Shielding Effectiveness of Some Composite Materials Alternative to Lead

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Abstract: ***Lead provide effective shielding against radiation because lead has a high density and atomic number, allowing it to efficiently absorb x-ray photons. Lead aprons are radiation protection garments used to protect patients from unnecessary exposure and radiology staffs from occupational exposure. Besides good radiation protection lead is considered a heavy metal and aprons made from this material can be cumbersome and tiring to wear, especially for extended periods. Also lead is highly toxic substance posing environmental and health risks if not handled and disposed of properly. Researchers are actively exploring alternatives to lead in radiation shielding aprons, with materials like tungsten, bismuth, barium sulfate, and certain polymer composites emerging as potential replacements due to their comparable radiation shielding effects while being less toxic than lead. Three combinations of lead alternative composite materials W-Sn-Ba-PVC, W-Sn-Cd-PVC, Sn-Gd-W-PVC investigated in the energy range of diagnostic radiology in broad beam geometry. Radiation shielding effects of these materials in terms of radiation attenuation was assessed between 30-60 keV and the results compared with standard lead containing composite material. No lead alternative composites provide better protection in low energie 30 keV.*** **Composite W-Sn-Ba-PVC provide considerable attenuation but always lower than standard.** ***Composite material W-Sn-Cd-PVC showed better attenuation within 40-60 keV and Sn-Gd-W-PVC showed better attenuation at 60 keV. Thus lead alternative composite shields could be effective for shielding against x-ray energies in the range of 40 to 60 keV.***

Keywords: shielding effectiveness, radiation shielding, alternative to lead, composite materials, Monte Carlo simulation

1. Introduction

Radiation shielding garments or lead aprons are commonly used to protect medical patients and workers from exposure to direct and secondary radiation during diagnostic imaging in hospitals, clinics and dental offices. Similar materials are employed for other applications such as baggage scanner used to protect personnel working in the vicinity of airport scanners or similar devices. In most of these environments, typical peak x-ray energies range from 60 to 120 kVp, corresponding to mean energies of approximately 35–60 keV [1]. The photoelectric effect overwhelmingly dominates energy transfer and absorption in this energy range. The effectiveness of radiation shielding varies significantly with the photoelectric attenuation coefficients of the constituent materials, the thickness of the garments, and the energy spectrum of the radiation [1]. Conventionally aprons made of lead have been used in diagnostic radiology and interventional trials because of their extraordinary efficiency in reducing radiation doses in patients and operators, respectively. Without these shields, direct and secondary exposure to ionizing radiation might lead to biological damages in healthy tissues.

Although lead shields are so beneficial to mitigate radiation doses reaching patient and radiation staff, questions have been raised about the safety of prolonged use of them. Because of the density of lead, these shields are so heavy, so its carrying is a burdensome task especially in long procedures, for example in interventional angiography, as Moore et al. demonstrated the relationship between the use of lead aprons and development of back pain [3]. Moreover, since lead is a toxic element, its long use may endanger the user's health [4]. Recently, researchers have shown an increased interest in looking for alternative non-toxic materials with less weight and possibly same attenuation to use instead of lead to overcome its mass and toxicity problems [5]. A recent study demonstrations lead free shields are completely effective for protection against x-ray energies in the range of 60 to 120 kVp where composite W-Sn-Cd-EPVC has shown the best radiation attenuation features in 60 and 90 kVp and the composite W-Sn-Ba-EPVC represents the best attenuation in 120 kVp even better than lead containing composites [2].

The study was aimed to investigate the shielding effectiveness of some lead alternative composite materials W-Sn-Ba-PVC, W-Sn-Cd-PVC, Sn-Gd-W-PVC which have less density and toxicity compared to lead. Lower energy range of diagnostic radiology from 30-60 keV studied in broad beam geometry. Radiation shielding effects of these materials in terms of radiation attenuation was assessed at 30, 40, 50 and 60 keV and the results compared with standard lead containing composite material.

