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Calculation of exposure buildup factors for point isotropic gamma ray sources in stratified spherical shields of water surrounded by lead and optimization of water-lead combination

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Abstract

Exposure buildup factors have been calculated by Monte Carlo method for point isotropic gamma ray sources, penetrating a two-layer spherical shield of water surrounded by lead, and the effect of bremsstrahlung radiation on buildup factors has, in particular, been investigated, the results of which are in good agreement with previous works. The buildup factors were then calculated for various combinations of water and lead layers at some gamma ray energy points in the range from 0.04 MeV to 10 MeV and for shield thicknesses from 1 to 10 mean free paths (mfp). From the results obtained, one can select the proper (or optimum) water and lead combination which results in minimum value of buildup factor for a two-layer water-lead shield of a given thickness (in mfp) at each energy point. Here the optimization analysis has been performed for a shield of 10 mfp thick at gamma ray energies from 0.04 MeV to 10 MeV.

Keywords*:* Stratified shields; Monte Carlo simulation; buildup factors; bremsstrahlung radiation

1. Introduction

The photon build up factor is defined as the ratio of the total photon beam response (e.g., flux, dose or exposure) to the response of the uncollided photon beam fraction. Buildup factors which account for multiple scattering of photons and secondary sources of annihilation, fluorescence and bremsstrahlung radiation are basic data for point kernel methods that are used in gamma-ray shielding and dosimetry calculations. The buildup factor can be obtained, in principle by experiment, but since the attenuation coefficients and scattering cross sections are known with reasonable accuracy, buildup factors are customarily obtained either by solution of the photon transport equation or by Monte Carlo method. A detailed historical review on build up factor calculation and use is given by Harima [1]. Although buildup factors have been widely calculated and used for mono-layer shields [2-8], they have also been considered for multi-layer shields [9-14].

In this work, a Monte-Carlo program was written to simulate the transport of gamma rays through matter and to calculate the exposure buildup factors for a point mono-energetic isotropic gamma ray source located at the center of a stratified spherical shield of water (as a low Z-value material) surrounded by lead (as a high Z-value material). We began our study by taking into account coherent and incoherent scatterings and investigated the effects of these phenomena on buildup factors up to gamma ray energies of 3 MeV, the results of which were published in ref. [14]. In the present work we completed the program by taking into account secondary sources of bremsstrahlung and calculated the buildup factors up to gamma ray energies of 10 MeV. The (infinite-medium) buildup factors were calculated for various combinations of water and lead layers at some gamma ray energy points in the range from 0.040 to 10 MeV and for shield thicknesses from 1 to 10 mean free path (mfp). In order to consider the infinite medium condition in the program, total thickness of the shield was taken to be 13 mfp (that is 3 mfp more than the maximum distance considered in the calculations). From the results obtained, one can select the proper (or optimum) water and lead combination which results in minimum value of buildup factor (and therefore in minimum value of gamma ray exposure) for a shield of given thickness (in mfp) at each energy point. Here, the optimization analysis has been performed for a shield of 10 mfp thick at gamma ray energies from 0.040 to 10 MeV. It is to be noted that for a shield of (say) 10 mfp thickness, the intensity of uncollided photon beam is attenuated

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exponentially by a factor of e^{-10} and is independent of shield material combination, but the total beam response is material-combination dependent and is minimum when the buildup factor is minimum. Other limitations like space and material weight are of course of special importance which should also be taken into consideration in practice.

2. Method of calculation

The method of calculation is fully described in (our previous paper) ref. [14]. The cross-sections used were taken from ref [15]. The type of interactions considered in the program are: photoelectric, incoherent scattering (which is Compton scattering considering binding effects of electrons), coherent (Rayleigh) scattering and pair production. Fluorescence and bremsstrahlung radiations are also taken into account. As the main object of this study was to consider the effect of bremsstrahlung radiation on buildup factor, in the following section a brief description of the formulas concerning bremsstrahlung radiation is given.

