MONTE CARLO SIMULATION OF MULTILAYER RADIATION SHIELDING

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ABSTRACT

Lead (^{82}Pb) is one of the most used materials for attenuating x-rays and gamma rays in high-dose rate radiation facilities. However, it has been proven to have several pitfalls such as the heavy weight, toxicity of lead and its' high cost. This study was conducted to study the multilayer radiation shielding of non-lead materials to replace lead-based materials by using the Particle and Heavy Ion Transport code (PHITS) simulation. A parallel photon beam of mono-energy source was set in a vacuum environment. Multi-layered shielding composed of ^{13}Al, ^{50}Sn, ^{56}Ba, ^{64}Gd, ^{74}W and ^{83}Bi was simulated with a total thickness of 6 cm fixed for each multilayer combination. The distance from the point source-multilayer shielding-scoring region was kept constant at 50 cm throughout the series of simulation. The shielding properties of different materials at common energy ranges in radiology and nuclear medicine (100 keV until 1 MeV) were obtained. For each multilayer combination, the materials were encoded with their symbols and density in the PHITS task folder. Next, they were arranged in the desired orientation, either from low to high atomic number (orientation A), or high to low atomic number (orientation B). Among different non lead multilayer shield combinations proposed in this study, the two layered shielding consisting of W/Gd (orientation B) showed the most significant attenuation properties at 1 MeV photon energy. There is no optimal combination that provides equally effective attenuation in all cases as the proposed multilayer shielding materials must be individually tailored to match an application at a particular energy range.

ABSTRAK

Plumbum (^{82}Pb) ialah salah satu bahan yang paling biasa digunakan untuk melemahkan sinar-x dan sinar gamma dalam kemudahan sinaran kadar dos tinggi. Walau bagaimanapun, ia telah terbukti mempunyai beberapa perangkap seperti berat berat, ketoksikan plumbum dan kosnya yang tinggi. Kajian ini dijalankan untuk mengkaji pelindung sinaran berbilang lapisan bahan bukan plumbum bagi menggantikan bahan berasaskan plumbum dengan menggunakan simulasi kod Pengangkutan Zarah dan Ion Berat (PHITS). Rasuk foton selari sumber tenaga mono ditetapkan dalam persekitaran vakum. Perisai berbilang lapisan yang terdiri daripada ^{13}Al, ^{50}Sn, ^{56}Ba, ^{64}Gd, ^{74}W dan ^{83}Bi telah disimulasikan dengan jumlah ketebalan 6 cm tetap untuk setiap gabungan berbilang lapisan. Jarak dari kawasan pemarkahan perisai sumber-pelbagai lapisan dikekalkan malar pada 50 cm sepanjang siri simulasi. Sifat perisai bahan yang berbeza pada julat tenaga biasa dalam radiologi dan perubatan nuklear (100 keV *hingga 1 MeV) telah diperolehi. Untuk setiap gabungan berbilang lapisan, bahan telah dikodkan dengan simbol dan ketumpatannya dalam folder tugas PHITS. Seterusnya, ia disusun mengikut orientasi yang dikehendaki, sama ada dari nombor atom rendah ke tinggi (orientasi A), atau nombor atom tinggi ke rendah (orientasi B). Di antara kombinasi perisai berbilang lapisan bukan plumbum berbeza yang dicadangkan dalam kajian ini, dua perisai berlapis yang terdiri daripada W/Gd (orientasi B) menunjukkan sifat pengecilan paling ketara pada tenaga foton 1 MeV. Tiada kombinasi optimum yang memberikan pengecilan yang sama berkesan dalam semua kes kerana bahan pelindung berbilang lapisan yang dicadangkan mesti disesuaikan secara individu untuk memadankan aplikasi pada julat tenaga tertentu.*

Keywords: toxicity, PHITS simulation, multilayer radiation shielding, x-rays, gamma rays

INTRODUCTION

Over the years, lead has been heavily used and commercialised as radiation shielding in various fields [1, 2]. Grover et al. [3] in their study stated that old studies validated using lead is good, and lead aprons are recommended as shielding equipment for radiation workers. In their research also remarked lead as the most commonly used shielding material due to its high atomic number, high density and low cost. Lead apparels are categorised as a secondary defence to the effects caused by ionising radiation. Many scientists had proposed other materials to replace the lead element as a gamma or X-ray shielding such as clay and organic polymer [4, 5, 6, 7, 8, 9, 10, 11, 12, and 13]. As an example, the authors had successfully demonstrated the polymeric compounds doped with heavy element other than lead as an alternative shielding material for 150 keV photons with an affordable thickness [14, 15].

