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ХАРАКТЕРИСТИКИ ПОЛЕЙ ФОТОННОГО ИЗЛУЧЕНИЯ В СВИНЦЕ ДЛЯ ИСТОЧНИКОВ ФОТОНОВ С ЭНЕРГИЯМИ ОТ 10 ДО 50 МэВ

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По результатам расчетов методом Монте-Карло пространственных распределений энергии фотонов в свинце от точечных изотропных и плоских однонаправленных моноэнергетических источников с энергиями 10-50 МэВ определенные кратности ослабления воздушной кермы и дозовые факторы накопления рассматриваемым материалам. В расчетах учитывается вклад флуоресценции, аннигиляционного излучения и тормозного излучения. Показана независимость факторов накопления и кратностей ослабления от углового распределения излучения источника и слабая зависимость кратностей ослабления от его энергии в диапазоне энергий 30-50 МэВ. Определены поправки на барьерную защиту и отмечена их независимость от толщины защиты и энергии фотонов источника. Полученная информация позволяет уменьшить погрешности в результатах расчетов толщины противорадиационной защиты электронных ускорителей при высоких энергиях, используя разработанные инженерные методы расчета. Полученная информация может быть также использована в расчетах защиты от тормозного излучения электронных ускорителей инженерными методами.

Ключевые слова: электронные ускорители, тормозное излучение, защита, дозы, фактор накопления, Кратности ослабления, Монте-Карло.

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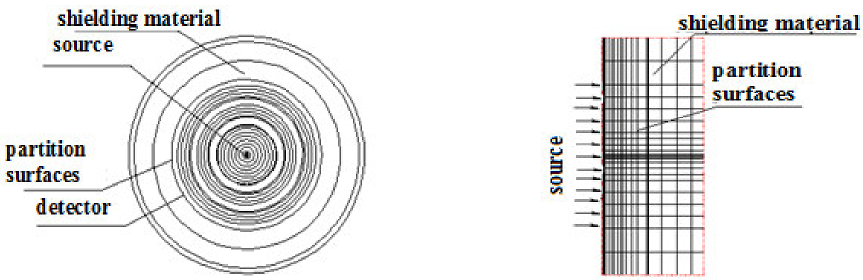
Introduction

The linear electron accelerators use with primary electron beam energy in the range of up to 50 MeV for remote radiation therapy , defectoscopy and an increase in the requirements for ensuring the radiation safety of personnel and the population necessitate the improvement of the methodological base for designing the protection of such installations [1]. It is important to obtain the attenuation characteristics of the bremsstrahlung photons used in their protection materials for this energy range, taking into account the scattered radiation. Accounting to scattered radiation in developed engineering methods for calculating photon protection is usually carried out using the attenuation factor and accumulation factors.

The information available in the literature on the transmission of photon radiation in various protective materials [2, 3, 4] is limited for the photon energies of the source below 15 MeV. The electron accelerators use in industry and medicine with primary electron beam energy in the range up to 50 MeV leads to serious demand to obtain data on the attenuation characteristics of bremsstrahlung photons for this energy range. Concrete, iron, and lead are used as shielding materials from the bremsstrahlung of electron accelerators, so the goal of this research was to obtain the characteristics of the photon radiation fields for one of these materials. The material that was studied in this article is lead.

The geometries of the studied compositions, differing only in size for different materials, were identical and are shown in figure 1.



a) b)

Figure1 – Geometries of the considered compositions: a) – point source, b) – mono-directional source)

To assess the influence of the composition geometry on the characteristics of the photon fields, two cases were considered: spherical geometry with a point isotropic source in the center of the sphere and cylindrical geometry with a flat mono-directional source whose radiation falls normally on the end surface of the cylinder. The dimensions of the defenses were chosen so that the geometry could be considered infinite. The thickness of the material was 45 mean free path for the photon energy source. The radius of the cylindrical protection was 300 cm for Lead. The radius of the mono-directional source was assumed to be 200 cm for Lead shield.

The shielding material under study is Lead with a density of 11.3 g/cm^3 [3]. The photon energies of the source were chosen equal to 10, 20, 30, 40, and 50 MeV.

Calculations of the characteristics of photon fields were performed using the Monte Carlo- FLUKA program [5]. An estimate was used for the intersections of the surfaces shown in Fig.1, located at different distances from the radiation source, and local estimation of the flow at a point isotropic source.