2. Literature Review

2.1 Basics of X-ray

X-rays are one form of electromagnetic radiation. Most X-rays have a wavelength ranging from 0.01 to 10 nanometers and energies in the range of 100 eV to 100 keV. X-rays with high photon energies (above 5–10 keV) are called hard X-rays, while those with lower energy are called soft X-rays. Due to their penetrating ability, hard X-rays are widely used to image the inside of body called medical radiography X-rays interact with matter in three main ways, through photo electric effect, Compton scattering, and Thomson scattering. The strength of these interactions depends on the energy of the X-rays and the elemental composition of the material. Photoelectric absorption of x-rays occurs when the x-ray photon is absorbed, resulting in the ejection of electrons from the outer shell of the atom, and hence the ionization of the atom. Subsequently, the ionized atom returns to the neutral state with the emission of an x-ray characteristic of the atom.

This subsequent emission of lower energy photons is generally absorbed and does not contribute to (or hinder) the image making process. Photoelectron absorption is the dominant process for x-ray absorption up to energies of about 500 KeV. At higher energies, Compton scattering dominates.

2.2 K-absorption edge

In a given material, the probability of photoelectric interactions occurring is strongly dependent on the energy of the photon and its relationship to the binding energy of the electrons. Photo electric interactions decreases as the photon energy increases and photoelectric interactions occur at the highest rate when the energy of the x-ray photon is just above the binding energy of the electrons also known as K-absorption edge or K-edge. Table 1 shows a list of elements used in commercial radiation shielding garments imbedded in polymer or natural rubber. For the purposes of shielding, the energy of the K-absorption edge is an important parameter in the diagnostic imaging range, as individual elements strongly absorb energy at levels immediately above their respective edges [1].All elements become less effective at attenuating higher energy photons as the photoelectric effect becomes less relevant, requiring thicker layers for significant attenuation.

Table 1: Elements commonly used in commercial radiation shielding garments [1]

Element	*Atomic Number*	*Density (g/cm3)*	*K- absorption edge (KeV)*
Cadmium (Cd)	48	8.65	26.7
Indium (In)	49	7.31	27.9
Tin (Sn)	50	7.31	29.2
Antimony (Sb)	51	6.69	30.5
Barium (Ba)	56	3.51	37.4
Gadolinium (Gd)	64	7.90	50.2
Tungsten (W)	74	19.25	69.5
Lead (Pb)	82	11.34	88.0
Bismuth (Bi)	83	9.75	90.5

2.3 Attenuation of x-ray

When a photon passes through an attenuator material, the probability that an interaction will occur depends on its energy and the composition and thickness of the attenuator. The thicker the attenuator material, the more likely an interaction will occur. The dependence on photon energy and attenuator composition is more complicated. If an incident beam of photons of intensity I is directed onto an attenuator (atomic number Z) of thickness Δx and the beam is mono energetic with energy E, the transmitted beam intensity decreases by following equation:

$$\ln\left(\frac{N}{N_0}\right) = -\mu\Delta x \quad (1)$$

The quantity μ is the linear attenuation coefficient, a characteristic of the attenuator material. The minus sign indicates the beam intensity decreases with increasing attenuator thickness. The linear attenuation coefficient represents the absorptivity of the attenuator. The quantity μ is found to increase with linearly with attenuator density ρ. Thus knowing the value of N/No attenuation can be measured.

2.4 Monte Carlo and PHITS

PHITS (Particle and Heavy Ion Transport code System) is a general purpose Monte Carlo particle transport simulation code developed under collaboration between JAEA, RIST, KEK and several other institutes. It can deal with the transport of all particles over wide energy ranges, using several nuclear reaction models and nuclear data libraries. PHITS can support researches in the fields of accelerator technology, radiotherapy, space radiation, and in many other fields which are related to particle and heavy ion transport phenomena. Many studies used Monte Carlo simulation to calculate photon attenuation and radiation dose [6]. It is proven that Monte Carlo is valid enough for modeling photon transportation through materials and dose calculation [7]. In this study, PHITS was used to assess the attenuation effect of shielding materials. PHITS is a general purpose Monte Carlo Particle and Heavy Ion Transport code System developed through a collaboration of several institutes in Japan and Europe. PHITS can deal with the transport of nearly all particles, including neutrons, protons, heavy ions, photons, and electrons, over wide energy ranges using various nuclear reaction models and data libraries [8]. The geometrical configuration of the simulation must be set with either general geometry (GG) or combinatorial geometry (CG). The interactive solid modeler SimpleGeo to be used for generating PHITS readable geometries in the GG format. Various quantities, such as track length, and particle attenuation, energy spectra is deduced from the PHITS simulation using implemented “tally” estimator functions. The code also has a function to draw 2D and 3D figures of the calculated results and the setup geometries using an original graphic tool named ANGEL. The platforms on which PHITS can be executed are Windows, Mac, Linux, and Unix.

