Simulation of photon attenuation coefficients for high effective shielding material Lead-Boron Polyethylene

L Zhang, M C Jia, J J Gong, W M Xia

Department of Nuclear Science and Engineering, Naval University of Engineering, Wuhan 430033, China
E-mail: 1761276990@qq.com

Abstract. The mass attenuation coefficient of various Lead-Boron Polyethylene samples which can be used as the photon shielding materials in marine reactor, have been simulated using the MCNP-5 code, and compared with the theoretical values at the photon energy range 0.001MeV—20MeV. A good agreement has been observed. The variations of mass attenuation coefficient, linear attenuation coefficient and mean free path with photon energy between 0.001MeV to 100MeV have been plotted. The result shows that all the coefficients strongly depends on the photon energy, material atomic composition and density. The dose transmission factors for source Cesium-137 and Cobalt-60 have been worked out and their variations with the thickness of various sample materials have also been plotted. The variations show that with the increase of materials thickness the dose transmission factors decrease continuously. The results of this paper can provide some reference for the use of the high effective shielding material Lead-Boron Polyethylene.

1. Introduction
Due to the space limitations of marine reactor, their weight and volume should be as small as possible. Meanwhile, the weight and volume of shielding materials occupy a large proportion of that of reactor plant [1]. Therefore, it is important to reduce the weight and volume of the shielding materials in order to make the marine reactor lightweight and compact. The use of high effective shielding materials is an important means to achieve this goal [2]. Lead-Boron Polyethylene (PbBPE) which is formed by diffusing the boron carbide powder and lead powder in the polyethylene is one of the high effective shielding materials [3-5]. The polyethylene has good neutron shielding capability because of its high hydrogen content, boron could absorb the thermal neutrons and lead has an excellent photon shielding capability.

Accurate values of photon attenuation coefficients of shielding materials are of great significance for its engineering applications and academic research [6]. In recent years, the photon attenuation coefficients of various shielding materials such as concrete [7-10], alloy [11] and glass [12] have been studied.

MCNP is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. This code can be used to simulate the photon attenuation coefficients of shielding materials.

The aim of this paper is to determine mass attenuation coefficient ($\mu_m$), linear attenuation coefficient ($\mu$), mean free path ($MFP$) as well as dose transmission factor ($DTF$) of the high effective
shielding material Lead-Boron Polyethylene by the MCNP code and consequently provide some reference for the use of the Lead-Boron Polyethylene as shielding materials.

2. Materials and methods

2.1. Materials specification of PbBPE
In this study, the PbBPE samples contain polyethylene (PE) and lead (Pb) as major weight fraction contributions. The specific compositions and density of each PbBPE samples are shown in Table 1. First four samples contain PE as a dominant contributor, while Pb is the predominant component in the rest samples. The atomic percentage of PbBPE samples is calculated from the component percentage of each sample multiplies the atomic percentage of each component. The atomic percentage of each PbBPE sample is introduced to the MCNP code by the material card.

| Element | Samples  | \(0.96\, \text{g/cm}^3\) | \(1.00\, \text{g/cm}^3\) | \(1.10\, \text{g/cm}^3\) | \(1.25\, \text{g/cm}^3\) | \(1.65\, \text{g/cm}^3\) | \(2.94\, \text{g/cm}^3\) | \(3.42\, \text{g/cm}^3\) |
|---------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| H       | B201     | 13.57           | 12.86           | 11.43           | 10.00           | 7.14            | 3.36            | 2.71            |
| B       | B202     | 3.91            | 7.83            | 15.65           | 0.78            |                 |                 |                 |
| C       | B203     | 82.52           | 79.32           | 72.92           | 60.00           | 42.86           | 20.14           | 16.50           |
| Pb      | P202     | 30.00           | 50.00           | 76.50           | 80.00           |                 |                 |                 |
|        | P203     |                 |                 |                 |                 |                 |                 |                 |
|        | P204     |                 |                 |                 |                 |                 |                 |                 |
|        | P205     |                 |                 |                 |                 |                 |                 |                 |
|        | P206     |                 |                 |                 |                 |                 |                 |                 |
|        | PB202    |                 |                 |                 |                 |                 |                 |                 |

2.2. Geometry system

Monte Carlo N-Particle Transport (MCNP) code version 5 which uses continuous-energy nuclear and atomic data libraries was used for the simulation. The cross-sectional view of geometric model is shown in Fig 1. Its source is an isotropic point source whose particle type, energy, position and direction are defined by PAR, ERG, POS, DIR and VEC data card respectively. The sample whose thickness can be adjusted among the range of 0.01cm-100cm according to the need of the simulation is 10cm far from the source. The detector cell is 120cm far from the source and of 1cm thickness. Sample and detector cell are defined by MCNP surface and cell card.

