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MONTE CARLO SIMULATION OF DOSE LOADS IN FORESTS OF THE CHERNOBYL ZONE

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A computer program for Monte Carlo calculation of the dose power of the external γ-radiation in three-dimensional geometry is developed. Results that can have practical applications are obtained with this program. The dose power in a radioactively contaminated forest for various sources of γ-radiation is estimated, which makes it possible to develop the most safe, from the viewpoint of radioactive safety of the personnel, scenarios of activities on contaminated territories.

As a result of the accident on the Fourth Block of the Chernobyl Atomic Power Station, which was accompanied by disintegration of the active zone, a considerable amount of radionuclides accumulated during its operation have fallen outside the station.

Radioactive fall-out has covered about a quarter of the Belarusian territory. The area of contaminated forests equals approximately 17,000 km^2, and 12% of them are situated in a zone with an activity of 15 to 40 Ci/km^2, and 1.7%, in a zone with an the activity exceeding 40 Ci/km^2 [1]. This situation has caused a decrease in stocks of raw materials and volumes of production in the lumber industry in the Republic of Belarus, and, therefore, investigation of the possibility of utilization of forests growing on contaminated territories is an extremely important problem.

Presently, special technologies and equipment which will make it possible to eliminate ecological and social damages are being developed within the framework of the National Program on Elimination of Consequences of the Chernobyl Accident. It should be kept in mind that restoration and preparation for utilization of contaminated forests should be preceded by estimation of the ratio of the risk connected with the acquisition of an additional (technogenic) irradiation dose by professionals and the commercial efficiency of utilization of lumber. To do this, we developed a Monte Carlo algorithm for evaluation of the dose power of γ-radiation in a radioactively contaminated forest.

Previously, when calculating dosages of external irradiation, only γ-radiation was taken into account, since the radioactive isotope composition of radionuclides fallen out in the forest and on the ground is characterized by a main component of long-lived γ-radiators. The largest contribution to the γ-component is made by the isotope ^{137}Cs (half-value period $\simeq$ 30 years), whose fraction lies within the region of 50 to 80% of the total activity.

The distribution of the absorbed energy over the material being irradiated is calculated based on the consideration of physical processes of the energy transfer to the substance irradiated. The soil, bedding, and trunks and crowns of trees are all sources of γ-radiation in the radioactively contaminated forest. Therefore, the problem of evaluation of the dose load of γ-radiation is reduced to the solution of the equation of radiation transfer from bulk sources with various configurations in a nonhomogeneous medium. The Monte Carlo method is the most efficient for the numerical solution of problems of the type.

The motion of γ-quanta in a medium is characterized by coordinates, energy, and the direction of motion (r, E, Ω). All these variables are random and change upon scattering according to certain probabilistic laws. Modeling of a number of trajectories of motion of γ-quanta upon passing from one medium to another by a set of

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cross-sections, densities of media, and boundary conditions makes it possible to obtain characteristics of the field of the scattered γ-radiation. To find the energy absorbed within the region under investigation, whose dimensions are small compared to the mean free path of γ-quanta, we use the method of the local estimate [2] In this case, the energy absorbed within a region of space in the vicinity of a point r^* localized at a large distance from the source will consist from the sum of contributions of energies of γ-radiation transferred from all k scattering points of the j-th trajectory of γ-quanta without additional scattering.

$$E_j = \sum_{k=1}^{j} W_{1k} \exp\left(-\mu (E_k)(r_k - r^*)\right) \frac{E_k' \mu_e (E_k')}{(r_k - r^*)^2 \sigma_k (E_k')} \frac{d\sigma (E_k')}{dE_k'} .$$

However, application of the local estimate method yields satisfactory results only in cases when the distance from the source to the volume being irradiated does not exceed seven mean free paths. At larger distances, results are undervalued due to the fact that contributions to the absorbed energies made by γ-quanta undergoing scattering within the region close to the volume being irradiated is underestimated.