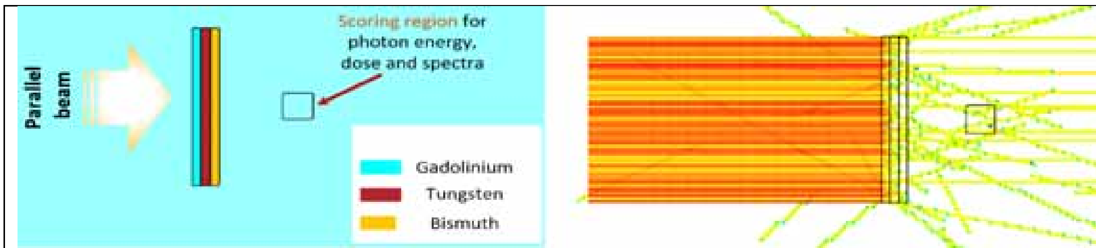
Recent studies have shown that lead is ought to be replaced due to several factors, including it having a blind absorption zone for X-rays with energies between 70 and 90 keV [16]. First, study and development of non-lead shielding materials either as single or mixtures of metal powders have been encouraged due to the disapproval towards weight of lead-based shielding and concerns about destruction of environment [17]. The weight of a typical lead apron is around 7 kg, which could lead to back problems [18].

In a study conducted by Al-Arif & Kakil [19], a single layer shield showed an increasing attenuation coefficient with decreasing atomic number when low photon energy is used and increasing with increasing atomic number at high photon energy. Rather than adhering to the ability of single-layered radiation shielding, many researchers have started to evaluate bilayer and multilayer shields as some of these experimented combinations resulted in good attenuation properties and can be considered as lead replacements. Muir et al. [20] also mentioned that in order to achieve the necessary lead equivalence, some manufacturers use a double layer of material, while others use a single layer.

A multilayer shield comprises two or more layers of different materials. These materials can be mixed and matched to resolve a particular problem depending on the application, as each material owns different shielding properties. According to McCaffrey et al. [17], multilayer attenuators which have been used to harden x-rays beam are placed in descending order of atomic number to enable the following layers to remove the fluorescence x-rays coming from the higher atomic number layers. They also presumed that these multilayer designs gave a better result than each material detached due to the subsequent layers absorbing scattered radiation of lower energy emerging from the earlier layer. In this study, the multilayer radiation shielding of non-lead materials were evaluated by using PHITS code [21].

CALCULATED LINEAR ATTENUATION COEFFICIENT (μ, CM^{-1}) OF THE ELEMENTS

To verify if the PHITS computation results are valid, we calculated the μ of the materials (^{82}Pb, ^{64}Gd and ^{13}Al) that were used in our study. All the main photon's interaction, such as photoelectric absorption, Compton scattering (including Rayleigh scattering), and pair productions were considered in our calculation. We calculated their respective μ at low (150 keV) and high (1000 keV) energies. From the graph of the percentage of transmitted photon as a function of material thickness, the value of μ was deduced by using an exponential fitting of the data. The values of μ acquired from PHITS for the elements were then compared with mass attenuation coefficient that obtained from XCOM database [22]. The mass attenuation coefficient was multiplied with their respective material density for its μ values. It has to be noted that the scattered photons that penetrate the material were ignored for effectively compared with the attenuation coefficients generated by XCOM.



(a) (b)

Figure 1. (a) A three-layered shielding geometry modelling in MC simulation performed in a vacuum environment for estimating the effect of elements on the transmitted and scattered photons. In (b) is an example of photon trajectory in MC simulation.

