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Using MCNP Code for Neutron and Photon Skyshine Analysis

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The MCNP Monte-Carlo code was used for the investigation of the sensitivity of neutron and neutron-induced secondary photon dose rate, total and thermal neutron fluxes and space-energy distributions to energy and angular distribution of radiation source, to thickness and composition of the ground, air density (including it changing with height), humidities of air and ground, thermalization effects, detector's dimension and its disposal above the ground level. The calculations were performed with the assumption that the source or released radiation into the atmosphere can be treated as a point source and the source containment structure has a negligible perturbation on the skyshine radiation field.

KEY WORDS: Monte-Carlo code, radiation source, neutron fluxes, photon dose rate, space-energy distributions, air-ground boundary, sensitivity analysis, skyshine radiation field, comparisons with experiment.

In studying the regularities of the formation of scattered radiation fields with the source placed on the ground-air boundary, calculation research allows to obtain the information that is difficult or impossible to derive from an experiment. It primarily concerns research into the role of soil in slowing down neutrons to thermal energy and forming secondary photons in the reactions of capture and inelastic scattering on the nuclei of air and soil elements, and separation of this component against the background of own radiation and further scattering of the source photons in the atmosphere. Besides, the study of the sensitivity of the neutron and photon flux density to different parameters describing characteristics of the source, atmosphere and soil, is much easier to realize in the calculation.

The sensitivity of the neutron and photon flux density was studied in this paper using MCNP code [(1)] and, in some cases, using DORT code [(2)]. Calculations were also performed for the comparison with the experimental results obtained during measurements at the RA reactor. The reactor as a radiation source, was modeled in the calculation by a point source with a specified energy and angular distribution of neutrons and photons (**Fig.1**). The energy spectrum of the source neutrons normalized for unit, is presented in Table 1 in a group breakdown corresponding to the CASK-40 library [(3)].

The source was located at the ground level. The bundle divergence angle θ (Fig.1) was $\approx 38°$. The radiation release within the bundle divergence angle limits was assumed as equally probable. The neutron and secondary photon detectors were specified as circular surfaces with the width in the radius of ~ 1 m located at the height of ~ 1 m of the soil surface.

Analyzed in the calculations were dependencies of the neutron dose rate D_n and the secondary photon dose rate D_γ, the total (integral by all energies) flux F_{tot} and the thermal neutron flux density F_{nt} on different parameters.

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In a series of preliminary calculations there were determined the optimal sizes of the calculation region (R_{max} is the maximum size of the calculation region in the radial direction and H_{max} is the maximum height of the air layer). The calculations showed that the specification of $R_{max} = H_{max} = 1200$ m ensures the obtaining of correct estimations of the said functionals. The height of 1200 m is approximately 5-6 runs of fast neutrons with $E_n \sim$ 4-6 MeV having maximum runs in the air and approximately 4 runs for photons with the energies of 8-10 MeV.

At a change in the bundle divergence angle by cosine from 1.0÷0.95 to 1.0÷0.0 (isotropic source), the values of the functionals change monotonously for all spatial points. A change in the bundle divergence by 5°-10° does not lead to a change of the functional values by more than 2-3%, so it may be assumed that the results depend little on the angular source distribution.

At the same time, the influence of the energy distribution of the radiation going out to the atmosphere is rather great. Hence, a calculation with two variants of the energy source distribution presented in **Table 1** (the values in brackets correspond to the measured energy spectrum of neutrons going out from the RA reactor surface to the atmosphere) produces a spread of the values in the D_n and F_{nt} dose rate of up to 10-12% and 20-30% respectively (for the point R=1000 m). Though, as it is clear from Table 1, a difference in the spectrums is not large and the deviation of the group values average by all groups is 1.04. At that, it is important to specify the spectrum in the entire energy range of energies from thermal ones of up to 10-12 MeV.

The correctness of the chosen effective source model was checked using «direct» calculations by MCNP code. The «direct» MCNP calculation was a calculation of the radiation from the reactor core in the vertical direction and formation of an intermediate surface source. Using this source, the spatial distribution of the neutron flux in the locality is further calculated.

It follows from **Table 2** that the effective source methods give underestimation from 5-8% for $R \geq 400$ m and up to 20% for the points nearer to the source as compared to the «direct»