The absorbed dose rates in the air, dose accumulation factors, and energy distributions of the photon flux density at different distances from the source were taken as characteristics of the photon radiation fields. At the same time, the average of these values on the cylinder axis were estimated for a mono-directional source. The FLUKA program calculates the energy distributions of the photon flux density in the material under consideration. These distributions were calculated at distances from the source from 0.25 to 30 mean free path. In this case, 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, cm^2/g

Energy of photons Source, MeV	shielding material
	Lead
10 [2]	0.0497
20 [2]	0.0621
30 [2]	0.0702
40 [6]	0.0765
50 [6]	0.0811

The transition from the energy distributions of the photon flux density to the power of the dose absorbed in the air was carried out on the basis of specific dose factors calculated by the formula (1):

$$\delta = 10^5\, E_\gamma\ 1{,}6 \cdot 10^{-13}\, \mu^{m}{}_{eni}(E_\gamma)\,, \quad c\ Gy\ cm^2\,/\,photon, \qquad (1)$$

in which Eγ is the photon energy, in MeV;

$\mu^{m}{}_{en,}(E_\gamma)$ – photon energy-absorption coefficient for air with energy E_γ;
in cm^2/g, $1{,}6 \cdot 10^{-13}$ *J/MэB – transition coefficient from joules to MeV.*

The values of δ for photon energy less than 10 MeV were taken from article [3], and for large photon energies are calculated using the formula (1.1) using $\mu^{m}_{en,}$ (E_γ), taken from article [6]. The obtained values δ are shown in table 2.

Table 2 – Specific dose coefficients for photons of different energies, c Gy cm^2 / photon*10^{-9}

E_γ	0.1	0.2	0,5	1	2	3	4	5	6	8	10	15	20	30	40	50
δ,	0.0037	0.0086	0.238	0.45	0.756	1	1.22	1.43	1.62	2.01	2.33	3.26	4.26	6.19	8.13	10.6

The total absorbed dose rate was then calculated using the formula (2):

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

Using linear interpolation.

Obtaining the characteristics of the photon fields at source energy of 10 MeV allowed us to compare the results obtained in this study with the available literature data and thus was used to test the calculation methodology and software used in this study.

Spatial distributions of the absorbed dose

Figure 2 and figure 3 show the spatial distribution of the total absorbed dose rate in air, taking into account the scattered radiation in Lead for two types of photon radiation sources, normalized to the unit source dose. Moreover, in the figure 1 for a point isotropic source, the results are multiplied by $4\pi R^2$, where R is the distance from the source to the detection point, to take into account geometric attenuation.

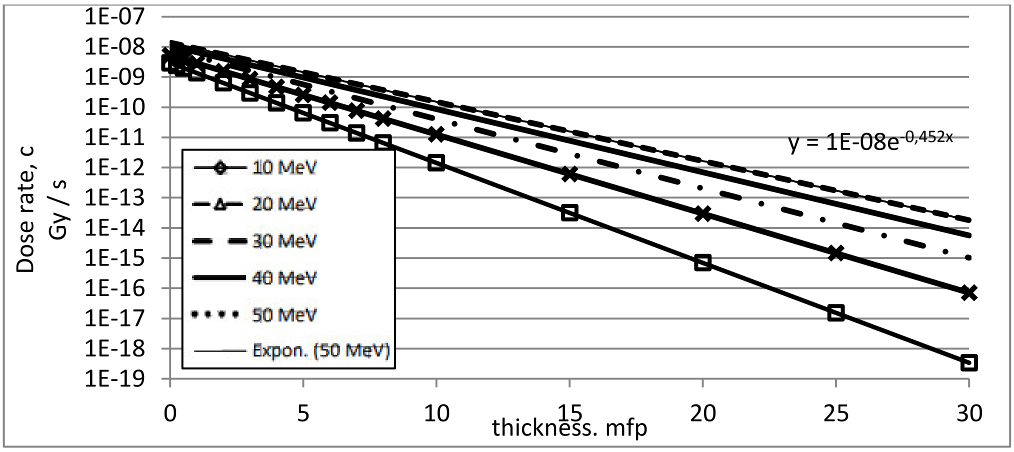


Figure 2 – Spatial distributions in Lead of the power of the absorbed dose of photons in the air from point isotropic photon sources with different energies with a power of 1 photon./s (results multiplied by $4\pi R^2$)