Figure 2 shows the calculation of transmitted photons as a function of material thickness for a pencil beam of 150 keV photon. From this graph, it can be seen that the percentage of calculated transmitted photon decreased exponentially with increasing thickness of material. Then, the data were fitted with an exponential equation to obtain the value of the linear attenuation coefficient (μ; cm^{-1}). Overall, the calculated μ value has a good agreement, within 1 % with the XCOM as in Table 1. Lead has the highest μ amongst all due to its high density and atomic number, 11.36 g cm^{-1} and 82 respectively. As the atomic number or density of the material increases, the attenuation produced by a given thickness increases. The agreement is important to ensure the input model of PHITS code was properly setup for shielding calculation at other photon energy and materials.

THE TRANSMITTED AMBIENT DOSE EQUIVALENT OF MULTILAYER SHIELDING

Table 2 demonstrates the multilayers shielding's ability dosimetry for all orientation and combination of two-, three- and four-layered shields. A single layer of lead (Pb-82) acts as a constant, while each multilayered shielding was simulated with two different orientations: orientation A and orientation B at 1 MeV. The results of multilayer shielding ability were discussed from two points; the most or better multilayer for Pb-equivalent attenuation, and the good orientation for photon attenuation. From Table 2, both of the two-layered studied, regardless of their orientation, are corresponding to the Pb-equivalent attenuation. The three-layer consisting of higher set of Z elements also show similar attenuation with Pb. Among them, W/Gd with orientation B has the lowest transmitted dose which is lower almost 24% than a single Pb. This output conforming to Zehtabian's et al. [23] study, W/Gd exhibited the most significant attenuation properties amongst two-layered shields and has lower x-ray flux than Gd/W/Bi at three different energies: 80, 120 and 140 keV.

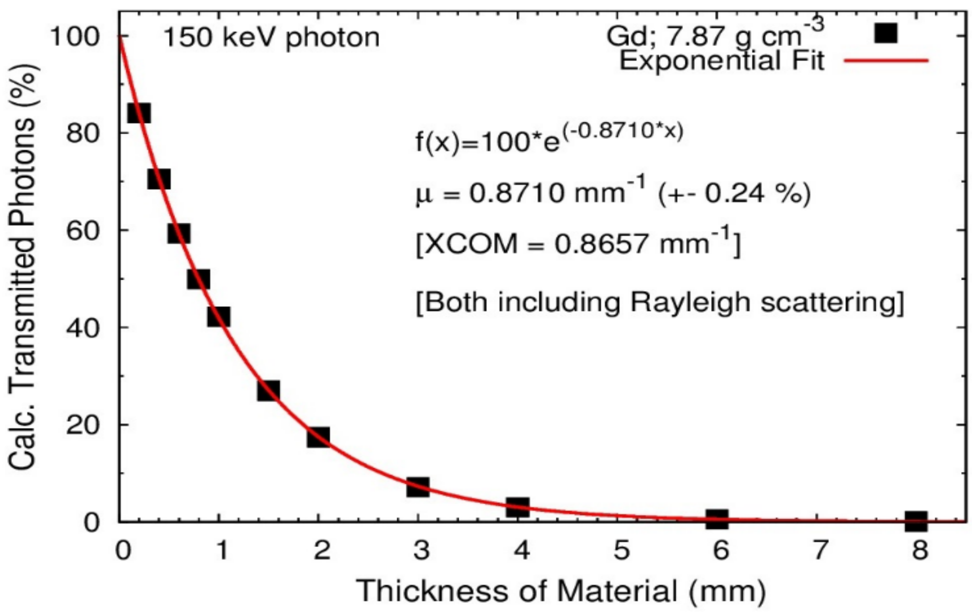


Figure 2. The calculated transmitted photons of Gd-64 for photon of 150 keV. The calculated and XCOM μ value is 8.694 cm^{-1} and 8.690 cm^{-1}, respectively.

Table 1. The percentage difference of linear attenuation coefficient for Al-13, Gd-64 and Pb-82.

Element	**LAC at 150 keV (μ; cm^{-1})**		
	PHITS	**XCOM**	**% of Diff.**
Pb-82	22.931	22.859	0.31
Gd-64	8.710	8.657	0.61
	LAC at 1000 keV (μ; cm^{-1})		
Al-13	0.166	0.165	0.60

For orientation of the atomic number (Z), the three-layer with set of lower Z elements follows descending and also set of higher Z follows ascending order would have a better photon attenuation for Pb-equivalency. While both four-layer shielding would follow ascending order for better photon attenuation. It is difficult to make a general conclusion for which orientation is better as it involves complex photon interactions such as K-edge absorption for every element, which requires further details investigation and analysis.

