Tri Dasa Mega Vol. 25 No. 3 (2023) 101–106

Jurnal Teknologi Reaktor Nuklir

Tri Dasa Mega

Journal homepage: jurnal.batan.go.id/index.php/tridam

Study of Alternative Shielding Material for Gamma Radiation using Monte Carlo Simulation

Gusti Atika Urfa[1*], Totok Wianto[1], Tetti Novalina Manik[1], Amar Vijai Nasrulloh[1]

[1]*Department of Physics, Faculty of Mathematics and Natural Sciences, Lambung Mangkurat University, Banjarbaru, Indonesia*

ARTICLE INFO

Article history:

Received: Sept 5th, 2023
Received in revised form: Oct 2nd, 2023
Accepted: Oct 9th, 2023

Keywords:

Shielding material
Radiation
Lead
Non-Lead
PHITS
Monte Carlo

A B S T R A C T

Lead is the most commonly used material for radiation shielding,-even though it has toxic properties. This study aims to identify alternative, lead-free, and non-toxic materials for gamma radiation shielding using Monte Carlo simulations. Bismuth Oxide (Bi_2O_3), Barium Oxide (BaO), Tungsten Trioxide (WO_3), Tungsten Dioxide (WO_2), and Molybdenum Trioxide (MoO_3) were selected as potential substitutes for lead. Pure lead (Pb) and Lead Oxide (PbO) were used for comparison. The simulation were performed using Particle Heavy Ion Tracking System (PHITS) software, with a gamma energy of 662 keV. The result of the simulation shows that the linear attenuation coefficient values for Pb and PbO were 0.902 mm^{-1} and 0.74 mm^{-1} respectively. Meanwhile, the simulation results of those simulated materials that are closest to Pb and PbO are Bi_2O_3 and WO_2 with an attenuation coefficient of 0.71 mm^{-1}. This simulation shows that for non-lead materials, BiO_2 and WO_2 have potential as alternative of non-lead radiation shielding.

1. INTRODUCTION

Gamma rays are a type of ionizing radiation used in the medical field for treating cancer through radiotherapy techniques. Furthermore, gamma rays can cause cellular damage upon exposure to the human body [1]. To protect the body from the negative effects of gamma rays, radiation shielding, commonly known as aprons, are required. Materials with high atomic number and density, such as lead and concrete, are effective in attenuating radiation [2]. The atomic number and density of a material influence its attenuation coefficient. Materials with higher attenuation coefficient are capable of absorbing more radiation [3].

Until now, lead has been the most commonly used material as a radiation shielding. However, research has demonstrated that lead is toxic and can pose risks to patients and workers due to its impact on the body's biochemical system [4]. Several studies have been conducted on the toxicity of lead [5–8]. The results of these studies have shown that lead can cause respiratory diseases, neudegenerative diseases, memory decline, and brain damage.

Lead-containing aprons must be handled in accordance with standards to prevent radiation leaks from the apron. The toxic nature and fragility of lead when mishandled necessitate the exploration of alternative radiation shielding materials [9]. One method that can be employed as a preliminary investigation of a material's ability to attenuate radiation energy is Monte Carlo simulation. One of the platform is PHITS (Particle Havy Ion Transport Code System) which was developed by the Japanese Atomic Energy Agency (JAEA). PHITS offers

*Corresponding author. Tel./Fax.: +6285132436720
E-mail: gusti.urfa@ulm.ac.id
DOI: 10.55981/tdm.2023.6925

various features applicable to field such as radiation shielding, radiation protection, and medical physics. It has the capability to simulate the transport of various particles with energies up to 1 TeV, utilizing different nuclear reaction models and data libraries [10].

This study aims to search for alternative radiation shielding materials that are non-toxic, lightweight and effective in attenuating gamma radiation. The parameters observed in this research are the attenuation coefficient values and HVL (Half Value Layer) of each alternative radiation shielding material, which can absorb radiation equally or more effective than lead. The radiation attenuation coefficient of a material is influenced by the fluence and energy deposit of gamma radiation passing through the material.

2. THEORY

Ionizing radiation is radiation that possesses sufficient energy to remove electrons from an atom and generate ions. Ionizing radiation can exist in the form of particles or electromagnetic waves. Ionizing radiation in the form of electromagnetic waves includes X-rays and gamma rays [11]. Gamma rays have higher energy than X-rays, resulting in greater penetration capability. X-rays are typically used in diagnostic equipment such as conventional radiography, CT-scan, and linear accelerator (Linac) [12]. On the other hand, gamma rays are commonly utilized in nuclear medicine applications [13].