3. Bremsstrahlung radiation

In the case of gamma-ray transport, the bremsstrahlung sources are photo–electrons, Compton electrons and electrons and positrons of pair production. When an electron (or positron) with kinetic energy E passes through a medium with atomic number (or a compound with effective atomic number) Z, the ratio of stopping power due to radiation to that due to collision is approximately given by [16]:

$$\frac{\left[\frac{dE}{dx}\right]_r}{\left[\frac{dE}{dx}\right]_c} = \frac{E\,Z}{750} = r. \qquad (1)$$

For such an electron, the probability of bremsstrahlung emission is therefore:

$$P = \frac{\left(\frac{dE}{dx}\right)_r}{\left(\frac{dE}{dx}\right)_c + \left(\frac{dE}{dx}\right)_r} = \frac{r}{r+1}. \qquad (2)$$

A simple description of the bremsstrahlung differential cross section (DCS) is provided by the Bethe–Hitler formula with screening. The Bethe–Hitler DCS for bremsstralung emission by electrons (or positrons) in the field of an atom of atomic number Z and screening radius R can be expressed as [17]:

$$\frac{d\sigma_{br}^{BH}}{dw} = r_e^2\,\alpha\,Z(Z+\eta)\frac{1}{w}\left[\varepsilon^2\,\varphi_1(b) + \frac{4}{3}(1-\varepsilon)\,\varphi_2(b)\right] \qquad (3)$$

where α is the fine–structure constant, r_e is the classical electron radius, w is the energy of the emitted photon,

$$\varepsilon = \frac{w}{E + m_e c^2} = \frac{w}{\gamma m_e c^2}, \quad \gamma = 1 + \frac{E}{m_e c^2} \quad b = \frac{R\,m_e c}{\hbar}\frac{1}{2\gamma}\frac{\varepsilon}{1-\varepsilon}$$

and

$$\varphi_1(b) = 4\ln(Rm_e c/\hbar) + 2 - 2\ln(1+b^2) - 4b\arctan(b^{-1}), \qquad (4)$$

$$\varphi_2(b) = 4\ln(Rm_e c/\hbar) + \frac{7}{3} - 2\ln(1+b^2) - 6b\arctan(b^{-1}) \qquad (5)$$

$$-b^2\left[4 - 4b\arctan(b^{-1}) - 3\ln(1+b^{-2})\right].$$

The quantity η in eq. (3) accounts for the production of bremsstrahlung in the field of the atomic electrons; in the high energy limit $\eta \simeq 1.2$.

To simulate the emission of bremsstrahlung radiation in the program, an electron (or positron) with kinetic energy E was assumed to radiate bremsstrahlung photons with a probability given by eq. (2). Z was taken to be 82 for lead and 7.2 for water. The energy of the emitted photon (w), which takes values in the interval 0 to E, was selected from distribution (3) by means of random numbers and the rejection sampling technique. The reduced screening radius, $R\,m_e\,c/\hbar$ was taken to be 23.922 for lead and 100 (which is the weighted mean value for two hydrogen atom and one oxygen atom) for water [17]. Bremsstrahlung photons were produced at the position of the electrons (or positrons) and were emitted in directions of electrons (or positrons), as in the discrete ordinate code, PALLAS [18]. The directions of Compton electrons were determined from Compton formulas and the directions of photo electrons and pair creation electrons (or positrons) were in the direction of the photon that caused the process.

4. Results and Discussion

4.1. Comparison with previous works

Using the point Monte Carlo code EGS4 [19], Harima and Hirayama [9] have calculated exposure buildup factors for a two-layer shield of 5 mfp water followed by 8 mfp lead, for gamma ray energies between 0.1 and 10 MeV. In our previous work, ref. [14], we have shown that under similar conditions our results are consistent with those of ref. [9] up to gamma–ray energies of 3 MeV. Here in Fig. 1 we have compared our results with those of ref. [9] at 10 MeV gamma–ray energy, where bremsstrahlung has significant effect on buildup factors. It is seen that the two results are consistent (with maximum discrepancy of less than 10 percent which could be due to small differences in the method of calculation in the two programs) and it could therefore be concluded that our program produces buildup factors with reasonable accuracy to be used for shielding designs. In addition, in the special case where water layer was taken zero and the shield was therefore considered to be lead alone, our two–layer program, with bremsstrahlung radiation included, resulted in exposure build up factors consistent with those of mono–layer lead shields of ref. [8]. This comparison is shown in Table 1. The buildup factors presented in this Table have been calculated (in lead medium) for both cases with and without bremsstrahlung radiation taken into account, and in particular show the effect of bremsstrahlung radiation on buildup factors. It is seen that bremsstrahlung radiation increases the buildup factors at all distances from the source and the effect increases with distance, such that at a distance of 10 mfp distance, the buildup factor with bremsstrahlung radiation is almost three times that without this radiation.

