

EXPOSURE BUILDUP FACTORS IN CONCRETE, LEAD FOR POINT ISOTROPIC AND UNIDIRECTIONAL PHOTON SOURCES IN THE ENERGY RANGE FROM 10 TO 50 MeV

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The exposure buildup factors in concrete and lead for a point isotropic and flat unidirectional photon source in the energy range from 10 to 50 MeV were determined using Monte Carlo simulation “FLUKA” software. The exposure buildup factors were also obtained for different material thickness up to 40 mpf. The calculations were done in a barrier geometry where the contributions of all photon-matter interactions were taken into account in the performed calculations. Amendments for the barrier-geometry effect for both materials under study were deduced. The results showed that barrier-effect amendments were independent of the material thickness, material type, and energy of the photon source

Keywords: *Bremsstrahlung, buildup factor, doses, electronic accelerators, isotropic, shielding.*

1. INTRODUCTION

The wide usage of linear electron accelerators (especially accelerators producing electron beam energy up to 50 MeV) in medicine and therapy increases the need to improve the radiation safety of personnel and the public. Such improvement requires the enhancement of the methodological basis for designing the shielding of such installations. A significant step in this direc-

tion is to obtain the attenuation properties of the shielding materials used in the radiation protection of these installations taking into account the scattered radiation [1]. One of these properties is the so-called buildup factor which can be calculated using advanced engineering methods by the calculation of the scattered radiations. The information available in the literature for photon buildup

factors for various protective materials [2]–[4] is limited especially for a point isotropic monoenergetic photon source in the energy range from 10 to 50 MeV.

In this study, we performed calculations of the dose (absorbed dose rate in air) distributions of photons in barriers made of concrete and lead with a density of 2.3 and 11.3 g / cm³[3], respectively, with thickness up to 30 mean free paths for a point isotropic source of monoenergetic photons with

energy of 10, 20, 30, 40 and 50 MeV. The calculations were done using the Monte Carlo method FLUKA [5]. All types of “photons with matter” interactions and contributions of characteristic, annihilation, and bremsstrahlung radiation to the calculated dose were taken into account. The transition from the free path length (mfp) to the true distance in linear dimensions was performed using the mass attenuation coefficients of photons from the publications [2], [6].

2. METHODOLOGY

The geometries of the concrete and lead

are identical and are shown in Fig. 1.

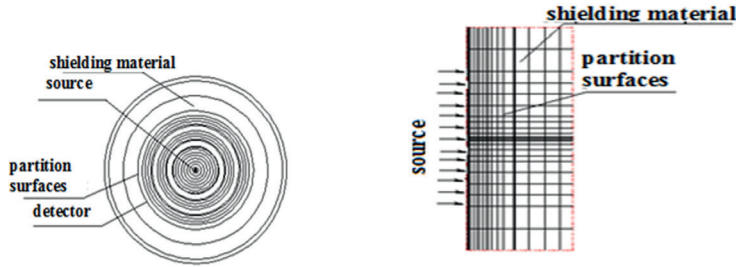


Fig. 1. Geometries of the considered compositions: a) – point source, b) – unidirectional source).

To examine the influence of the source geometry on the shielding properties of the concrete and lead, two cases were considered: (i) spherical geometry with a point isotropic source in the centre of the sphere and (ii) cylindrical geometry with a flat unidirectional source whose radiation falls normally on the end surface of the cylinder. In order to test the effect of barrier protection on shielding properties, calculations were performed selectively in the barrier geom-

etry. The thickness of the materials was selected to be ranged from 0 to 30 mean free paths for the point source. The radius of the cylindrical shielding was 1000 cm for concrete and 300 cm for lead. The radius of the unidirectional source was assumed to be 300 cm for concrete shielding and 200 cm for lead shielding. To calculate the absorbed dose rate in air, the specific dose coefficients given in Table 2 were used and the following formula was utilized:

$$\delta = 10^5 E_\gamma \cdot 1.6 \times 10^{-13} \mu_{\text{em}}^m(E_\gamma), \text{ cGy} \cdot \frac{\text{cm}^2}{\text{photon}}, \quad (1)$$

where E_γ – the photon energy, in MeV;

$\mu_{\text{em}}^m(E_\gamma)$ – a photon energy-absorption coefficient for air with energy E_γ ; cm²/g, 1.6×10^{-13} ;

J/MeV – a transition coefficient from Joule to MeV.

