in 20 regions of European part of Russia was 66200 pers.·Sv during 15 years after the Chernobyl accident. Of this value, the external collective dose was 23380 pers.·Sv, or 35%. The relation between the external and internal doses depends mainly on soil type in the region and on the efficiency of countermeasures, which were more efficient with respect to reduction of internal, but not external exposure to population.

FIG 5.Cumulative effective dose during 15 years after the Chernobyl accident (man·Sv) in different regions of Russia. The contribution of external dose in the total dose is given in brackets in %.

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DISCUSSION AFTER THE PRESENTATION OF V.Y. GOLIKOV

Yu.A. IZRAEL (Russian Federation-Session Chair): When estimating the doses resulting from nuclear explosions, did you take account of fractionation?

V.Y. GOLIKOV (Russian Federation): No, we did not.

Yu.A. IZRAEL (Russian Federation-Session Chair): In that case, zirconium-95 will not show up in your calculations.

E.D. STUKIN (Russian Federation): According to calculations performed by us, one and a half years after the Chernobyl accident the contribution of ^{134}Cs to the dose exceeded that of ^{137}Cs. What do you think the reason for that was?

V.Y. GOLIKOV (Russian Federation): The specific dose rate from ^{134}Cs is about 2.7 times that from ^{137}Cs. With a fallout ratio of about 0.5, for one and a half years the ^{134}Cs accounted for more of the gamma radiation dose than the ^{137}Cs.

E.V. KVASNIKOVA (Russian Federation): There is usually a direct correlation between deposition and gamma dose rate. In some situations, however, as the deposition increases owing to erosion the maximum caesium concentration decreases and there is a corresponding decrease in the dose rate-and perhaps a fairly significant decrease also in the external gamma dose. To what extent did you take such processes into account in your calculations, and can they significantly affect the total external dose from region to region?

V.Y. GOLIKOV (Russian Federation): Yes, they can. The curve on the slide which I showed relating to the long term migration of ^{137}Cs is a function of time. It reflects the dose rate decline due to migration. We can calculate the dose over any profile. Here is reflected the natural process of migration in virgin, open soil-for the Bryansk region. This decrease in dose is taken into account very correctly in that it is calculated over the real caesium profile in the soil.