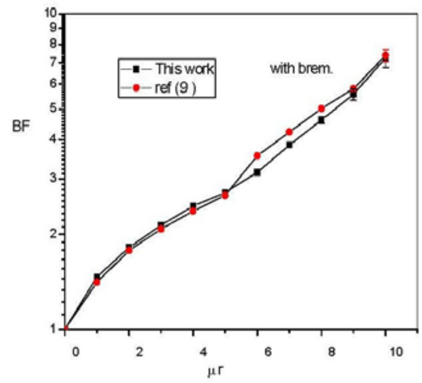

Fig. 1. Gamma ray exposure buildup factors versus shield thickness(in mfp) for a two-layer shield of 5 mfp water followed by 8 mfp lead and comparison with those of ref. [9] at 10 MeV gamma ray energy

Table 1. Comparison of exposure buildup factors with those of ref [8] at 10 MeV gamma ray energy for a single layer shield of lead at various distances (in mfp) from the source. Comparison has been made for both cases with and without bremsstrahlung radiation taken into account

mfp	This work with brem.	This work without brem.	PALLAS with brem.	PALLAS without brem.	EGS4 with brem.	EGS4 without brem.
1	1.55 ± 0.01	1.18 ± 0.01	1.51	1.19	1.55	1.19
2	2.08 ± 0.01	1.33 ± 0.01	2.01	1.31	2.02	1.33
3	2.71 ± 0.01	1.49 ± 0.01	2.63	1.47	2.57	1.50
4	3.47 ± 0.01	1.71 ± 0.01	3.42	1.68	3.20	1.71
5	4.43 ± 0.01	1.99 ± 0.01	4.45	1.96	3.98	1.96
6	5.62 ± 0.05	2.32 ± 0.01	5.73	2.31	4.89	2.30
7	7.04 ± 0.10	2.72 ± 0.01	7.37	2.77	6.12 ± 0.008	2.71
8	8.92 ± 0.21	3.31 ± 0.09	9.44	3.34	7.60 ± 0.009	3.26
9	11.07 ± 0.44	3.96 ± 0.16	—	—	—	—
10	14.16 ± 0.95	4.98 ± 0.34	15.4	4.99	11.5 ± 0.02	4.65

4.2. Exposure Buildup factor values.

With all types of gamma ray interactions (including bremsstrahlung radiation) considered in our program, exposure buildup factors were calculated for various combinations of water and lead layers at some gamma ray energy points in the range from 0.04. to 10 MeV and for shield thicknesses from 1 to 10 mfp.

These factors, which are given in Table 2 can be used in calculations of gamma ray transmissions through such shields. These results could also be used to develop formulas, similar to those of ref [13], for calculating exposure buildup factors for two layer shields in general.

4.3. Optimization of buildup factors.

The buildup factors at 10 mfp distance from the source, given in the first section of Table 2, are plotted versus water thickness, in mfp, at various gamma ray energy points from 0. 04 to 10 MeV in Fig. 2 (at each point the rest of the shield is lead). It is seen that at gamma ray energies below~0.5 MeV, where the photo–electric effect is dominant, buildup factor is minimum when water layer is zero and the shield is chosen to be lead alone. From~0.5 MeV to~3 MeV, where Compton scattering is dominant, the buildup factors are minimum up to about 4 mfp water and no significant variation is observed. At 4 MeV any combination of water and lead could be chosen without any significant variation in buildup factor values. Above 5 MeV, where the bremsstrahlung is significant the process is reversed and the buildup factor is minimum when above 7 mfp is taken to be water. At 10 MeV the buildup factor is minimum when the whole 10 mfp is taken to be water.

Table 2. Exposure buildup factors at various distances (in mfp) from the source for different thicknesses (in mfp) of water and lead at some gamma ray energies