2.3. Tally definition
Tally card F4 and tally energy (En) card was used to record the MCNP-5 simulation data when simulating the value of \(\mu_m\), \(\mu\), and \(MFP\). When the \(DTF\) was simulated, tally card F2 as well as dose energy (DEn) card and dose function (DFn) card were used. Depending on the thickness of the sample...
and the photon energy, the simulation histories as well as the variance reduction technique will change to ensure that all the simulation data passes all 10 statistical checks and the relative error is less than 1%.

2.4. Mass and linear attenuation coefficient, mean free path, dose transmission factor

The mass attenuation coefficient, linear attenuation coefficient, mean free path and dose transmission factor are simulated.

The intensity of the photons that penetrate the target without having a collision is:

\[ N = N_0 e^{-\mu t} \]  

(1)

Where \( N_0 \) (particles/cm\(^2\)) and \( N \) (particles/cm\(^2\)) are the average particle flux of Narrow beam photon in front of and behind the sample, \( \mu \) (cm\(^{-1}\)) is linear attenuation coefficient in the target, \( t \) (cm) is the thickness of the sample.

Transforming equation (1), \( \mu \) can be expressed as:

\[ \mu = \frac{\ln \frac{N_0}{N}}{t} \]  

(2)

The \( \mu \) value is a parameter which is dependent upon density of the target, atomic number of the elements and energy of incident photon.

Mass attenuation coefficient is defined as following:

\[ \mu_m = \frac{\mu}{\rho} \]  

(3)

For mixtures and compounds, the mass attenuation coefficient can be calculated by the following equation:

\[ \mu_m = \sum_{i=1}^{n} (\mu_m)_i \omega_i \quad i = 1,2,3 \ldots n \]  

(4)

Where \((\mu_m)_i\) and \(\omega_i\) are the mass attenuation coefficient and weight percentage of the \(i\)th element in the material respectively.

The average distance that a photon moves between collisions is called the mean free path. It can be defined as:

\[ MFP = \frac{1}{\mu} \]  

(5)

The dose transmission factor which can expresses the shielding effect can be defined as:

\[ DTF = \frac{H}{H_0} \]  

(6)

Where \(H_0\) (Sv) and \(N\) (Sv) are photon dose in front of and behind the sample. The smaller the \(DTF\), the better the shielding effect.

3. Results and discussion

3.1. Mass attenuation coefficient (\(\mu_m\))

The mass attenuation coefficient values from theory based on Eq. (4) as well as those from MCNP simulation of the seven PbBPE samples for photons of energy range from 0.001MeV to 20MeV have been shown in Table 2. From this table, it can be seen that the theoretical and MCNP values are in good agreement across most energy points, only individual points have a certain difference because the use of different cross-section library.
Table 2. The theoretical and MCNP value of $\mu_m$ for different samples