The method of variance minimization [1] makes it possible to avoid the above-mentioned difficulties and does not require radical changes in the scheme of modeling of nonanalogous trajectories of γ-quanta. When modeling the free path, a bias is introduced into the distribution density of the random quantity of the free path. The parameter a_k [4] is determined as a function of the position of the scattering point with respect to r^*, and the actual free path increases or decreases to minimize the variance of the random quantity $\exp(-\Sigma r)/r^2$, which is the contribution to the absorbed energy of the next scattering.

The weighting factor that compensates for the bias of the free path is as follows [3]:

$$W_{2k} = \frac{1}{a_k} \exp\left(-\Sigma l_k (1 - a_k)\right) .$$

It is known that the local estimate has a diverging variance. In order to pass to a finite variance of the local estimate, we use general methods of reducing the variance and the method of biasing of the scattering kernel (biasing along the polar angle θ) [4].

The density of the flux of γ-quanta from scattering of the first degree is proportional to $1/\sin\theta$. If one takes into account this regularity when modeling the scattering probability density by computing only those values of the polar angle directed to the given region, the dispersion will be finite.

The compensation for the biasing from the Klein-Nishina distribution is given by the weighting factor

$$W_{3k} = \frac{\pi^2 \frac{d\sigma}{d\Omega}(\theta) \sin\theta}{\sigma_c (\pi - \theta)} .$$

Thus, the complete weighting factor after the m-th scattering equals the product of the three above-described weighting factors:

$$W_m = \prod_{k=1}^{m} W_{1k} W_{2k} W_{3k} .$$

By using the method of mathematical expectation, we obtain the estimate of the absorbed energy by averaging all possible contributions from N trajectories

$$E = \frac{1}{N} \sum_{j=1}^{N} E_j .$$

The given algorithm was taken as a basis when developing a three-dimensional program for evaluation of the power of γ-radiation in radioactively contaminated forests.

TABLE 1. Power of Absorbed Dose of γ-Radiation at a Height of 3 cm, S/sec

Distance from the symmetry center, m	P	
	calculation	experiment
$x=0$, $y=0$	0.268	0.27
$x=0$, $y=10$	0.280	0.30
$x=20$, $y=0$	0.313	0.32
$x=0$, $y=20$	0.248	0.26
$x=0$, $y=40$	0.237	0.24
$x=160$, $y=0$	0.036	0.04

TABLE 2. Power of Dose of γ-Radiation P of Radioactive Fall-outs, nS/sec

Variant	A_f/A_s	P_{up}	P_{low}	P
1	10/25	$0.2\cdot10^{-2}$	1.508	1.51
2	10/0	$0.63\cdot10^{-1}$	0.223	0.288
3	0/25	0	1.38	1.38
4	5/25	$0.21\cdot10^{-2}$	1.107	1.109
5	25	0	1.82	1.82

A program for a personal computer was developed according to the method described. In order to check the performance of the program, we compared calculated quantities with experimental data obtained on the UGU-200 enlarged γ-installation. A two-dimensional irradiator consisting of extended ^{60}Co sources mimics well the physical model of a forest area. Table 1 presents a comparison of experimental data with results of calculations and shows a satisfactory agreement.

We carried out a series of calculations on evaluation of the power of the absorbed dose of the radioactive fall-out in a forest as a function of the activity level of the forest A_f (Ci/km^2) and the bedding surface (soil) A_s (Ci/km^2). We assumed in calculations that trees have equal size and their planting density is such that their crowns contact each other.

We considered several variants with the following sources: 1) forest and soil, 2) only forest, 3) only forest soil, 4) forest and soil, except that the planting density of trees was decreased twofold, and 5) air and soil (open area).