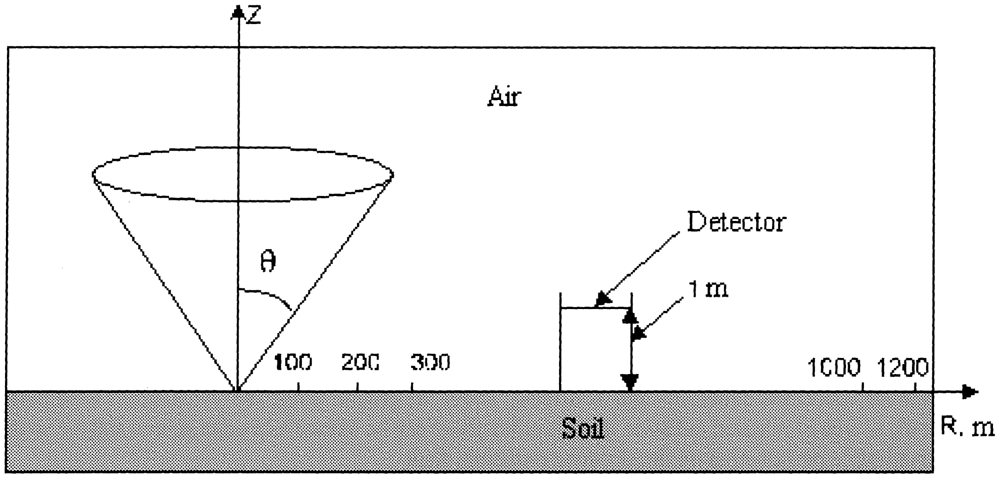

Fig. 1 Calculational mock-up for air-scattered radiation.

Table 1 Normalized energy spectrum of source neutrons.

ΔE_n, MeV	F(E)	ΔE_n, MeV	F(E)	ΔE_n, MeV	F(E)
0 - 4.14-7	7.87-2*(5.41-2)	- 3.35-3	6.69-2 (6.83-2)	- 3.01	1.20-2 (1.82-2)
- 1.12-6	2.51-2 (2.90-2)	- 1.11-3	2.00-1 (2.29-1)	- 4.06	1.09-2 (1.20-2)
- 3.05-6	2.77-2 (1.13-2)	- 5.55-1	1.88-1 (1.73-1)	- 4.96	6.31-3 (4.60-3)
- 1.07-5	3.83-2 (4.52-2)	- 1.10	1.09-1 (9.90-2)	- 6.39	4.87-3 (3.29-3)
- 2.90-5	3.31-2 (1.24-2)	- 1.83	6.95-2 (7.92-2)	- 8.18	2.36-3 (1.78-3)
- 1.01-4	4.09-2 (4.72-2)	- 2.35	2.43-2 (3.04-2)	- 10.0	5.29-4 (7.16-4)
- 5.83-4	5.70-2 (4.70-2)	- 2.46	3.88-3 (3.70-2)	- 12.2	1.50-4 (1.98-4)
				- 15.0	6.00-5 (6.77-5)

* 7.82-2 means 7.82 10^{-2}

Table 2 Spatial distribution of D_n and F_{tot} for two variants of calculation by MCNP code.

Distance from source R, m	D_n, μSv/hour			F_{tot}, n/cm^2·s		
	MCNP1	MCNP2	Experiment	MCNP1	MCNP2	Experiment
100	7.20+4	8.56+4	1.10+5	4.95+5	6.60+5	4.60+5
200	1.52+4	1.71+4	1.84+4	9.85+4	1.21+5	1.07+5
300	4.50+3	5.02+3	6.38+4	2.78+4	3.31+4	2.96+4
400	1.54+3	1.67+3	1.95+3	9.35+3	1.05+4	8.21+3
500	5.87+2	6.35+2	7.60+2	3.44+3	3.64+3	3.29+3
600	2.30+2	2.41+2	2.82+2	1.36+3	1.33+3	1.11+3
800	4.16+1	4.16+1	4.61+1	2.40+2	2.34+2	2.09+2
1000	8.70+0	9.30+0	8.90+0	4.30+1	4.85+1	3.85+1

MCNP1 - MCNP calculation with an effective source,
MCNP2 - «direct» MCNP calculation.

calculation. At the same time, the comparison with the experiment shows that both sets of the results have approximately equal discrepancies.

The influence of the parameters determining the state of the atmosphere is very different. A change of the functionals depending on relative humidity takes place by a linear law (for all spatial points). The biggest changes are observed for F_{nt} for which the relative humidity growth from 25% to 100% leads to a reduction of F_{nt} by a factor of 1.4 (for the points with R > 600 m). When measured in the locality, humidity could change by a factor of 1.5 during the day which may lead to a 8% change of F_{nt} in 1000 m which is lower than the measurement error in this spatial point.

More pronounced is the influence on the results of the atmosphere density change with height. The consideration of this factor leads to an increase in the values of the D_n, F_{tot} and F_{nt} functionals for R ≤ 800 m by 4.3%, 4.07% and 3.3% respectively (the average atmosphere density over the height was taken as equal to $\rho = 1.20$ kg/m^3).

Generally, air density is the parameter that has the biggest influence on the result as compared to other meteorological data: temperature, pressure and relative air humidity.

Thermalization effects were taken into account for the compositions in which hydrogen in the air and the soil was free

Table 3 Dn and D*γ for different cases of substituting soil with air (D*γ - secondary photons only), rem/hour.