3. Materials and Methodology

Simulation coding was done using Monte Carlo (PHITS). The general geometry was produced using SimpleGeo modeler and Graphic images produced with the help of Angel graphic tool. Elements to be studied were selected based on their density, K-absorption edge and nontoxicity characteristics. Different combinations of elements, Cadmium (Cd), Gadolinium (Gd), Tin (Sn), Barium (Ba), Tungsten (W), Lead (Pb) were used as shield and their density calculated. Low density (1.11 g/cm3) Poly Vinyl Chloride (PVC) has chemical composition of C_2H_3Cl is used as matrix for different combinations of composite materials.

Table 2 shows the composition and weight fraction of lead free materials used as shields in this study. In order to compare the attenuation characteristics of attenuator materials lead-PVC composition (commercially used) were simulated in the same geometry.

Table 2: Composition of shielding materials investigated in the study

Material	*Composition (weight factor)*	*Density (g/cm3)*
Lead-PVC	87%Pb, 13%PVC	5.131
Composite 1	52%W, 31%Sn, 4%Ba, 13%PVC	5.025
Composite 2	37%W, 46%Sn, 4%Cd, 13%PVC	4.879
Composite 3	59%Sn, 24%Gd, 4%W, 13%PVC	4.323

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2023: 1.843

Composites density were calculated from individual element density and weight. Density calculation was found using equation:

$$V_c = \frac{m1}{\rho 1} + \frac{m2}{\rho 2} + \frac{m3}{\rho 3} + ...\frac{mn}{\rho n} \quad (2)$$

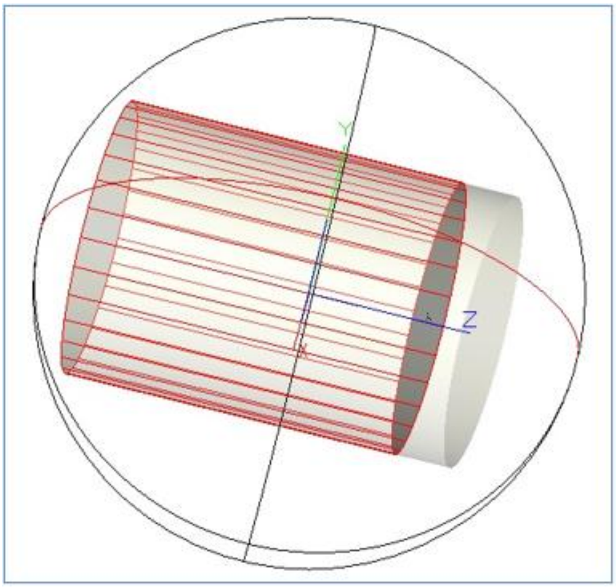
$$\rho_c = \frac{V_c}{100} \quad (3)$$

where, m1, m2, … are weight of individual elements and ρ1, ρ2,… are density of individual elements in the composition. In Equation- 3, V_c denotes the volume of the composite ρ_c is the calculated density of the composite.