Results of calculations of the dose power P (nS/sec) in the forest in the point under investigation located at a height of 1.5 m are presented in Table 2. Dosage loads in the forest and open area differ substantially due to the screening of the district by the forest (see variants 1 and 5). The dependence of the dose power on the planting density of trees n (Fig. 1a) (contamination level A_f/A_s = 10/25) is also explained by the ratio of doses from the forest and open area. The dosage load decreases with decreasing planting density $n < 1$, and a minimum is observed at $n = 0.5$. A further decrease in the planting density of trees leads to an increase in the dosage load due to a decrease in the screening of the region by the forest. It is evident from data presented in Table 2 that the

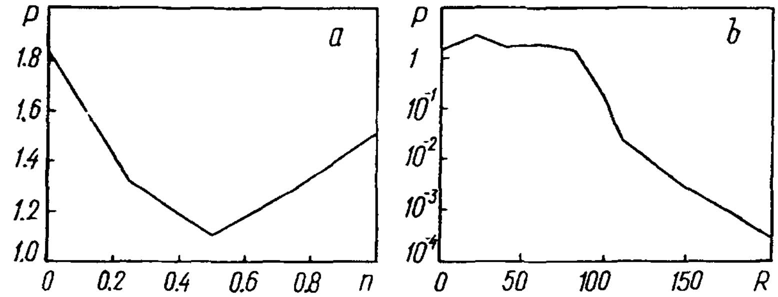

Fig. 1. Dependence of the dose power (P, ns/sec) on the planting density of trees (n, relative units) (a) and on distance from center of spot (R, m) (b).

contribution of the γ-radiation coming from the upper half-space P_{up} to the dose is approximately three times smaller than that for the lower half-space P_{low}.

We have found a dependence for the dose power on the distance (the center of a radioactive spot is taken as an origin, the contamination level $A_f/A_s = 10/25$), which is presented in Fig. 1b.

As is evident from the plots and Table 2, the dose power in the forest depends strongly on the planting density of trees and distance from the source due to screening of the area by the forest. Therefore, doses acquired by workers and crews depend on the way work is carried out and the type of timber-cutting technique.

In order to obtain more detailed information on the dosage levels for professionals carrying out timber cutting or deactivation, one should estimate the dose power of γ-radiation of containers with lumber, waists or bedding (during deactivation) on operator's workplaces. The program can be supplied by additional modules that will make it possible to estimate protection parameters preliminarily (according to the necessary level of protection) and choose the safest work scenario.

The method proposed makes it possible to estimate dosage loads on personnel depending on the type of the timber-cutting technique, its efficiency, method of deactivation, level of the radioactive contamination, etc.

NOTATION

$\sigma_C(E_k')$, complete microcross-section of Compton scattering; $d\sigma(E_k')/dE_k'$, differential cross-section of scattering for energy E_k' of γ-quantum; $\mu_e(E_k') = (\mu_k T_k^C + \mu_{pe} T_k^{pe} + \mu_p T_k^p)/E_k$, coefficient of energy absorption; T_k^C, mean energy of recoil electron (Compton effect); T_k^{pe}, mean energy of photoelectron; T_k^p, mean energy of positron; μ_C, coefficient of energy absorption in Compton scattering; μ_{pe}, coefficient of photoelectric absorption of energy; μ_p, coefficient of energy absorption due to pair production; $W_{1k} = W_{1k-1}\sigma_C/\sigma$, weighting factor for elimination of biasing when modeling nonanalogous trajectories of γ-quanta; l_k, free path before the k-th scattering; a_k, parameter of the free path bias; A_f, activity level of forest; A_s, activity level of soil; P, power of absorbed dose; P_{up}, contribution of γ-radiation coming from upper half-space to the dose power; P_{low}, contribution of γ-radiation coming from lower half-space to the dose power; n, planting density; R, distance from the center of contamination spot.

REFERENCES

1. Yu. A. Izraél' (ed.), Chernobyl: Radioactive Contamination of Natural Media [in Russian], Leningrad (1990), pp. 40-56.
2. V. G. Zolotukhin and S. M. Ermakov, in: Problems of Reactor Protection Physics [in Russian], Moscow (1968), pp. 171-181.
3. V. G. Zolotukhin and A. I. Ksenofontov, in: Problems of Dosimetry and Radiation Protection [in Russian], Issue 13, Moscow (1973), pp. 21-25.
4. V. G. Zolotukhin, A. I. Ksenofontov, A. M. Panchenko, and V. N. Sinev, in: Problems of Reactor Protection Physics [in Russian], Issue 6, Moscow (1974), pp. 72-78.