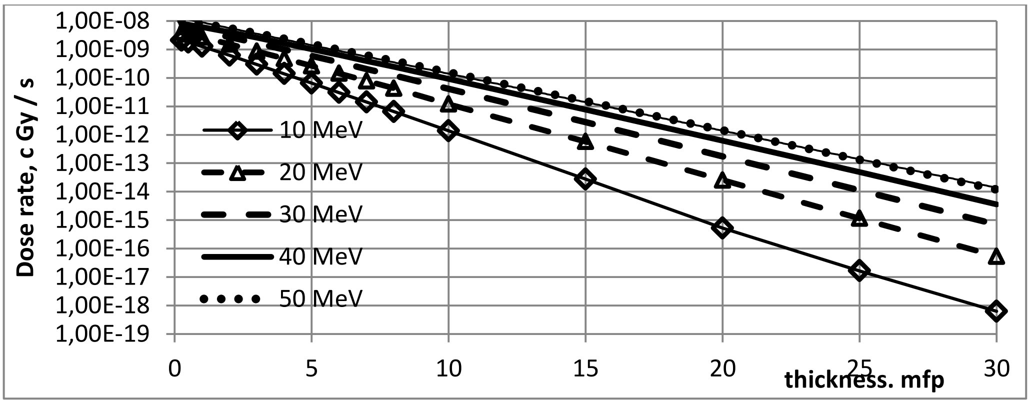
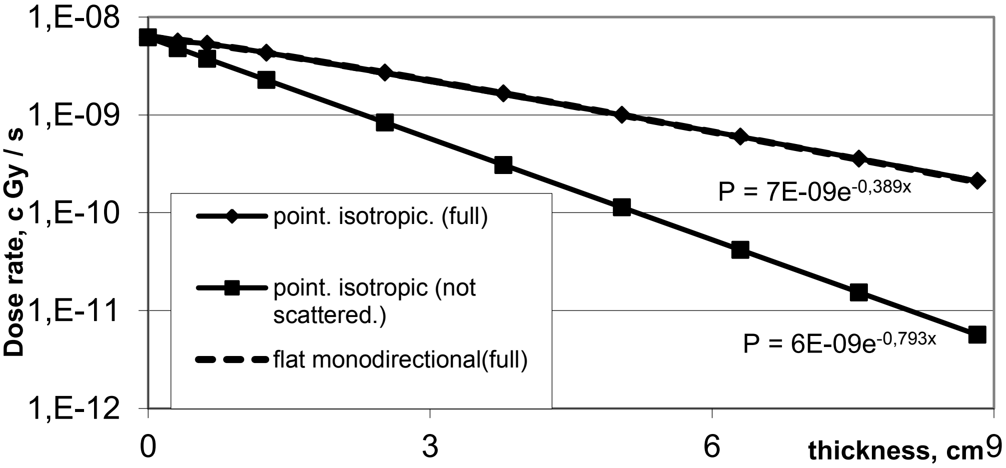
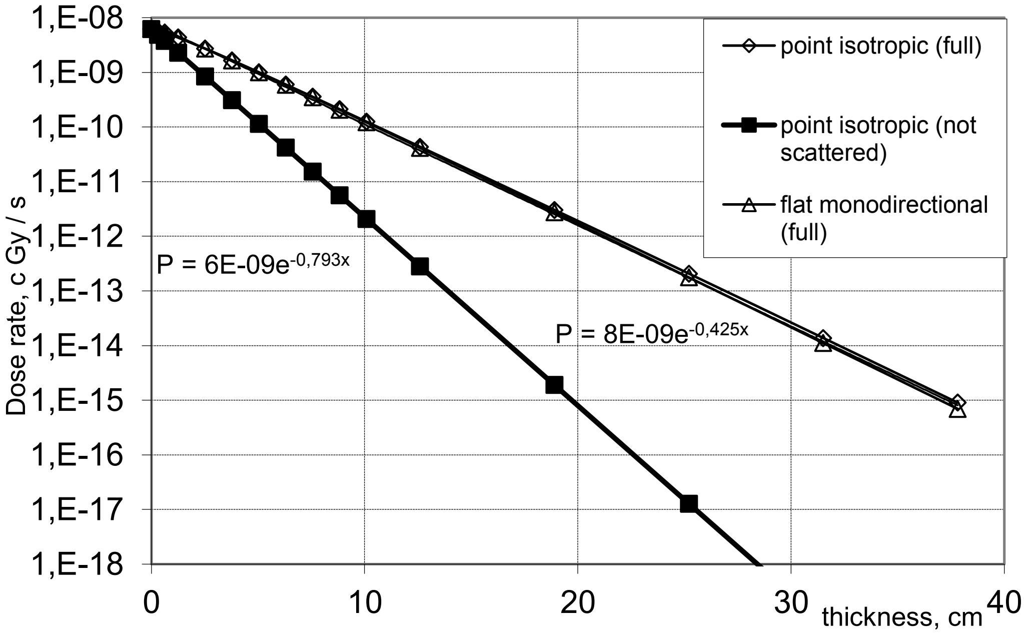