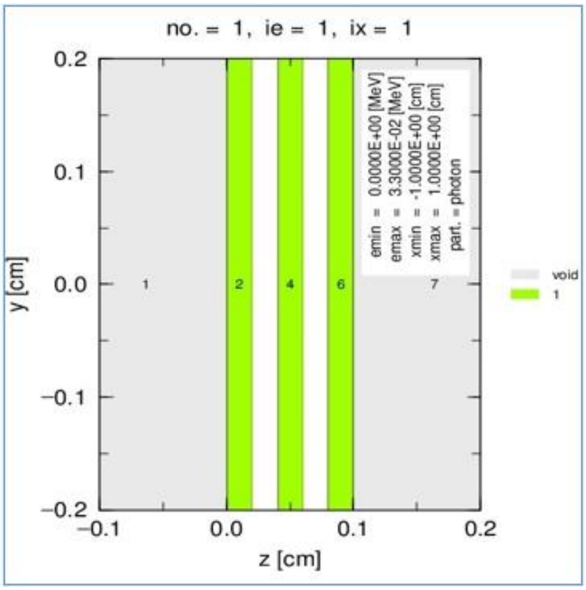
The simulation was performed in broad beam geometry with the x-ray source at 50 cm away from the attenuator. The geometry of the study is explained in Fig.1 The source used was a mono energetic cylindrical volume source with 10 cm radius. The attenuator was a cylinder with 25 cm radius and 0.1 cm thickness.

To assess the attenuation characteristics, PHITS program was introduced to visualize the track of particles crossing regions of the attenuator. The attenuator was divided into 5 no of regions each with 0.2 mm thickness as shown in Fig.1(b) to track particles in more detail. Fig.2 shows the particle track output generated by Angel graphic tool.

Using T-cross tally, the ratio of transmitted photons to initial photons (N/No) was recorded as the output data. The output data gives a measure of attenuation performance of the attenuator. The Simulation study was performed with all materials including lead-PVC and lead alternative composites W-Sn-Ba-PVC, W-Sn-Cd-PVC and Sn-Gd-W-PVC as attenuator and all energies 30, 40, 50, 60 keV were used as the x-ray source energy at individual study.



(a)



(b)

Figure 1: (a) 2D Geometry using PHITS (Source, Attenuator, and Surface), (b) 3D Geometry using SimpleGeo modeler. Black part indicates attenuator (0.1 cm) and red part indicates void space where the source is at 50 cm from attenuator.