The values of δ for photon energy less than 10 MeV were taken from [5], and large photon energies are calculated by means of Eq. (1) using $\mu_{\text{em}}^m(E\gamma)$, taken from [6].

Moreover, the photon mass attenuation coefficients [2], [6] given in Table 1 were used for the transition from the mean free path to the true distance in linear dimensions.

Table 1. Photon Mass Attenuation Coefficient for Lead and Concrete, cm^2 / g

Energy of photon sources, MeV	Shielding materials	
	Lead	Concrete
10 [2]	0.02311	0.0497
20 [2]	0.02105	0.0621
30 [2]	0.02105	0.0702
40 [6]	0.0212	0.0765
50 [6]	0.0217	0.0811

Table 2. Specific Dose Coefficients for Photons of Different Energy Ranges, $\text{c Gy cm}^2 / \text{photon} \times 10^{-9}$

$E\gamma$	δ
0.1	0.0037
0.2	0.0086
0.5	0.238
1	0.45
2	0.756
3	1
4	1.22
5	1.43
6	1.62
8	2.01
10	2.33
15	3.26
20	4.26
30	6.19
40	8.13
50	10.6

The total absorbed dose rate was then calculated using Eq. (2):

$$\dot{D} = \int \varphi(E)\delta(E)dE. \quad (2)$$

FLUKA (Fasso et al., 2005) is a broadly useful tool for computations of particle transport and interactions with matter, covering a drawn-out scope of utilizations traversing from proton and electron accelerator shielding to target design. FLUKA can simulate of about 60 different particles with high exactness, including photons, electrons, neutrons, heavy ions, and antiparticles. The program

can also transport polarized photons (e.g., synchrotron radiation) and optical photons. The lowest transport limit for all particles is 1 keV [7].

FLUKA Monte Carlo code gives a BEAM input file by which picking the particle kind, its energy, its direction and beginning position is conceivable. For more complicated circumstances, a dedicated “user routine” is liked. FLUKA input file comprises various data commands, each consisting of at least one line in the file [8], [9]. Input data for FLUKA were organised in a specific successive order according to code details. A simple cylinder

geometry with the axis along the z-direction was described in the input file.

A concrete material was defined by a MATERIAL card in addition to as many COMPOUND words as required to describe

concrete composition. The MATERIAL card used to define a compound composition carried the compound name, density, and material number (if input is explicitly number based) etc.

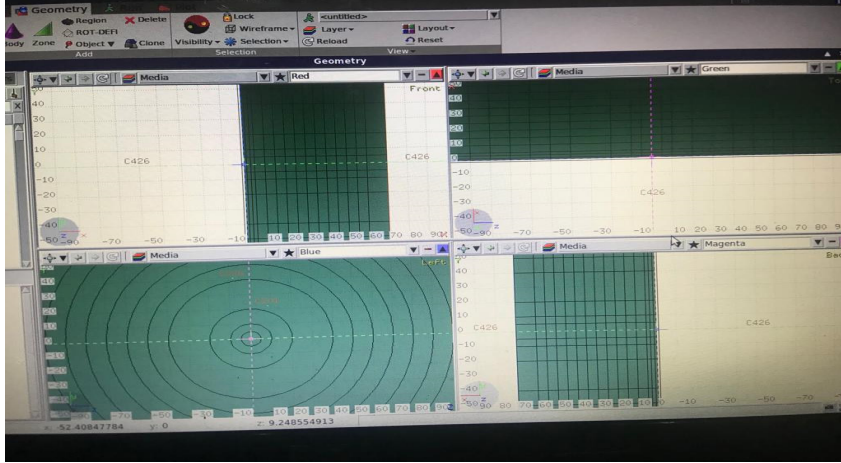


Fig. 2. Screenshot of Flair interface for top view of target geometry.

The transmission values were acquired utilizing USRBDX score card, after the code run for five cycles, with various sample thicknesses. USRBDX is the order used to characterise a detector for the boundary-crossing estimator. It calculates fluence, mono or bidirectional, differential in energy and angle on any boundary between two

selected regions [2]. The uncertainty in transmission data values for all calculations was under 1%. Photon transmission results of simulations were taken from output files using Flair (see Fig. 2), which is FLUKA Advanced Interface, a data analysis interface compatible with FLUKA [10].