R, m	soil $0 \le R \le 1000$ m			soil $0 \le R \le 500$ m, air $R > 500$ m			soil $R > 500$ m, air $0 \le R \le 500$ m			air instead soil $0 \le R \le 1000$ m		
	D_n	F_{nt}	D^*_γ	D_n	F_{nt}	D^*_γ	D_n	F_{nt}	D^*_γ	D_n	F_{nt}	D^*_γ
100	3.48-14	6.79-10	1.07-15	3.48-14	6.82-10	1.07-15	1.97-14	4.92-11	3.76-17	1.91-14	4.31-11	3.85-17
200	6.90-15	1.22-10	2.26-16	6.89-15	1.22-10	2.27-16	3.73-15	6.34-12	1.40-17	3.62-15	5.78-12	1.31-17
400	6.56-16	9.86-12	2.49-17	6.53-16	1.00-11	2.49-17	3.42-16	5.60-13	3.04-18	3.41-16	4.62-13	3.14-18
500	2.30-16	3.51-12	1.10-17	2.30-16	3.32-12	1.10-17	1.42-16	5.10-13	2.29-18	1.26-16	1.73-13	1.76-18
600	8.90-17	1.28-12	4.60-18	8.31-17	8.46-13	3.96-18	7.59-17	8.68-13	2.36-18	4.44-17	4.62-13	1.15-18
800	1.55-17	2.05-13	1.24-18	8.95-18	1.81-14	9.08-19	1.37-17	1.63-13	6.09-19	7.86-18	9.30-15	3.70-19
1000	2.63-18	3.11-14	4.16-19	1.72-18	3.41-15	3.75-19	2.58-18	3.11-14	2.02-19	1.50-18	1.54-15	1.58-19

and was part of water. In the first case, the scattering of thermal neutrons is described in MCNP within the framework of a heavy gas model, and thermalization effects are taken into account using $S(\alpha,\beta)$ functions in the second case[1] The calculations showed that the consideration of thermalization effects for all spatial points does not lead to changes of the functionals by more than 2.0 - 3.0% (which is comparable with the statistical error of the calculation results for $R \approx 1000$ m).

The influence of the soil on the neutron and photon fields formation is very great. **Table 3** presents the results of the calculations of D_n, $D\gamma$, F_{tot} and F_{nt} for the same meteorological conditions in the event of the presence of the soil and without it. The following soil composition with $\rho = 1.77$ g/cm^3 was assumed in the calculations: H - $9.60 \cdot 10^{21}$ nuc/cm^3, O - $3.69 \cdot 10^{22}$ nuc/cm^3, Si - $1.18 \cdot 10^{22}$ nuc/cm^3, Al - $4.93 \cdot 10^{21}$ nuc/cm^3. As the presented data shows, the soil contribution dominates during estimations of the thermal neutron flux density (more than 95%) and the secondary photons dose rate (from 96% in 100 m to 70% in 1000 m). The neutron dose rate is determined by the soil contribution approximately by 40-60%.

The D_γ calculation results indicate that even small shares of elements yielding a lot of capturing photons should be taken into account in determining the soil composition. At the same time, the calculations done for the same soil composition but with the addition of 2.5% of Fe (by weight) did not show changes in the $D\gamma$ values within the limits of the statistical error of the calculation. The presence of iron is found only in the energy distribution of photons in the spatial points with $R \ge 600$ m by the appearance of poorly noticeable peaks in the energy regions of 7.50 - 8.00 MeV. As it follows from the results presented in Table 2, the values of F_{nt} and D_n are determined by neutrons going out from local soil region near the detection point. Contrary to this, the secondary photons dose is determined to a large extent by the soil regions that are nearer to the source that the detection point.

The energy spectrum of the neutrons scattered in the air and the soil is much more milder than the bundle going out to the atmosphere. The soil substantially mitigates the neutron spectrum in the energies range from thermal energy to 2.5 MeV. When it is higher than 2.5 MeV, the spectrum is fully determined by the scattering on the air nitrogen nuclei.

The biggest contributors to the D_n dose rate are neutrons with the energies of 0.1 to 2.5 MeV (up to 70% for all spatial points), some 20% are the slowdown neutron are $E_n < 0.1$ MeV) and the remaining portion is the contribution of fast neutrons with $E_n > 2.5$ MeV.

The D_n and F_{tot} weakening curves are practically parallel and their spatial dependence is described by the expression:

$$D(R) = \frac{D_0 \cdot e^{-R/\lambda}}{R}, \qquad (1)$$

where R is the distance from the source to the detector, D_0 and λ are empirical parameters. Though these empirical ratios describe the calculated and experimental data rather accurately, they are of a little practical value as they are limited by the type of the source that was used in the calculation. Taking into account the role of the energy spectrum of the neutrons going out to the atmosphere, we may say that the value of the empirical ratios is limited by the initial neutron spectrum (Table 1).

The consideration of the dependencies that were revealed during the parametric calculation research has allowed to considerably optimize the calculation pattern. As an example, Table 4 presents the results of a calculation and an experiment for one of the series of measurements of 30.09.97 that were done on the Baykal bench with an RA reactor. The MCNP calculations were done with a constant library using ENDF/B-VI data. It also presents the results of the calculation using DORT code [3]with a 22 group library of constants calculated using NJOY program [4]also from ENDF/B-VI files.

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