Paper ID: SR241222113205 DOI: https://dx.doi.org/10.21275/SR241222113205

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2023: 1.843

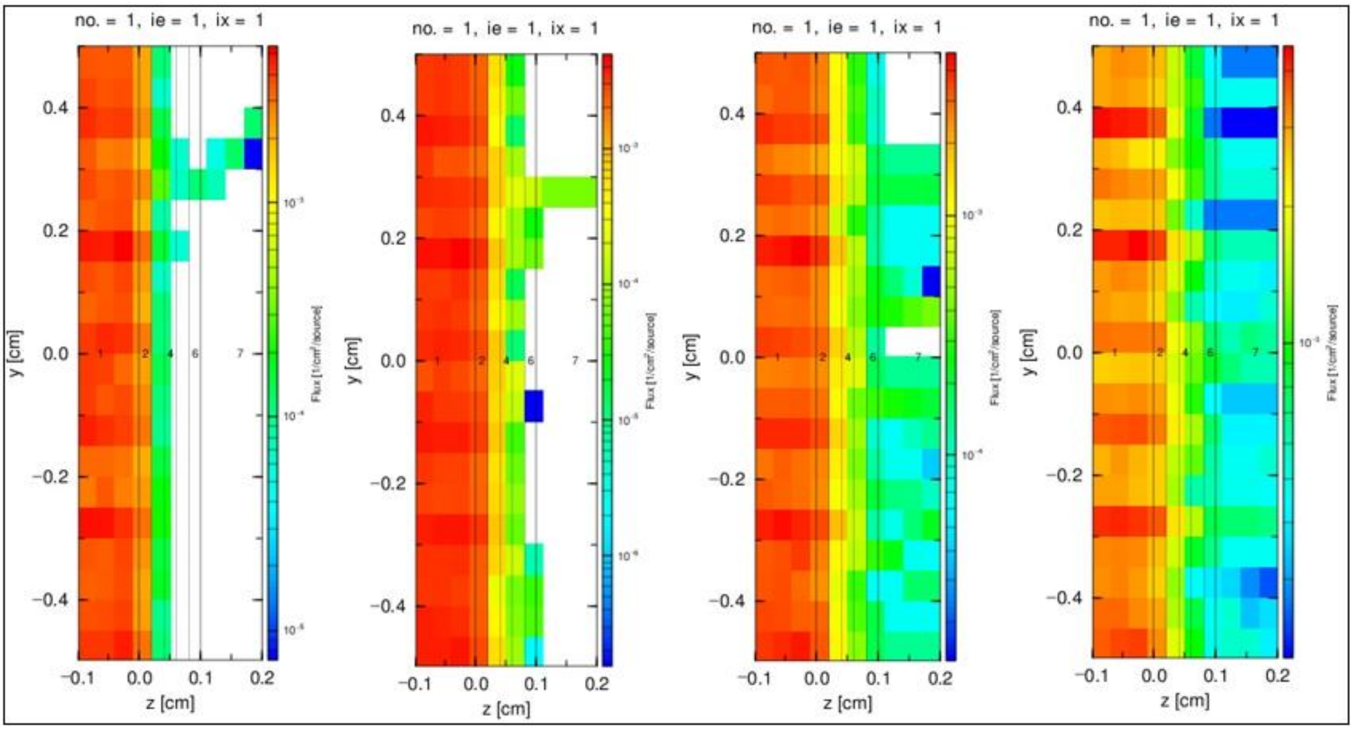
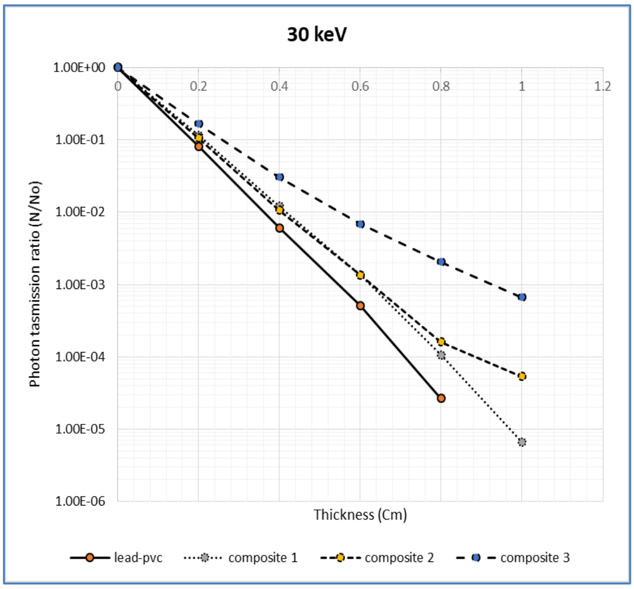


Figure 2: Track of photons in z-axis for composite 2 at different energies

4. Results and Discussion

The ratio of transmitted photons or output data N/No for different attenuator material were used to plot in a logarithmic scale against thickness of the attenuator. Comparison of attenuation of photons by different materials at different energies as shown in Fig.3. Transmitted photon ratio N/No above the surface of attenuator at different energies were summarized in Table 3. Transmitted photon ratio of designed composite materials was plotted with that of standard lead-PVC as shown in Fig.4. Results from Fig.4 and Table 3 shows that no lead alternative composites provide better attenuation in low energy 30 keV. Composite material W-Sn-Ba-PVC provide considerable attenuation but lower than lead-PVC at all energies studied. Composite material W-Sn-Cd-PVC showed better attenuation within 40-60 keV and composite material Sn-Gd-W-PVC showed highly better attenuation at 60 keV. Thus lead alternative composite shields could be effective for shielding against x-ray energies in the range of 40 to 60 keV.



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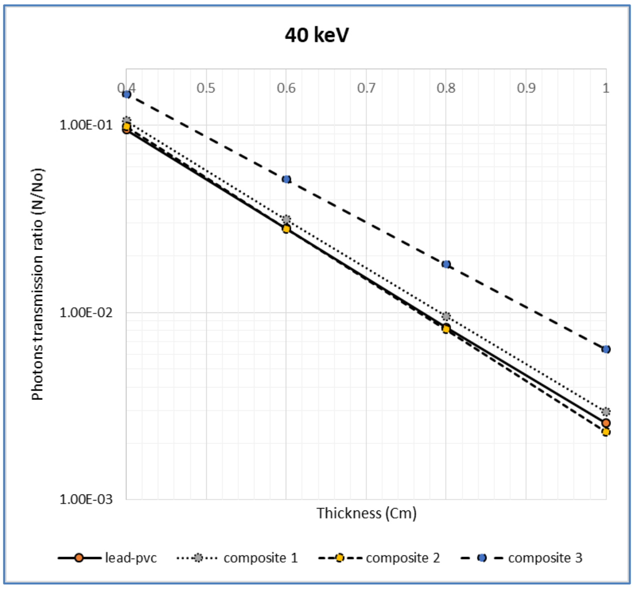