3. RESULTS AND DISCUSSION

Figure 3 shows the calculated spatial distributions of the absorbed dose in the air for concrete and lead shielding materials for two types of sources with the photon energy of 40 MeV. To compare both results, the results of the absorbed dose for the point isotropic source must firstly be multiplied by $4\pi R^2$, where R is the distance between the source and the detector. Then they can be compared with data for the flat unidirectional source. The comparison showed that the spatial distributions for all shielding materials at thicknesses up to 15 mfp were

in a good agreement with an uncertainty of 5 %. The difference in large thicknesses of shielding, reaching up to 30 %, is due to uncertainty in the results for a unidirectional source. The dose rate resulting from the source's non-scattered radiation was calculated analytically, which made it possible to determine the dose factors of photon accumulation. The buildup factor depends on the angular distribution of the photons generated from the point isotropic source as shown in Table 3, Table 4, and Fig. 4. The exposure buildup factors of concrete

for a point isotropic photon source with an energy of 10 MeV calculated by FLUKA are presented in Fig. 5. Also, Fig. 5 shows the exposure buildup factors of concrete for the flat unidirectional source with an energy of 10 MeV calculated by FLUKA. Furthermore, these results are also compared with results of other studies [1], [11]. The comparison shows an excellent agreement of about 5 %. Similarly, the exposure buildup factors of lead for a point isotropic photon source with an energy of 10 MeV calculated by FLUKA are presented in Fig. 6. Also, Fig. 6 shows the exposure buildup factors of concrete for the flat unidirectional source with an energy of 10 MeV calculated by FLUKA. In addition, these results are also compared with results of other studies [2], [3], [11]. The comparison shows an excellent agreement of about 5 %. These results indicate the reliability of the calculated

results and the acceptability of the calculation method used.

Further investigations were done in this study. The buildup factors for lead obtained for monoenergetic photon sources in our study were compared with those buildup factors for lead presented in [12] for sources of bremsstrahlung photon radiation generated by electrons with different energies as seen in Fig. 7. The buildup factors for concrete obtained for monoenergetic photon sources in our study were compared with those buildup factors for concrete presented in [12] for sources of bremsstrahlung photon radiation generated by electrons with different energies. It was found that for all photon energies of the source, the buildup factors for monoenergetic sources were higher than the corresponding buildup factors for bremsstrahlung radiation sources as seen in Fig. 7.

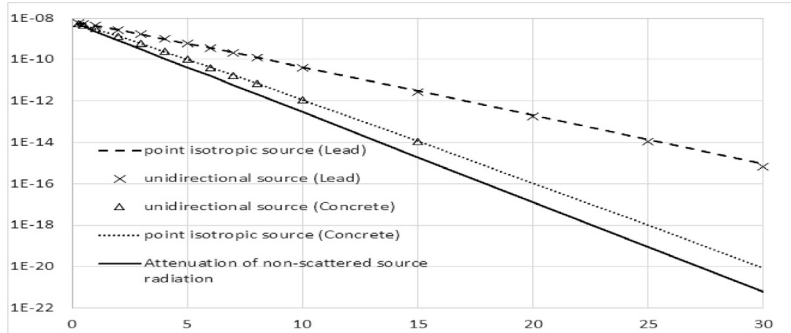


Fig. 3. Spatial distribution of the photon dose absorbed in lead, and concrete, from point isotropic and planar unidirectional photon sources with an energy of 30 MeV. Attenuation of non-scattered source radiation.

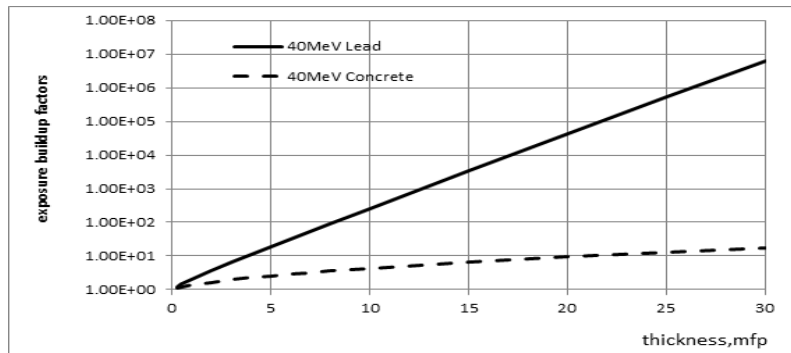


Fig. 4. Exposure buildup factors of photon in concrete and lead for a point isotropic photon source with energy of 40 MeV.