Figure 3 – Spatial distributions in lead of of the absorbed dose of photons in the air from flat mononirectional photon sources with different power energies 1 photon / s. cm^2

The attenuation character of the total absorbed dose rate in Lead is close to exponential, but still different from it, as can be seen from the exponential trend lines shown in the figures for sources with different emitted photon energies. For a more visual representation of this fact as an example in figure 4. The data on the distribution of the total dose rate and dose rate of unscattered radiation for a source with photon energy of 30 MeV are presented.



a)



b)

Figure 4 – Spatial distribution of the absorbed dose rate of photons in lead at thicknesses (0-9) cm (a) and (0-40) cm (b) from a point isotropic power of 1 s^{-1} and a flat mono-directional power of 1 $cm^{-2}.s^{-1}$ sources with photon energy of 30 MeV (for a point source, the results are multiplied by $4\pi R^2$)

The attenuation characteristics of the total dose rate for a point isotropic and a flat mono-directional source practically coincide. The drawn trend lines show that upon interpolation of distributions in the 0–10 cm section of Lead thickness, the exponent is 0.389 cm $^{-1}$, and in the 0–40 cm section, it is 0.425 cm $^{-1}$ and the intersection points of these exponentials with Y axis do not coincide.

The dose rate generated by the undistracted radiation of the source was calculated analytically and Fig. 3 shows, for example, these data for a photon source with energy of 30 MeV.

In the data practical use, the attenuation of photons in Lead, it seems advisable to use dose factors for the accumulation of photons that take into account the difference in the nature of attenuation from exponential or to use the Exposure Buildup Factors of the power of the total absorbed dose. These results are consistent with those reported in [10].

Attenuation coefficient of absorbed dose rate

These data show that in almost the entire range of Lead shielding thicknesses considered, regardless of the source photon energy, the attenuation coefficient of the absorbed dose, does not depend on the angular distribution of the source photons with an error less than 10-15%. Only when the shielding thickness is 30 *fmp*, the difference increases, which is explained by errors in the calculation of doses for a mono-directional source.

The dependence of the power attenuation coefficient of the absorbed dose on the Lead thickness for point isotropic photon sources of different energies is shown in figure 5.

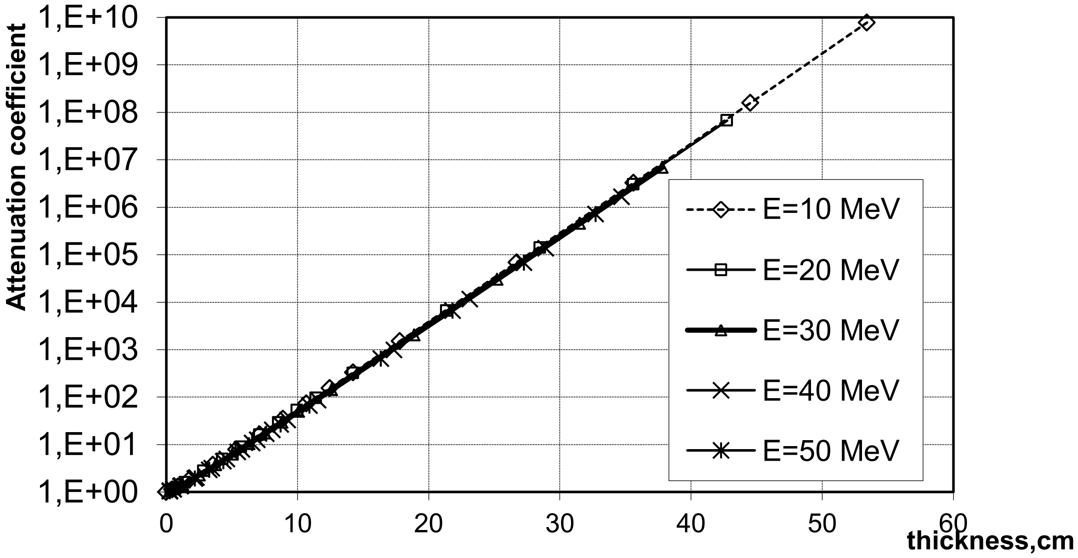


Figure 5 – Dependence of the attenuation coefficient of the absorbed dose in lead on the protection thickness for point isotropic photon sources with different initial energy