Exposure to ionizing radiation can cause physical and chemical damage when interacting with the organs of the body. The resulting health effect may vary, ranging from exposure to low doses to high doses that may result in death. Other effects include leukimia, breast cancer, lung cancer, and so on [14, 15].

The adverse effects of X-rays and gamma rays can be reduced by applying the principles of radiation protection, which involve minimizing exposure time, increasing distance, and using radiation shielding [16]. For medical workers such as specialist doctor, nurses, radiographers, and medical physicists, minimizing time and increasing distance is challenging due to their involvement in patient care. Therefore, the use of radiation shield is mandatory [17] .

An effective material for radiation shielding is lead, which is an element with an atomic number of 82 and symbol Pb. Lead has several characteristics, including a low melting point, easy fabrication, acid resistance, and the ability to attenuate mechanical and electromagnetic waves. The density of lead at 20° is 11.3 g/cm^3 [18].

The thicker the radiation shielding material, the more radiation it absorbs. The percentage of radiation absorption in a material follows an exponential decay curve, where the intensity or energy of radiation passing through a material decreases exponentially as the thickness of the material increases. This relationship can be empirically represented by Eq. 1 below.

$$I = I_0 e^{-\mu\,\Delta x} \qquad \text{Eq.1}$$

where I represents the radiation intensity after passing through the attenuator, I_0 represents the initial radiation intensity, μ represents the attenuation coefficient, and Δx represents the thickness of the radiation attenuating material [3].

Some studies have shown that lead has toxic properties and pose potential hazards to individuals who are exposed. The research findings are outlined as follows. Eid et al.'s research demonstrated that lead exposure can result in neurodegenerative disease such as Alzheimer's and Parkinson's [5].

In the medical field, numerous studies have been conducted on the negative impact of lead. Hung et al. conducted an investigation on lead concentrations among radiography workers who used lead shields compared to non-lead shield users. The results demonstrated that lead concentration in the hair of radiography workers was higher than that of regular workers [6]. Research conducted by Burns et al. and Manocchio et al. also indicated that lead-containing shieldings had lead dust on their surfaces. It is this lead dust that can enter the respiratory system of healthcare workers [7]. Shoag et al. conducted a study on 58 radiography workers and found that low-dose lead was detected in the worker's blood samples [8].

Typically, protective cloths or aprons used by medical workers to shield themselves from radiation are made of vinyl or rubber and contain a lead layer with a thickness of approximately 0.2=0.5 mm [19]. Due to its rigidity, lead aprons need to be periodically tested to ensure there are no leaks, usually every 12=18 months [14]. Special attention to lead aprons is crucial to avoid any leakage.

Monte Carlo simulation plays a crucial role in radiotherapy, particularly as a method to evaluate physical properties that are impossible or difficult to measure [20]. Values of fluence and energy deposition can be obtained from Monte Carlo simulation. Fluence, denoted as ϕ , is defined as the number of particles or energy entering a surface or volume. Fluence is also commonly referred to as flux. On the other hand, energy deposition $\left(E_{dep}\right)$ refers to the energy deposited in a specific volume [21].

3. METHODOLOGY

Materials used in this research are gamma source data, radiation shielding material data, and PHITS software. Additionally, the necessary equipment includes a computer with a minimum of 2 GB of RAM.

The radiation source data inputted into PHITS consists of a cylindrical geometry with a radius of 0.1 cm. The gamma ray energy used is 662 keV, which is equivalent to the output energy of Cs-137. The source is pointed towards the positive z-axis and positioned 1 cm away from the target material.

The radiation shielding materials simulated in this research include pure lead, lead (II) oxide, bismuth oxide, tungsten trioxide, tungsten dioxide, and molybdenum trioxide. The details are provided by Table 1.

Table 1. Data of radiation shielding material

Material	Density (gr/cm^3)	Atomic Number (Z)
Pure Pb	11.34	Pb = 82
PbO	9.53	Pb = 82 O = 8
Bi_2O_3	8.9	Bi = 83 O = 8
BaO	5.72	Ba = 56 O = 8
WO_3	7.16	W = 74 O = 8
WO_2	10.8	W = 74 O = 8
MoO_3	4.69	Mo = 74 O = 8

To simulate gamma radiation directed at various types of different materials, three steps are required. The first step is to create the input file for PHITS, which includes the source geometry data and atomic number and density data for the different radiation shielding materials. The second step is divided into two parts. The first part is the calibration phase, which involves simulating gamma radiation on materials that have known attenuation coefficients based on NIST data. The number of gamma particles bombarding the materials during the calibration phase is one million. The materials used in this calibration phase are pure lead, pure tungsten, and water.