Table 3. Exposure Buildup Factors of Photon in Concrete and Lead Shielding for a Ppoint Isotropic Source with Photon Energy from 10 to 50 MeV

Material	Concrete					Lead				
E. MeV	10	20	30	40	50	10	20	30	40	50
mfp										
0.25	1.13	1.06	1.1	1.1	1.1	1.13	1.16	1.17	1.22	1.25
0.5	1.24	1.13	1.19	1.19	1.2	1.27	1.37	1.42	1.45	1.44
1	1.44	1.27	1.35	1.36	1.37	1.49	1.71	1.9	2.01	2.06
2	1.78	1.51	1.62	1.66	1.72	1.97	2.68	3.24	3.68	3.85
3	2.12	1.76	1.89	1.95	2.05	2.57	4.06	5.38	6.42	6.94
4	2.47	1.99	2.16	2.26	2.42	3.33	6.17	8.82	11.04	12.31
5	2.81	2.23	2.44	2.55	2.79	4.29	9.26	14.34	18.95	21.44
6	3.16	2.48	2.72	2.88	3.22	5.51	13.94	23.23	32.04	37.46
7	3.51	2.73	3.02	3.21	3.65	7.06	20.81	37.48	54.03	65.15
8	3.87	2.99	3.42	3.73	4.13	9.02	31.2	60.32	91.4	112.92
10	4.63	3.51	3.97	4.3	5.19	14.55	69.3	154	256	337
15	6.5	4.98	5.87	6.51	8.61	47.46	497	1603	3345	5049
20	8.56	6.63	8.12	9.32	13.68	150	3488	1.62E+4	4.23E+4	7.42E+4
25	10.74	8.34	11.38	12.77	20.54	461	2.38E+04	1.60E+05	5.28E+05	1.07E+06
30	12.79	9.11	14.81	17.58	27.46	1378	1.60E+05	1.55E+06	6.49E+06	1.51E+07

Table 4. Comparison of Exposure Buildup Factors of Photon in Concrete and Lead for a Point Isotropic Photon Source (FLUKA) with Energy of 10 MeV Obtained in Different Publications (P.S – point isotropic source, U.S – unidirectional source)

Material	Concrete				Lead				
Mfp	P.S	[1]	[11]	U.S	P.S	[2]	[3]	[8]	U.S
0.25	1.13			1.14	1.13				1.16
0.5	1.24	1.23	1.25	1.24	1.27	1.28	1.29	1.32	1.27
1	1.44	1.42	1.44	1.42	1.49	1.51	1.51	1.55	1.48
2	1.78	1.73	1.79	1.75	1.97	2.01	1.97	2	1.97
3	2.12	2.03	2.13	2.08	2.57	2.63	2.54	2.51	2.55
4	2.47	2.34	2.46	2.39	3.33	3.42	3.26	3.13	3.27
5	2.81	2.64	2.79	2.71	4.29	4.45	4.17	3.89	4.16
6	3.16	2.94	3.12	3.03	5.51	5.73	5.32	4.82	5.26
7	3.51	3.26	3.46	3.35	7.06	7.37	6.78	5.97	6.63
8	3.87	3.57	3.79	3.68	9.02	9.44	8.6	7.4	8.33
10	4.63	4.2	4.47	4.34	14.55	15.4	13.8	11.4	12.96
15	6.5	5.8	6.21	6.33	47.46	50.8	42.8	33.7	38.46
20	8.56	7.47	8		150	161	128	100	108.5
25	10.74	9.18	9.83		461	4.95E+02	3.69E+02	2.94E+02	3.89E+02
30	12.79	11	11.7		1378	1.47E+03	1.03E+03	8.52E+02	2.87E+03

As mentioned above, Tables 3 and 4 above show that the buildup factors in concrete and lead in the considered range of photon energies of the source depend on the angular distribution of the photons. In addition, the results presented in Tables 3 and 4 for point isotropic sources and for flat uni-

directional sources are in a good agreement and the difference does not exceed 5 % for a given concrete thickness and does not exceed 10 % for lead thickness below 20 mfp. This leads to the conclusion that we can use any of both types of radiation sources when performing approximate

shielding calculations. Depending on the photon energy of the source, the minimum values of the buildup factors for concrete are observed at energy of 20 MeV, and then they increase with the growth of the pho-

ton energy of the source. As the thickness of lead increases, the difference increases to 30 %, and the buildup factor for a point isotropic source is higher than the buildup factor for a flat unidirectional source.