It can be noted that the attenuation coefficient of the absorbed photon dose at source energies from 10 to 50 MeV practically does not depend on this energy, if Lead thickness is measured in linear dimensions, and not in mean free path lengths of the source photons. These results are consistent with the results given in the [10].

Tenfold attenuation layer

Often, the values of the tenfold attenuation layer are used to calculate the thickness of the shield that provides a given attenuation coefficient, and their dependence on the thickness of the shielding is often neglected. The inadmissibility of this approach is shown in table 3. Calculated tenfold attenuation layer of dose rate attenuation at different Lead shielding thicknesses for a point isotropic source with different photon energies.

Table 3 – Tenfold attenuation layer of the absorbed dose power by lead shielding, cm

No. layer's	Thickness, cm	Source energy, MeV				
		10	20	30	40	50
1	0-6	6	6	6.2	6.4	6.4
2	6-12	5.4	5.5	5.6	5.6	5.6
3	12-18	5.5	5.5	5.5	5.4	5.4
4	18-23	5.4	5.4	5.4	5.4	5.4
5	23-28	5.3	5.4	5.4	5.4	5.4
6	28-34	5.3	5.4	5.4	5.4	5.4

Data analysis shows that the first two layers of tenfold attenuation are weaker than the next, and this is most clearly visible when the first layer differs from the rest. Starting with a layer thickness of 12 cm, the value of the tenfold attenuation layer is almost independent of the thickness of the Lead shielding and the photon energy of the source. In this range, it can be assumed to be equal to 5.4 ± 0.1 cm. As a result, table 3 can be reduced to table 4.

Table 4 – Averaged tenfold attenuation layer of the absorbed dose power by Lead shielding, cm

No. layer's	Thickness, cm	The energy of source photons, MeV				
		10	20	30	40	50
1	0-6	6		6.2	6.4	
2	6-12	5.6±0,1				
others	12-60	5.4±0,1				

Exposure Buildup Factors

In practical data use for photon attenuation in Lead, it seems appropriate, as for concrete and iron, to use dose buildup factors of photon that take into account the difference in the nature of the attenuation from the exponential one, or to use attenuation coefficient of the total absorbed dose [1]. On the basis of data on the total dose rate and the dose of non-scattered radiation, the Exposure Buildup Factors of photon in Lead were calculated, given for two types of sources in table 5.

Table 5 – Exposure Buildup Factors for photons in lead for point isotropic and flat mono-directional sources of photons with different energies

μd	The energy of source photons, MeV							
	20		30		40		50	
	point isotropic source.	flat mono-directional source	point isotropic source	flat mono-directional source .	point isotropic source	flat mono-directional source	point isotropic source	flat mono-directional source
0.25	1.16	1.19	1.17	1.21	1.22	1.23	1.25	1.23
0.5	1.37	1.36	1.42	1.42	1.45	1.46	1.44	1.47
1	1.71	1.72	1.9	1.89	2.01	2.02	2.06	2.06
2	2.68	2.67	3.24	3.23	3.68	3.67	3.85	3.84
3	4.06	4.06	5.38	5.37	6.42	6.42	6.94	6.92
4	6.17	6.13	8.82	8.78	11.04	11.03	12.31	12.26
5	9.26	9.15	14.34	14.22	18.95	18.8	21.44	21.39
6	13.94	13.63	23.23	22.88	32.04	31.67	37.46	37.17
7	20.81	20.19	37.48	36.67	54.03	53.11	65.15	64.28
8	31.2	29.92	60.32	58.52	91.4	89	112.92	111
10	69.3	62.3	154	147	256	246	337	326
15	497	440	1603	1451	3345	3072	5049	4685
20	3488	2908	16207	13802	42327	36963	74254	6.55E+04
25	2.38E+04	1.95E+04	1.60E+05	1.29E+05	5.28E+05	4.35E+05	1.07E+06	9.06E+05
30	1.60E+05	1.34E+05	1.55E+06	1.20E+06	6.49E+06	4.73E+06	1.51E+07	1.20E+07

Comparison of the Buildup Factors obtained in this study with similar data given in [2, 3, 8] for the photon energy of a 10 MeV point isotropic source (tab. 6) showed their consent within 5%. This indicates the reliability of the calculated results obtained and the acceptability of the calculation method used.