	Water-lead (mfp)	40 keV	200 keV	1 MeV	2 MeV	3 MeV	6 MeV	10 MeV
BF at 10 mfp	0-13	1.97 ± 0.133	2.456 ± 0.163	4.901 ± 0.326	5.854 ± 0.389	6.263 ± 0.416	7.376 ± 0.490	13.827 ± 0.918
	1-12	5.669 ± 0.400	4.347 ± 0.293	4.611 ± 0.306	5.722 ± 0.380	5.918 ± 0.393	6.672 ± 0.443	8.009 ± 0.532
	2-11	4.902 ± 0.350	3.966 ± 0.268	4.765 ± 0.317	5.764 ± 0.382	5.975 ± 0.397	7.060 ± 0.469	8.721 ± 0.579
	3-10	3.968 ± 0.286	3.664 ± 0.249	4.803 ± 0.319	5.588 ± 0.371	6.296 ± 0.418	6.709 ± 0.445	8.099 ± 0.538
	4-9	3.951 ± 0.285	3.254 ± 0.222	4.982 ± 0.331	5.895 ± 0.391	6.125 ± 0.407	6.814 ± 0.452	7.306 ± 0.485
	5-8	4.430 ± 0.318	3.418 ± 0.233	4.870 ± 0.323	5.939 ± 0.394	6.799 ± 0.451	6.820 ± 0.453	6.966 ± 0.462
	6-7	5.241 ± 0.373	3.459 ± 0.236	5.233 ± 0.348	6.233 ± 0.414	6.666 ± 0.442	6.467 ± 0.429	6.329 ± 0.420
	7-6	7.067 ± 0.498	4.253 ± 0.290	5.556 ± 0.369	6.434 ± 0.427	6.657 ± 0.442	6.084 ± 0.404	5.663 ± 0.376
	8-5	9.827 ± 0.684	6.259 ± 0.425	6.184 ± 0.411	6.698 ± 0.445	6.788 ± 0.451	5.695 ± 0.378	5.018 ± 0.333
	9-4	15.848 ± 1.089	12.442 ± 0.839	7.834 ± 0.520	7.283 ± 0.483	6.957 ± 0.462	5.301 ± 0.352	4.427 ± 0.294
	10-3	40.923 ± 2.770	134.416 ± 8.944	20.236 ± 1.344	10.810 ± 0.718	8.159 ± 0.541	5.212 ± 0.346	3.992 ± 0.265
BF at 9 mfp	0-13	1.583 ± 0.067	2.128 ± 0.086	4.377 ± 0.177	5.282 ± 0.213	5.641 ± 0.227	6.181 ± 0.249	11.173 ± 0.450
	1-12	3.468 ± 0.156	2.912 ± 0.122	4.299 ± 0.174	5.113 ± 0.206	5.215 ± 0.210	5.489 ± 0.221	6.469 ± 0.260
	2-11	3.192 ± 0.145	2.851 ± 0.120	4.225 ± 0.171	5.149 ± 0.207	5.279 ± 0.212	5.897 ± 0.237	6.737 ± 0.271
	3-10	3.204 ± 0.145	2.670 ± 0.113	4.298 ± 0.173	5.307 ± 0.214	5.657 ± 0.228	5.931 ± 0.239	6.552 ± 0.264
	4-9	3.565 ± 0.161	2.933 ± 0.125	4.423 ± 0.178	5.419 ± 0.218	5.697 ± 0.229	5.917 ± 0.238	6.182 ± 0.249
	5-8	4.230 ± 0.188	3.035 ± 0.129	4.719 ± 0.190	5.627 ± 0.227	5.926 ± 0.239	5.755 ± 0.232	5.634 ± 0.227
	6-7	5.341 ± 0.234	3.790 ± 0.161	5.053 ± 0.204	5.952 ± 0.240	5.980 ± 0.241	5.433 ± 0.219	5.099 ± 0.205
	7-6	7.742 ± 0.333	5.418 ± 0.228	5.779 ± 0.233	6.063 ± 0.244	6.020 ± 0.242	5.238 ± 0.211	4.575 ± 0.184
	8-5	12.950 ± 0.545	10.635 ± 0.439	6.962 ± 0.281	6.446 ± 0.260	5.971 ± 0.240	4.887 ± 0.197	3.977 ± 0.160
	9-4	33.338 ± 1.376	103.415 ± 4.177	17.538 ± 0.707	9.657 ± 0.389	7.211 ± 0.290	4.816 ± 0.194	3.595 ± 0.145