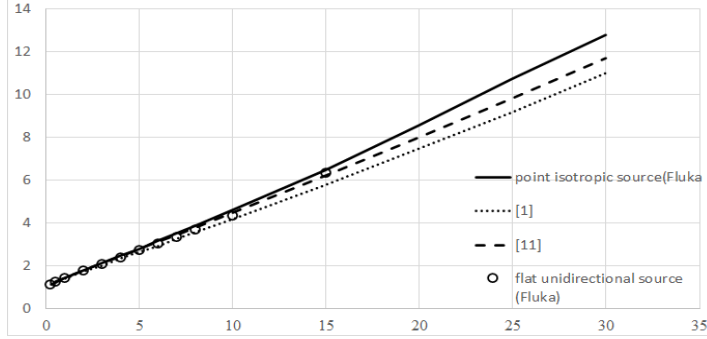


Fig. 5. Comparison of exposure buildup factors in concrete for a point isotropic photon source with energy of 10 MeV [1], [11].

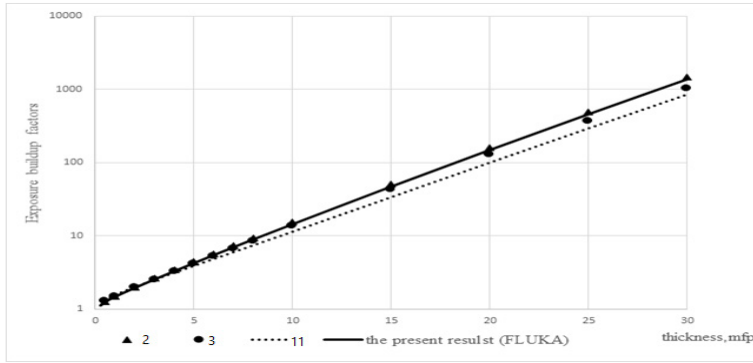


Fig. 6. Comparison of exposure buildup factors of photon in lead for a point isotropic photon source (FLUKA) with energy of 10 MeV [2], [3], [11].

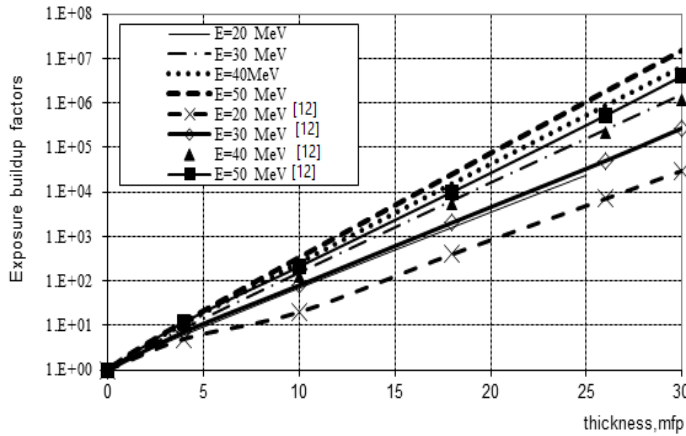


Fig. 7. Comparison of buildup factors of photon for lead obtained for monoenergetic photon sources in this paper and sources of bremsstrahlung [12].

4. AMENDMENT FOR THE BARRIER ENVIRONMENT FOR CONCRETE AND LEAD

Based on the results of calculations of the dose characteristics of photon fields in the materials under consideration in barrier geometry at shielding thickness of 5 and 10 mfp, amendment for barrier shielding was determined in the form of the ratio of buildup factor in barrier geometry to similar

ones in an infinite medium. The calculated amendment was given for the materials under consideration in Tables 5 and 6; the amendment did not depend on the source photon energy and the protection thickness and was equal to 0.961 ± 0.006 for concrete, and 0.982 ± 0.004 for lead, respectively.