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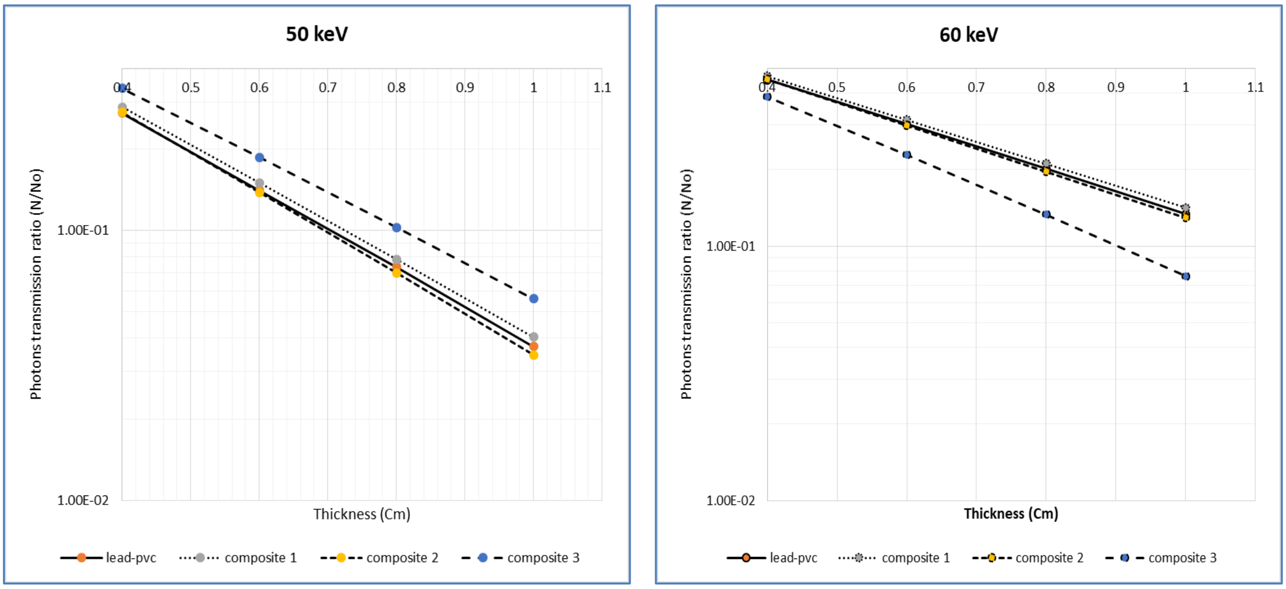

(c) (d)

Figure 3: Comparison of attenuation by different materials at different energies.

Table 3: Ratio of photons transmitted through the surface of attenuator at 30 keV, 40 keV, 50 keV and 60 keV energies

Material	*Density (g/cm3)*	*N/No*			
		30 keV	*40 keV*	*50 keV*	*60 keV*
Lead-PVC	7.31	0.0000E+00	2.5733E-03	3.7240E-02	1.3378E-01
W-Sn-Ba-PVC	7.31	6.6667E-06	2.9467E-03	4.0440E-02	1.4167E-01
W-Sn-Cd-PVC	6.69	5.3333E-05	2.3067E-03	3.4587E-02	1.2950E-01
Sn-Gd-W-PVC	3.51	6.6667E-04	6.3600E-03	5.5940E-02	7.6293E-02