The second part of the second step involves simulating gamma radiation on the seven mixed materials listed in Table 1. The number of gamma particles used in this step is 10,000 due to the limitation of computational power. The third step is to plot the data obtained from the computer program calculations on a graph. Then, an exponential fitting is performed on the graph to obtain the attenuation coefficients and HVL for each material.

In this research, the geometry of all the materials used is in the form of a cylinder with a radius of 5 cm and a height of 20 cm. The cylinders are placed parallel to the z-axis, so the gamma rays are directed towards the circular face of the cylinder. The information of energy deposit and fluence is stored every 2 mm along the cylinder. A visualization of the simulated geometry of the materials is depicted in Fig. 1.

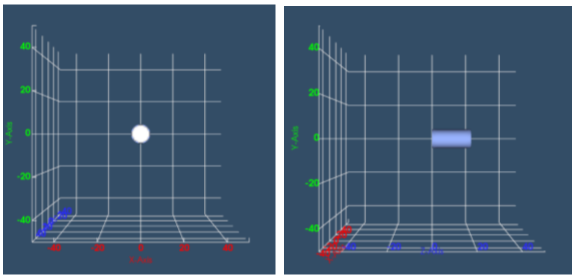

Fig. 1. Geometry of radiation shielding material (left) front view, (right) side view

4. RESULTS AND DISCUSSIONS

CALIBRATION RESULT

The results of this simulation are in the form of radiation dose distribution in each material. To test the accuracy of the Monte Carlo simulation results, calibration was performed by comparing the range of gamma ray penetration with NIST data. In phase, material with known attenuation coefficient, namely lead, tungsten, and water, were used. Fig. 2 shows a 662 keV gamma ray energy incident on a cylindrical shape of pure lead material. The results obtained in this calibration phase include gamma ray fluence and radiation energy deposition in each material.

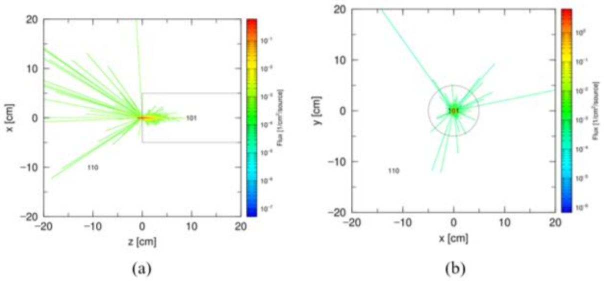

Fig. 2. Fluence of gamma radiation with energy 662 keV in Lead (a) x-z surface (b) x-y surface.

Every energy deposition obtained was recorded at every 2 mm depth, and the results obtained are depicted in Fig. 3.

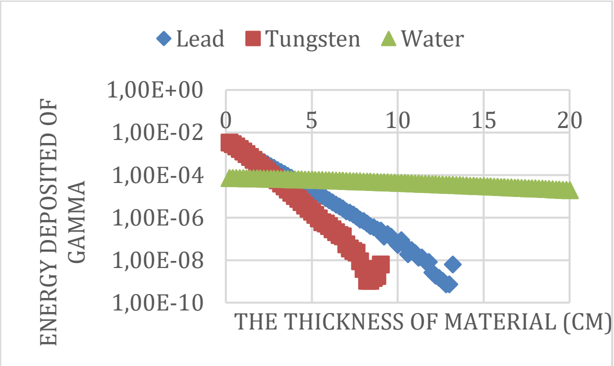

Fig. 3. Deposit energy of gamma radiation in each materials

By performing an exponential fitting on the graph and comparing it with NIST data, the results obtained are presented in Table 2.

Table 2. List of attenuation coefficient and Half Value Layer for reference materials

Material	Attenuation Coefficient $\mu\ (mm^{-1})$		Half Value Layer (mm)	
	Simulation	Theory	Simulation	Theory
Lead	1.146	1.248	0.604	0.555
Tungsten	1.729	1.930	0.401	0.359
Water	0.068	0.089	10.191	7.786

From the data provided, the attenuation coefficients, from smallest to largest, are water, lead, and tungsten. The smaller attenuation coefficient of water is due to its lower density and atomic number compared to lead and tungsten. This is in line with theory that materials with higher density and atomic number tend to have larger attenuation coefficients.