Table 5. Amendment for the Barrier Nature for a Medium of Concrete

mfp	5					10				
E, МэВ	10	20	30	40	50	10	20	30	40	50
δ	0.950	0.964	0.964	0.962	0.970	0.950	0.954	0.962	0.959	0.968

Table 6. Amendment for the Barrier Nature for a Medium of Lead

mfp	5					10				
E, МэВ	10	20	30	40	50	10	20	30	40	50
δ	0.979	0.979	0.980	0.980	0.980	0.982	0.978	0.982	0.978	0.976

5. CONCLUSIONS

Comparison of the calculated buildup factor with those available in the literature [2], [3], [6] for a photon source with an energy of 10 MeV, for concrete and lead showed their agreement within 5 %, which indicated the reliability of the calculated results and the acceptability of the calculation technique used. Moreover, some over-estimation of the buildup factor obtained in this work more coincides with reality, since our calculations took into account all the processes of interaction of photons with matter, but the result in the literature did not take into account the coherent scattering of photons, which led to noticeable errors in

calculation of the buildup factor obtained in these works.

Based on the results of calculations of the dose characteristics of photon fields in the materials under consideration in the barrier geometry at shielding thickness above 3 mfp, amendment for the barrier shielding was determined in the form of the ratio of buildup factors in the barrier geometry to similar ones in an infinite medium. In the considered range of material thickness, the amendment did not depend on the source photon energy and the shielding thickness and was equal to 0.960 ± 0.006 for concrete, and 0.982 ± 0.004 for lead, respectively.

REFERENCES

1. Sakharov, V. K., & Borisenko, A. V. (2014). Photon Dose Accumulation Factor in Concrete, Iron, and Lead for 10–50 MeV Microenergetic Sources. *Atomic Energy*, 114, 225–228. doi:10.1007/s10512-014-9845-9
2. American National Standard. (1991). *Gamma-Ray Attenuation Coefficients and Buildup Factors for Engineering Materials*. ANSI/ANS-6.4.3-1991.
3. Durani, L. (2009). *Update to ANSI/ANS-6.4.3-1991 for Low-Z and Compound Materials and Review of Particle Transport Theory*. PhD Thesis. Available at <http://dx.doi.org/10.34917/1363554>
4. Mashkovich, V.P., & Kudryavtseva A.V. (1999). *Protection from Ionizing Radiation*. Reference book. Moscow: Energoatomizdat.
5. Fasso, A., Ferrari, A., & Sala, P. R. (2001). Electron – photon transport in FLUKA: Status. In *Proceedings of the Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation, and Applications* (pp. 159–164), Lisbon, 2000. Berlin; Heidelberg: Springer.
6. Storm, E., & Israel', K.H. (1973). *Cross Sections for the Interaction of Gamma Radiation*. Spravochnik. Per. s angl. Pod red. Klimanova V. A. Chistova Ye.D. M. Atomizdat. (in Russian).
7. Patil, B. J., Chavan, S. T., Pethe, S. N., Krishnan, R., Bhoraskar, V. N., & Dhole, S. D. (2010). Simulation of $e-\gamma-n$ Targets by FLUKA and Measurement of Neutron Flux at Various Angles for Accelerator Based Neutron Source. *Annals of Nuclear Energy*, 37 (10), 1369–1377. <http://dx.doi.org/10.1016/j.anucene.2010.05.009>
8. Ferrari, A., Sala, P. R., Fasso, A., & Johannes, R. (2005). *FLUKA: A Multi-Particle Transport Code* (Program version 2005). Geneva: CERN. Doi: 10.5170/cern-2005-010.
9. Mark, S., Khomchenko, S., Shifrin, M., Haviv, Y., & Schwartz, J. R. (2007). TVF-NMCRC—A Powerful Program for Writing and Executing Simulation Inputs for the Fluka Monte Carlo Code System. *Nuclear Instruments and Methods in Physics Research. Section A, Accelerators, Spectrometers, Detectors and Associated Equipment*, 572 (2), 929–934. <https://doi.org/10.1016/j.nima.2006.12.007>
10. Vlachoudis, V. (2009). FLAIR: A powerful but user-friendly graphical interface for FLUKA. In *International Conference on Mathematics, Computational Methods & Reactor Physics 2009*, (pp. 790–800). 3–7 May 2009, Saragota Springs, New York.
11. Ashimizu, A., Onda, T., & Sakamoto, Y. (2004). Calculation of Gamma-Ray Buildup Factors up to Depths of 100 mfp by the Method of Invariant Embedding, (III). *J. Nucl. Sci. and Technology*, 41 (4), 413–424.
12. Bespalov, V.I. (2011). *Lectures on Radiation Protection*. Study guide (3rd ed.) Tomsk: Publishing House of Tomsk Polytechnic University. (in Russian).