Table 6 – Exposure Buildup Factors of photon accumulation for lead for point isotropic and planar mono-directional photon sources with an energy of 10 MeV

μd	The energy of source photons, MeV				
	10				
	point isotropic source	[2]	[3]	[8]	flat monodirectional source
0.25	1.13				1.16
0.5	1.27	1.28	1.29	1.32	1.27
1	1.49	1.51	1.51	1.55	1.48
2	1.97	2.01	1.97	2	1.97
3	2.57	2.63	2.54	2.51	2.55
4	3.33	3.42	3.26	3.13	3.27
5	4.29	4.45	4.17	3.89	4.16
6	5.51	5.73	5.32	4.82	5.26
7	7.06	7.37	6.78	5.97	6.63
8	9.02	9.44	8.6	7.4	8.33
10	14.55	15.4	13.8	11.4	12.96
15	47.46	50.8	42.8	33.7	38.46
20	150	161	128	100	108
25	461	495	369	294	389
30	1378	1470	1030	852	2869

Data in tables 5 and 6 indicate a weak dependence of exposure buildup factors of photons in Lead for the considered energy range of the source on the angular distribution of the source radiation. The difference between the data about buildup factors for a point isotropic source and the results for a flat mono-directional source does not exceed 10% for a Lead thickness below 20 mfp, which allows using any of them when performing approximate shielding calculations. As the thickness increases, the difference increases to 30% and the buildup factors for a point isotropic source is higher than the buildup factors for a flat mono-directional source.

Depending on the photon energy of the source, the expected growth of Buildup Factors is observed, and at large thicknesses of shielding, its values reach 10^6-10^7 at the source photon energy of 40-50 MeV. This is due to an increase in the photon attenuation coefficient with an increase in their energy due to the vaporization effect, which leads to a decrease in the contribution of non-scattered radiation, on the other hand, the accumulation of scattered photons with energies in the range of 2-3 MeV, at which there is a minimum in the full cross-section of the interaction of photons with Lead.

In figure, 6 the results obtained for a point isotropic photon source with an energy of 10 MeV are compared with the available literature data. It can be seen that they coincide with an error not exceeding 10%, which is a criterion for the reliability of the calculation method used.

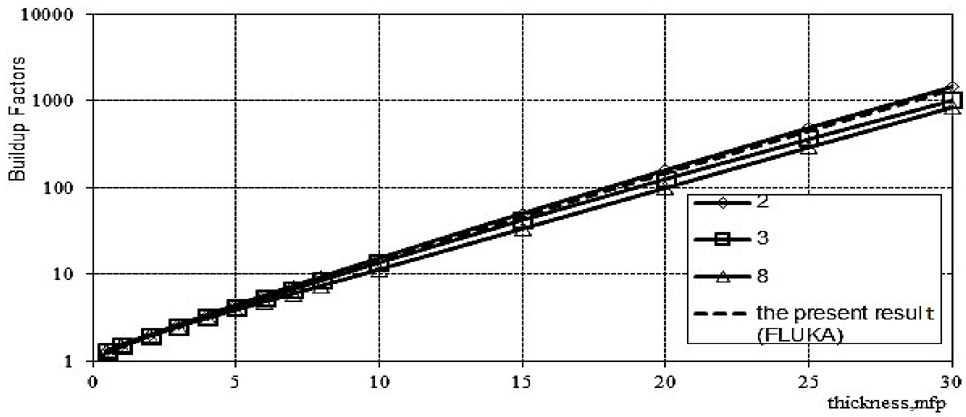


Figure 6 – Comparison of Exposure Buildup Factors of photon in lead for a point isotropic photon source (FLUKA) with an energy of 10 MeV obtained in different literatures

Comparison of the exposure buildup factors obtained in this study with similar data given in [2, 3, 8] for the photon energy of a 10 MeV point isotropic source (table 5.) showed their agreement within 5% . This indicates the reliability of the calculated results obtained and the acceptability of the calculation method used.