| Photon energy (MeV) | P202 | P204 | P206 | PB202 | B201 | B202 | B203 |
|---------------------|------|------|------|-------|------|------|------|
|                     | Theory | MCNP | Theory | MCNP | Theory | MCNP | Theory | MCNP | Theory | MCNP | Theory | MCNP | Theory | MCNP |
| 1.00E-03            | 2890  | 3185 | 3553  | 4057  | 5209  | 4543 | 5361  | 1873  | 1856  | 1851  | 1831  | 1805  | 1782  |
| 1.50E-03            | 1127  | 1173 | 1478  | 1552  | 2055  | 2003 | 2123  | 592.8 | 598.3 | 585.1 | 590.0 | 569.8 | 574.0 |
| 2.00E-03            | 567.2 | 574.7| 772.3 | 783.6 | 1044  | 1062 | 1079  | 252.6 | 254.9 | 252.6 | 254.9 | 245.8 | 247.9 |
| 3.00E-03            | 643.8 | 597.6| 1021  | 945.6 | 1521  | 1409 | 1587  | 76.44 | 76.11 | 75.73 | 75.00 | 73.24 | 72.71 |
| 4.00E-03            | 398.0 | 443.8| 641.7 | 719.4 | 964.6 | 1873 | 1856  | 1851  | 1831  | 1805  | 1782  |
| 5.00E-03            | 230.6 | 246.3| 373.4 | 400.9 | 562.6 | 606.0| 587.6 | 633.8 | 16.21 | 15.33 | 15.98 | 15.09 | 15.51 | 14.64 |
| 6.00E-03            | 146.8 | 152.0| 238.3 | 248.3 | 359.6 | 376.3| 375.6 | 393.8 | 76.44 | 76.11 | 75.73 | 75.00 | 73.24 | 72.71 |
| 8.00E-03            | 71.39 | 71.15| 116.3 | 116.5 | 175.9 | 177.4| 183.7 | 185.8 | 3.921 | 3.484 | 3.863 | 3.426 | 3.749 | 3.322 |
| 1.00E-02            | 40.64 | 40.04| 66.34 | 65.85 | 100.4 | 100.4| 104.9 | 105.1 | 2.060 | 1.805 | 2.030 | 1.778 | 1.971 | 1.725 |
| 1.50E-02            | 34.00 | 33.36| 56.17 | 55.41 | 85.55 | 84.93| 89.90 | 0.736 | 0.621 | 0.726 | 0.612 | 0.707 | 0.596 |
| 2.00E-02            | 26.21 | 25.40| 43.40 | 42.25 | 66.17 | 64.70| 67.79 | 0.427 | 0.356 | 0.422 | 0.352 | 0.412 | 0.343 |
| 3.00E-02            | 9.285 | 8.779| 116.3 | 116.5 | 175.9 | 177.4| 183.7 | 185.8 | 3.921 | 3.484 | 3.863 | 3.426 | 3.749 | 3.322 |
| 4.00E-02            | 4.467 | 4.161| 7.294 | 6.846 | 100.4 | 100.4| 104.9 | 105.1 | 2.060 | 1.805 | 2.030 | 1.778 | 1.971 | 1.725 |
| 5.00E-02            | 2.558 | 2.330| 4.125 | 3.780 | 6.200 | 5.760| 6.474 | 6.049 | 0.736 | 0.621 | 0.726 | 0.612 | 0.707 | 0.596 |
| 6.00E-02            | 1.644 | 1.477| 2.860 | 2.734 | 4.285 | 4.122| 4.473 | 4.333 | 0.736 | 0.621 | 0.726 | 0.612 | 0.707 | 0.596 |
| 8.00E-02            | 0.853 | 0.748| 1.391 | 1.242| 2.326 | 2.123| 2.398 | 2.280 | 0.268 | 0.234 | 0.265 | 0.231 | 0.260 | 0.227 |
| 1.00E-01            | 0.467 | 0.416| 0.794 | 0.686 | 1.104 | 1.030| 1.153 | 1.080 | 0.225 | 0.205 | 0.223 | 0.203 | 0.219 | 0.199 |

The variation of mass attenuation coefficient of PbBPE samples versus incident photon energy is shown in Fig 2. It shows that for material P202, P204, P206 and PB202, multiple peaks of mass attenuation coefficient in the low energy region were observed because of the K, L and M absorption edges of Pb. The $\mu_m$ decreases with the photon energy increasing at first but increases when the energy
exceed 3MeV. For B201, B202 and B203, the mass attenuation coefficient decreases rapidly with the increase of the photon energy in the low energy region, whereas slowly in the high energy region. The P202, P204, P206 and PB202 has higher $\mu_m$ than others when the photon energy is below 0.6MeV or over 3MeV, while it is approximately equal at the photon energy range from 0.6MeV to 3MeV.

3.2. Linear attenuation coefficient ($\mu$)

Fig 3 shows the variation of linear attenuation coefficient of PbBPE samples versus incident photon energy. It is observed that the variation of $\mu$ is similar to $\mu_m$ but the gaps of each graph becomes larger by a factor according to the density of each material, especially when the photon energy range is between 0.6MeV and 3MeV. The PB202 sample has the highest linear attenuation coefficient over all the photon energy range due to its high density and the high containment of element Pb. The linear attenuation coefficients of B201, B202 and B203 are basically equal over all the photon energy range.

3.3. Mean free path (MFP)

As shown in Fig 4, The mean free path increases rapidly with the increase of the photon energy in the low energy region, whereas slowly in the high energy region for B201, B202 or B203. For the P202, P204, P206 and PB202, multiple peaks of MFP in the low energy region were observed because of the K, L and M absorption edges of Pb, and the MFP decreases when the photon energy exceed 3MeV. Mathematically MFP is inversely proportional to $\mu$ hence the PB202 sample has the lowest MFP over the entire photon energy range. So PB202 is better than other samples for photon attenuation.