BF at 8 mfp	0-13	1.708 ± 0.046	1.999 ± 0.050	4.074 ± 0.100	4.798 ± 0.117	4.803 ± 0.117	5.337 ± 0.130	8.837 ± 0.216
	1-12	2.411 ± 0.069	2.364 ± 0.062	3.879 ± 0.096	4.650 ± 0.114	4.797 ± 0.117	4.707 ± 0.115	5.294 ± 0.129
	2-11	2.625 ± 0.074	2.453 ± 0.065	3.880 ± 0.095	4.697 ± 0.115	4.858 ± 0.119	5.095 ± 0.124	5.363 ± 0.131
	3-10	2.916 ± 0.082	2.567 ± 0.069	4.034 ± 0.099	4.753 ± 0.116	5.019 ± 0.123	5.171 ± 0.126	5.270 ± 0.129
	4-9	3.464 ± 0.096	2.763 ± 0.074	4.093 ± 0.100	4.934 ± 0.121	5.106 ± 0.001	5.032 ± 0.123	4.992 ± 0.122
	5-8	4.456 ± 0.121	3.302 ± 0.087	4.512 ± 0.111	5.069 ± 0.124	5.163 ± 0.126	4.969 ± 0.121	4.681 ± 0.114
	6-7	6.336 ± 0.168	4.532 ± 0.118	4.957 ± 0.121	5.291 ± 0.129	5.328 ± 0.130	4.800 ± 0.117	4.235 ± 0.104
	7-6	10.532 ± 0.272	8.677 ± 0.220	6.064 ± 0.149	5.715 ± 0.140	5.434 ± 0.133	4.473 ± 0.109	3.844 ± 0.094
	8-5	26.969 ± 0.679	78.151 ± 1.917	14.841 ± 0.364	8.566 ± 0.209	6.571 ± 0.160	4.459 ± 0.109	3.571 ± 0.087
BF at 7 mfp	0-13	1.550 ± 0.272	1.930 ± 0.300	3.59 ± 0.054	4.292 ± 0.064	4.326 ± 0.064	4.525 ± 0.067	7.039 ± 0.104
	1-12	2.027 ± 0.037	2.083 ± 0.035	3.535 ± 0.054	4.106 ± 0.061	4.160 ± 0.062	4.046 ± 0.060	4.258 ± 0.063
	2-11	2.386 ± 0.423	2.238 ± 0.038	3.555 ± 0.054	4.276 ± 0.063	4.305 ± 0.064	4.306 ± 0.064	4.464 ± 0.066
	3-10	2.854 ± 0.049	2.423 ± 0.041	3.699 ± 0.056	4.307 ± 0.064	4.441 ± 0.066	4.365 ± 0.065	4.334 ± 0.064
	4-9	3.654 ± 0.062	2.817 ± 0.047	3.952 ± 0.059	4.526 ± 0.067	4.604 ± 0.068	4.405 ± 0.065	4.113 ± 0.061
	5-8	5.145 ± 0.084	3.786 ± 0.061	4.412 ± 0.066	4.714 ± 0.070	4.737 ± 0.070	4.241 ± 0.063	3.800 ± 0.056
	6-7	8.462 ± 0.134	7.030 ± 0.109	5.210 ± 0.078	5.069 ± 0.075	4.824 ± 0.072	4.095 ± 0.061	3.494 ± 0.052
	7-6	21.888 ± 0.337	57.467 ± 0.856	12.477 ± 0.186	7.424 ± 0.110	5.830 ± 0.865	4.086 ± 0.606	3.270 ± 0.484
BF at 6 mfp	0-13	1.467 ± 0.016	1.816 ± 0.018	3.274 ± 0.030	3.717 ± 0.034	3.745 ± 0.034	3.866 ± 0.035	5.587 ± 0.050
	1-12	1.827 ± 0.020	1.950 ± 0.021	3.203 ± 0.030	3.631 ± 0.033	3.656 ± 0.033	3.477 ± 0.031	3.451 ± 0.031
	2-11	2.238 ± 0.024	2.103 ± 0.022	3.271 ± 0.030	3.762 ± 0.034	3.842 ± 0.034	3.672 ± 0.033	3.599 ± 0.032
	3-10	2.926 ± 0.031	2.436 ± 0.025	3.348 ± 0.032	3.871 ± 0.035	3.960 ± 0.037	3.767 ± 0.034	3.597 ± 0.032
	4-9	4.150 ± 0.042	3.172 ± 0.032	3.767 ± 0.035	4.142 ± 0.038	4.097 ± 0.037	3.776 ± 0.034	3.422 ± 0.031