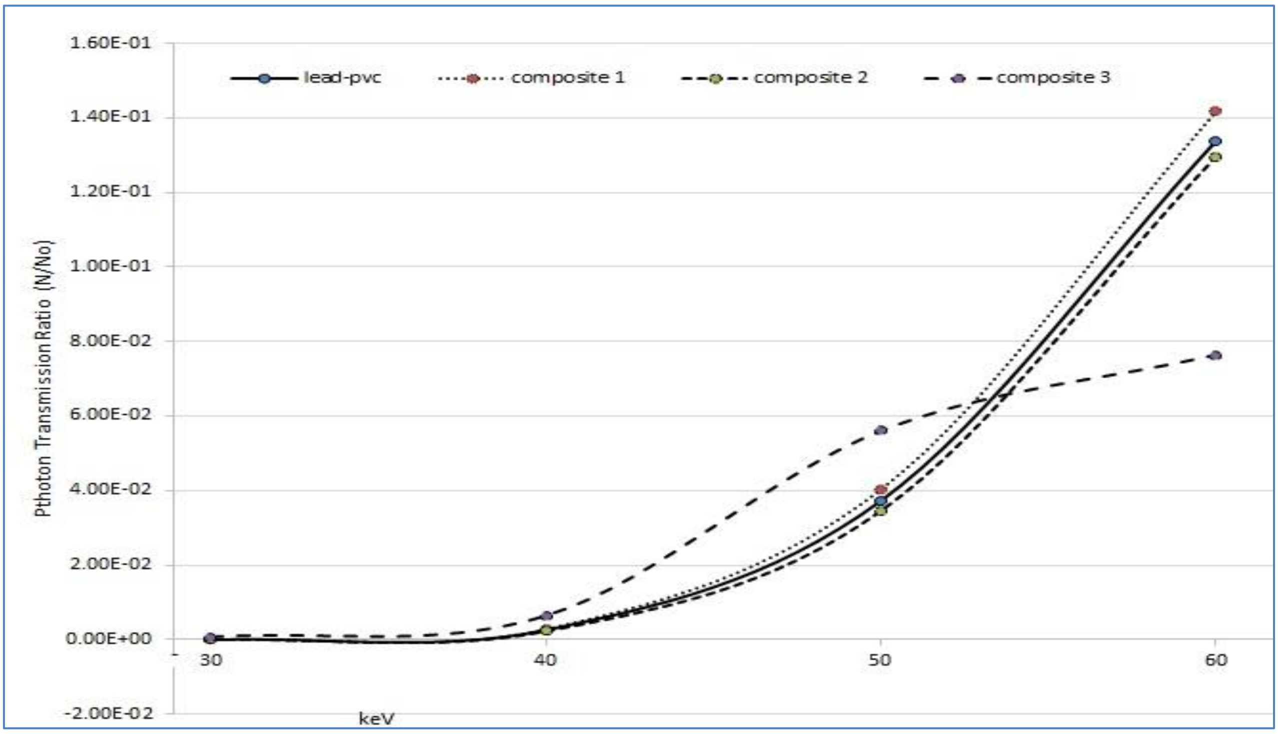

Figure 4: Attenuation comparison of composite materials with lead-PVC

5. Conclusion

In this study, three lead free shielding materials with lower density were introduced of which two materials showed better attenuation performance in comparison with lead-content composite Pb-PVC. The analysis of data and results revealed that at low energy 30 keV, no lead alternative composites provide better attenuation. However within 40-60 keV energy range W-Sn-Ba-PVC provide lower but considerable attenuation and W-Sn-Cd-PVC provides better attenuation than lead-content composite Pb-PVC. Another composite Sn-Gd-W-PVC provides highly better attenuation at 60 keV. Shields made of lead alternative composites can be considered as a replacement for lead in radiation shielding issue in a wide energy ranges of diagnostic radiology. Due to particular K-edge of each element, a single element cannot offer the best radiation protection for wide energy ranges. However, with suitable choice of elements for an especial range of energy, we can significantly improve shielding per unit weight over conventional lead-content shields. The present study has been investigated based on simulation therefore, further experimental study can support the findings.

6. Acknowledgement

The author attended an educational course- Postgraduate Educational Course on Radiation Protection and Safety of Radiation Sources (PGEC) organized by IAEA and hosted by Nuclear Agency Malaysia in 2017. As a part of fulfillment of the course the research work was done at the lab of Nuclear Malaysia. The author express his warm regards to Nuclear Malaysia for using there lab and provide all other supports toward this work.

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