For instance, McCaffrey et al [17] had proposed that ascending order of the metal bilayers to provide substantially more attenuation than the reverse order. The ascending order transmits only 56% of the energy that the opposite order transmits. However, the study was performed only for two-layer shielding materials and this hypothesis only works at 50 kVp x-rays. In contrast, several scientists [20, 23] had mentioned multilayer shielding materials in descending order, to allow subsequent layers to remove the emission of K x-rays that originate in the above higher Z layer. However, descending order was better for 150 kVp x-rays, arguing that the x-rays would lose their energy as they transmitted through the high Z layer so they could be shielded smoothly by the subsequent low Z layer. In spite of that, the proposed multilayer shielding materials must be individually calculated or measured to obtain reliable results of photon attenuation with respect to lead.

Table 2. Multilayers shielding's attenuation ability for the calculated transmitted dose.

Number of layers	**Transmitted Ambient Dose Eq. (Sv/inc./cm²/s)**		**Orientation order of atomic number (Z) for better attenuation**
	Orientation A (↓Z to ↑Z)	Orientation B (↑Z to ↓Z)	
1 (Pb as standard)	0.014362		
2			
Sn/W	0.013588	0.014439	Ascending order
Gd/W	0.011322	0.010934	Descending order
3			
Al/Sn/W	0.0398	0.0396	Descending order
Gd/W/Bi	0.0142	0.0153	Ascending order
4			
Al/Sn/W/Bi	0.0336	0.0347	Ascending order
Sn/Ba/Gd/W	0.0462	0.0492	Ascending order

Table 3. Weight and Estimated Cost of Multilayer Shields

Number of layers	Weight (g)	Estimated Cost in RM [24 -28]
Pb	270	116.25
Sn/W	320	236.39
Gd/W	330	506.25
Al/Sn/W	230	158.52
Gd/W/Bi	300	341.17
Al/Sn/W/Bi	230	121.64
W/Gd/Ba/Sn	230	260.88

According to Table 3, three combinations of multi-layered shields has lower weight of 15% than lead, which are Al/Sn/W, Al/Sn/W/Bi and W/Gd/Ba/Sn. Al/Sn/W/Bi in both orientation A and B has similar transmitted photon energy with lead and the closest estimated cost to lead. However, none of these three combinations possesses a better shielding ability (dosimetry) than lead, which is a crucial element for a radiation shielding material. Although Gd/W weighs approximately 1.2 times more and costs 4.35 times more than lead, it has a good radiation shielding ability with lower dosimetry (Table 2), with lead which outweighs the weight and cost factor. The W/Gd/Ba/Sn has the lowest weight amongst all, which includes comparison with Sn/W, Gd/W and Gd/W/Bi combinations. The weight of a 0.5 mm W/Gd/Ba/Sn shield was the lowest amongst all the combinations studied when being ratioed with 0.5 mm lead shield.

CONCLUSION

Both two-layer Sn/W and Gd /W and three-layer non-lead shielding materials, Gd/W/Bi have similar lead equivalent attenuation for the transmitted ambient dose, regardless of their orientation. There is also no significant difference in term of average transmitted photon energy for all multi-layer materials studied when compared to lead. As for orientation of the atomic number (Z), there is no optimal orientation could be concluded as every element has K edge values that was assumed to have an impact towards the photon attenuation. The orientation planning requires further investigation and analysis by evaluating individual transmitted photon spectra.

Considering all four properties of a good radiation shielding (dosimetry, average transmitted photon dose, weight and cost), the two layered shielding consisting of W/Gd (orientation B) is the best non lead shielding replacement at 1 MeV. It is able to attenuate transmitted dose 24% lower than lead and has similar transmitted photon energy to that of lead. Although its weight and cost is higher than lead, the fact that these materials are non/less toxic makes them a good non lead radiation protection. Lastly, there is no optimal combination that provides equally effective attenuation in all cases. The proposed multilayer shielding materials must be individually tailored to match an application at a particular energy range.

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