	5-8	6.749 ± 0.066	5.563 ± 0.053	4.438 ± 0.041	4.429 ± 0.040	4.236 ± 0.038	3.645 ± 0.033	3.181 ± 0.029
	6-7	17.306 ± 0.163	40.828 ± 0.370	10.243 ± 0.093	6.418 ± 0.058	5.164 ± 0.036	3.673 ± 0.033	2.987 ± 0.027
BF at 5 mfp	0-13	1.375 ± 0.010	1.688 ± 0.011	2.878 ± 0.017	3.231 ± 0.018	3.198 ± 0.018	3.263 ± 0.018	4.427 ± 0.024
	1-12	1.742 ± 0.012	1.822 ± 0.012	2.859 ± 0.017	3.235 ± 0018	3.204 ± 0.018	2.987 ± 0.017	2.880 ± 0.016
	2-11	2.286 ± 0.015	2.055 ± 0.013	2.980 ± 0.017	3.354 ± 0.019	3.362 ± 0.019	3.183 ± 0.017	3.007 ± 0.016
	3-10	3.213 ± 0.020	2.632 ± 0.017	3.212 ± 0.019	3.507 ± 0.019	3.506 ± 0.019	3.224 ± 0.018	2.947 ± 0.016
	4-9	5.247 ± 0.032	4.356 ± 0.026	3.756 ± 0.022	3.767 ± 0.021	3.667 ± 0.020	3.220 ± 0.018	2.815 ± 0.015
	5-8	13.436 ± 0.078	27.774 ± 0.153	8.131 ± 0.452	5.437 ± 0.301	4.447 ± 0.024	3.285 ± 0.018	2.707 ± 0.015
BF at 4 mf	0-13	1.306 ± 0.006	1.576 ± 0.006	2.505 ± 0.009	2.769 ± 0.010	2.734 ± 0.009	2.702 ± 0.009	3.468 ± 0.012
	1-12	1.722 ± 0.072	1.739 ± 0.007	2.521 ± 0.009	2.781 ± 0.010	2.752 ± 0.009	2.523 ± 0.009	2.383 ± 0.008
	2-11	2.441 ± 0.010	2.132 ± 0.008	2.697 ± 0.010	2.920 ± 0.010	2.931 ± 0.010	2.693 ± 0.009	2.490 ± 0.008
	3-10	3.983 ± 0.015	3.335 ± 0.012	3.069 ± 0.011	3.151 ± 0.011	3.076 ± 0.010	2.750 ± 0.090	2.440 ± 0.008
	4-9	10.049 ± 0.036	17.871 ± 0.060	6.231 ± 0.021	4.432 ± 0.016	3.738 ± 0.013	2.868 ± 0.010	2.402 ± 0.008
BF at 3 mfp	0-13	1.233 ± 0.003	1.477 ± 0.004	2.150 ± 0.005	2.321 ± 0.005	2.275 ± 0.005	2.237 ± 0.005	2.707 ± 0.005
	1-12	1.754 ± 0.004	1.713 ± 0.004	2.203 ± 0.005	2.375 ± 0.005	2.342 ± 0.005	2.139 ± 0.004	2.000 ± 0.004
	2-11	2.873 ± 0.007	2.477 ± 0.006	2.463 ± 0.006	2.547 ± 0.006	2.508 ± 0.005	2.280 ± 0.005	2.078 ± 0.004
	3-10	7.111 ± 0.016	10.637 ± 0.022	4.556 ± 0.010	3.477 ± 0.007	3.036 ± 0.006	2.441 ± 0.005	2.101 ± 0.004
BF at 2 mfp	0-13	1.163 ± 0.002	1.368 ± 0.002	1.783 ± 0.030	1.892 ± 0.003	1.854 ± 0.003	1.819 ± 0.002	2.078 ± 0.003
	1-12	1.902 ± 0.003	1.781 ± 0.003	1.910 ± 0.030	1.982 ± 0.003	1.954 ± 0.003	1.802 ± 0.002	1.683 ± 0.002
	2-11	4.603 ± 0.006	5.698 ± 0.007	3.088 ± 0.040	2.586 ± 0.003	2.358 ± 0.003	2.008 ± 0.003	1.792 ± 0.002
BF at 1 mfp	0-13	1.091 ± 0.001	1.264 ± 0.001	1.416 ± 0.001	1.470 ± 0.001	1.457 ± 0.001	1.446 ± 0.001	1.556 ± 0.001
	1-12	2.513 ± 0.002	2.646 ± 0.002	1.876 ± 0.002	1.743 ± 0.001	1.680 ± 0.001	1.556 ± 0.001	1.457 ± 0.001