In figure 7 the calculated Buildup Factors for Lead are compared with similar data obtained in [9] for sources of bremsstrahlung photon radiation generated by electrons with different energies. For all source photon energies, the buildup factors for mono-directional sources are higher than the corresponding buildup factors for bremsstrahlung radiation sources.

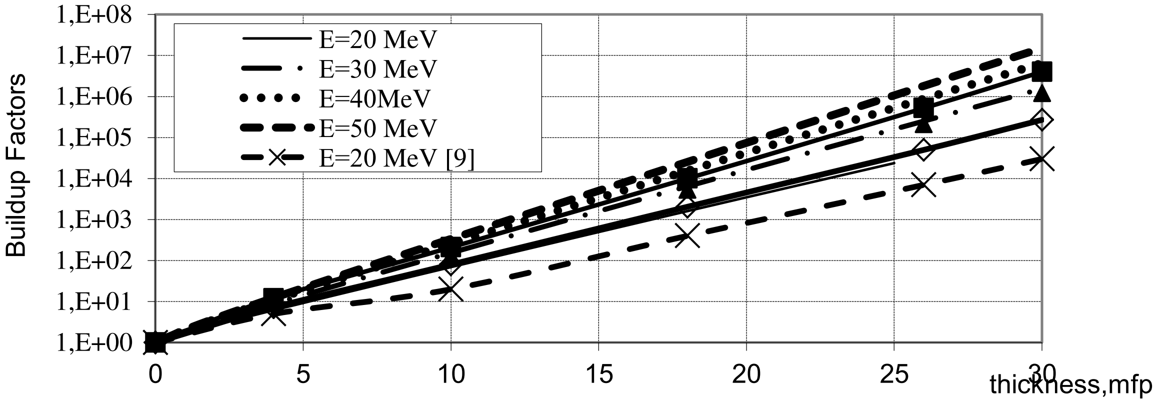


Figure 7 – Comparison of Buildup Factors of photon for lead obtained for monoenergetic photon sources in this article and sources of bremsstrahlung [9]

Table 7 – Lead Barrier Corrections

mfp	5					10				
E, MeV	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

In the considered range of material thicknesses, these corrections are independent of the photon energy of the source and the thickness of the shield and are equal to 0.980 ± 0.002 for lead.

Conclusion

Based on the results calculations of the dose characteristics of photon fields in the materials under consideration in the barrier geometry at shield thicknesses above 3 mfp, corrections for the barrier shielding were 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 thicknesses, these corrections do not depend on the photon energy of the source and the shield thickness, which are equal to 0.980±0.002 for Lead. Asymptotic Tenfold attenuation layer for Lead was obtained in [9, 11] depending on the energy of the electrons accelerators. In the range of electron energies of 20-100 MeV, which corresponds to the effective photon energy of the bremsstrahlung radiation of about 6-33 MeV [7], they are practically independent of the electron energy. The obtained characteristics of the photon dose attenuation in various shielding materials for photon sources with energies in the range from 10 to 50 MeV Supplement the data that are not available in the literature for photon energies of sources above 30 MeV and provide more accurate estimates of the required thickness of shielding against the bremsstrahlung radiation of electronic accelerators.

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Photon Radiation Fields Characteristics in Lead for Photon Sources With Energies From 10 to 50 MeV

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Abstract – According to Monte Carlo calculations of spatial distributions of photon energy in Lead from point isotropic and plane mon-directional monoenergetic sources with energies of 10-50 MeV, define the attenuation coefficient of air Kerma and the dose buildup factors are determined for the studied material. The calculations take into account the contribution of fluorescence, annihilation radiation, and bremsstrahlung radiation. The independence of the Buildup Factors and attenuation coefficient from the angular distribution of the source radiation and the weak dependence of the attenuation coefficient on its energy in the range of 30-50 MeV are shown. Corrections for barrier protection were determined and their independence from the thickness of the shielding material and the photon energy of the source was noted. The obtained information makes it possible to reduce errors in the results of calculations of the thickness for anti-radiation protection of electronic accelerators at high energies, using the developed engineering methods of calculation. The obtained information can also be used in calculations of protection against bremsstrahlung radiation of electronic accelerators by engineering methods.

Keywords: electronic accelerators, bremsstrahlung radiation, protection, dose, accumulation factor, attenuation Multiplicity, Monte Carlo.