3.4. Dose transmission factor (DTF)

Fig 5 Variation of DTF versus shielding thickness for Cesium-137 (0.662MeV) source
The variation of dose transmission factor of PbBPE samples versus shielding thickness for Cesium-137 (0.662MeV), Cobalt-60 (1.1732MeV) and Cobalt-60 (1.3325MeV) source are shown in Figs. 5-7. It can be seen that the source energy has a great impact on DTF, for the Cesium-137 (0.662MeV) source which shown in Fig. 5 the $DTF \approx 10^{-16}$ when the shielding thickness of PB202 is 100cm, whereas these values are $10^{-10}$ and $10^{-9}$ for the Cobalt-60 (1.1732MeV) and Cobalt-60 (1.3325MeV) source as shown in Fig. 6 and 7. These figures show that the variation law of dose transmission factor for these sources are similar, but they drop all according to the following order: PB202>P206>P204>P202>B203>B202>B201.

4. Conclusion

In this study, the mass attenuation coefficient ($\mu_m$), linear attenuation coefficient ($\mu$), mean free path (MFP) as well as dose transmission factor (DTF) of the high effective shielding material Lead-Boron Polyethylene are simulated by MCNP code. It can be concluded that the photon attenuation coefficients of any shielding material depends on the photon energy, material density and atomic composition. To select an appropriate shielding material, all this parameters should be considered thoroughly. For source Cesium-137 (0.662MeV), Cobalt-60 (1.1732MeV) and Cobalt-60 (1.3325MeV), PB202 is a good shielding material among the seven PbBPE samples. The results of this paper can provide some reference for the future use of the Lead-Boron Polyethylene. We can also conclude that the simulation way based on MCNP to obtain photon attenuation coefficients can be used to simulate other types of shielding materials.

References

[1] Akio, Y., Kiyoshi, S., 1994. Shielding design to obtain compact marine reactor. J. Nucl. Sci. Technol. 31, 510-520.
[2] Lv, J., Chen, J., 1994. High effective shielding material lead-boron polyethylene. Nucl. Power Eng. 15, 370-374.
[3] Shin, J.W., Lee, J.W., Yu, S., Baek, B.K., Hong, J.P., Seo, Y., Kim, W.N., Hong, S.M., Koo, C.M., 2014. Polyethylene/boron-containing composites for radiation shielding. Thermochim. Acta 585, 5-9.
[4] Elmahroug, Y., Tellili, B., Souga, C., 2015. Determination of total mass attenuation coefficients, effective atomic numbers and electron densities for different shielding materials. Ann. Nucl. Energy 75, 268-274.
[5] Biswas, R., Sahadath, H., Mollah, A.S., Huq, M.F., 2016. Calculation of gamma-ray attenuation parameters for locally developed shielding material: Polyboron. J. Radiat. Res. Appl. Sci. 9, 26-34.
[6] Tarim, U.A., Gurler, O., Ozmutlu, E.N., Yalcin, S., 2013. Monte Carlo calculations for
gamma-ray mass attenuation coefficients of some soil samples. Ann. Nucl. Energy 58, 198-201.

[7] Oto, B., Gür, A., Kaçal, M.R., Dogan, B., Arasoglu, A., 2013. Photon attenuation properties of some concretes containing barite and colemanite in different rates. Ann. Nucl. Energy 51, 120-124.

[8] Adem, U., Faruk, D., 2013. Determination of mass attenuation coefficients, effective atomic numbers and effective electron numbers for heavy-weight and normal-weight concretes. Appl. Radiat. Isot. 80, 73-77.

[9] Singh, V.P., Ali, A.M., Badiger, N.M., El-Khayatt, A.M., 2013. Monte Carlo simulation of gamma ray shielding parameters of concretes. Nucl. Eng. Des. 265, 1077-1071.

[10] Sharifi, S., Bagheri, R., Shirmardi, S.P., 2013. Comparison of shielding properties for ordinary, barite, serpentine and steel–magnetite concretes using MCNP-4C code and available experimental results. Ann. Nucl. Energy 53, 529-534.

[11] Tellili, B., Elmahroug, Y., Souga, C., 2014. Determination of mass attenuation coefficient, effective atomic number and effective electron density for tungsten alloys. Int. J. Nucl. Energy Sci. Technol. 8, 238-248.

[12] El-Khayatt, A.M., Ali, A.M., Singh, V.P., 2014. Photon attenuation coefficients of Heavy-Metal Oxide glasses by MCNP code, XCOM program and experimental data: A comparison study. Nucl. Instrum. Methods Phys. Res. Sect. A 735, 207-212.