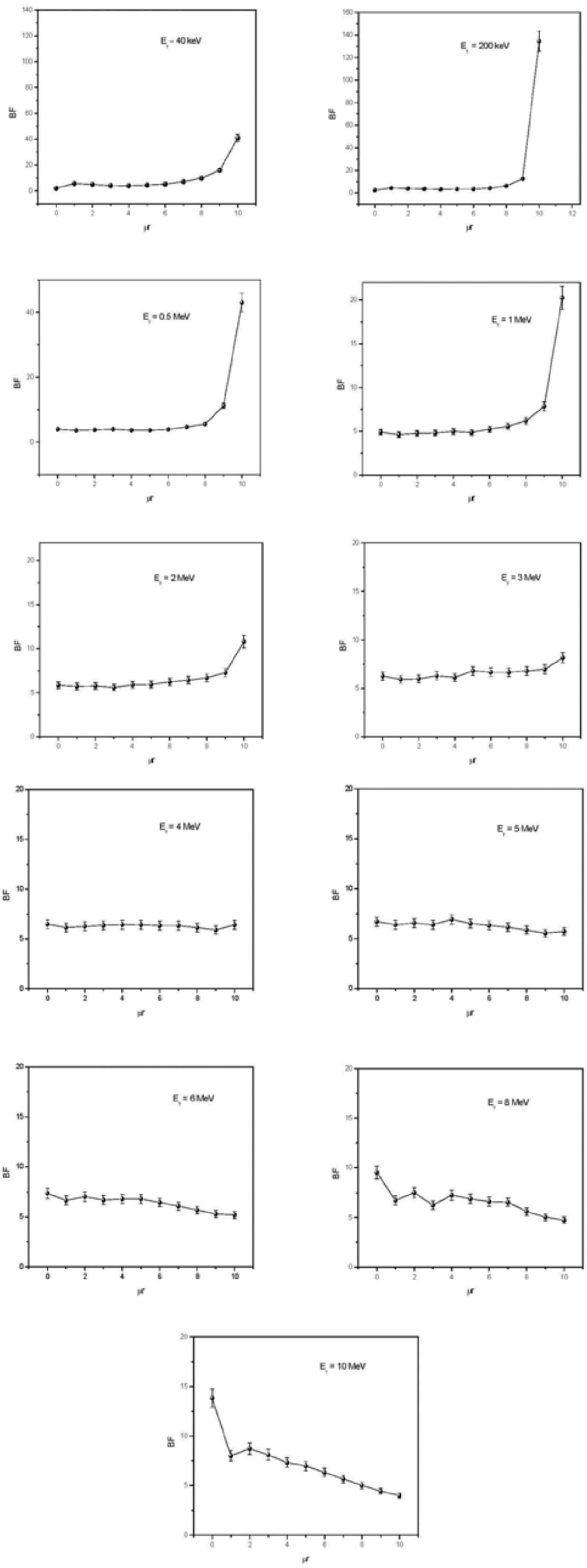

Fig. 2. Exposure buildup factors at 10 mfp distance from the source versus water thickness. At each point the rest of the shield thickness (i.e. 10-μr) is made of lead

5. Conclusion

In this work, exposure buildup factors were calculated by Monte Carlo method for point isotropic gamma ray sources located at the center of a stratified spherical shield of water surrounded by lead. All types of gamma ray interactions including photoelectric, coherent scattering, bound-electron Compton scattering, annihilation gamma rays, fluorescence and bremsstrahlung radiations were considered in the calculations. The exposure buildup factors were calculated for various combinations of water and lead layers at some gamma ray energy points in the range from 0.04 to 10 MeV and for shield thicknesses from 1 to 10 mfp, which could be used in designing such shields for gamma ray sources. The buildup factors at 10 mfp distance from the source were analyzed at some gamma ray energy points to obtain the optimum water-lead combination which results in minimum buildup factor value at this distance. The general features of the analysis show that at low gamma ray energies (E_γ<0.5 MeV) where photoelectric effect is dominant, the best combination is zero mfp water -10 mfp lead (lead alone), at intermediate energies (1 MeV< E_γ <3 MeV) where Compton scattering is dominant 5 mfp water-5 mfp lead (half water-half lead) could be taken as optimum combination, and finally at E_γ =10 MeV where bremsstrahlung is dominant in lead the best combination is 10 mfp water- zero mfp lead (water alone). The buildup factors presented in Table 2 show that this general behaviour is seen at other distances from the source.

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