SIMULATIONS RESULT

From the simulations conducted using the PHITS program, the results obtained are in the form of gamma ray fluence and dose distribution of radiation in each material. Fig. 4 illustrates the gamma ray fluence obtained for various types of materials namely pure Pb, PbO, Bi_2O_3, BaO, WO_3, WO_2, and MoO_3.

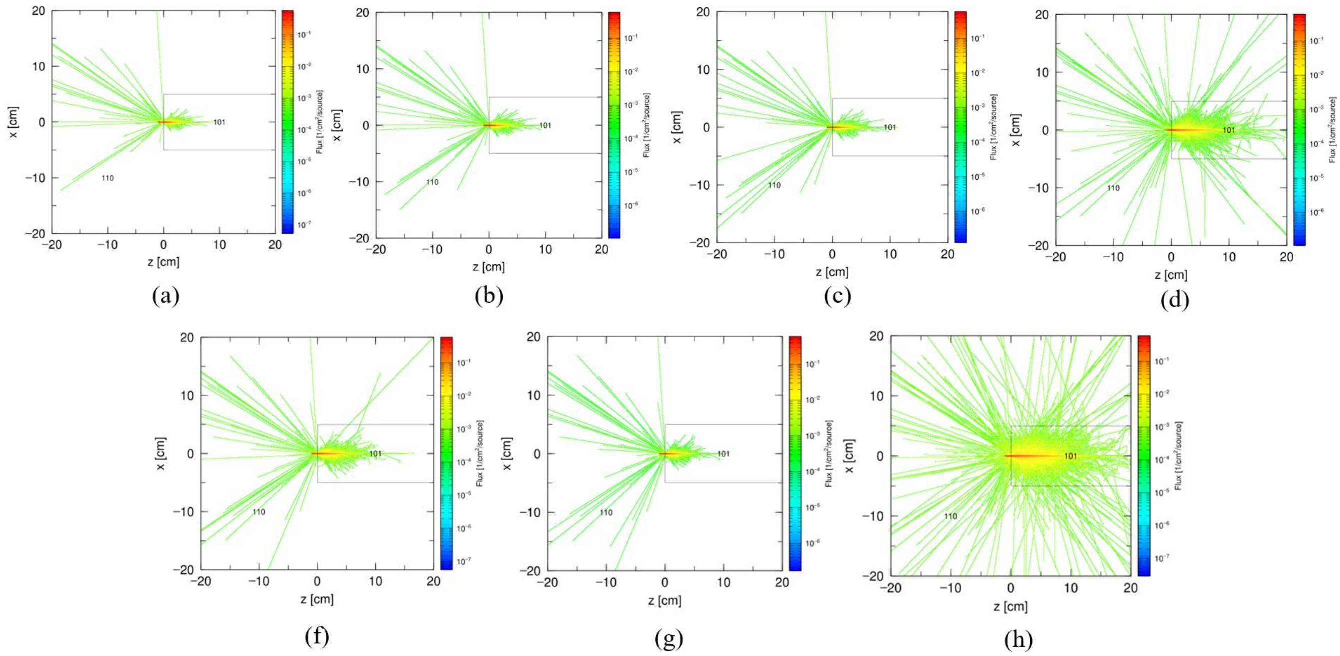

Fig. 4. Radiation fluence of incident gamma with energy 662 keV in material (a) pure Lead, (b) PbO, (c) Bi_2O_3, (d) BaO, (e) WO_3, (g) WO_2, (h) MoO_3.

The gamma ray fluence results shown in Fig. 4 provide a clear picture of how different materials interact with gamma radiation. Pure Pb typically exhibits the highest gamma ray fluence, given its high atomic number and density. For other materials like PbO, Bi_2O_3, BaO, WO_3, WO_2, and

MoO_3, there are variation in fluence due to differences in their atomic composition and density.

The energy deposition within the cylinder is represented in Fig. 5, where the graph visually depicts the variations. Pure Pb exhibits the steepest line, followed by PbO, Bi_2O_3, and WO_2 in desending order of steepness. Radiation shielding effectiveness depends upon the radiation energy, type, and thickness of shielding material. All of the graphs were fitted using an exponential fitting method to determine the attenuation coefficient and HVL.

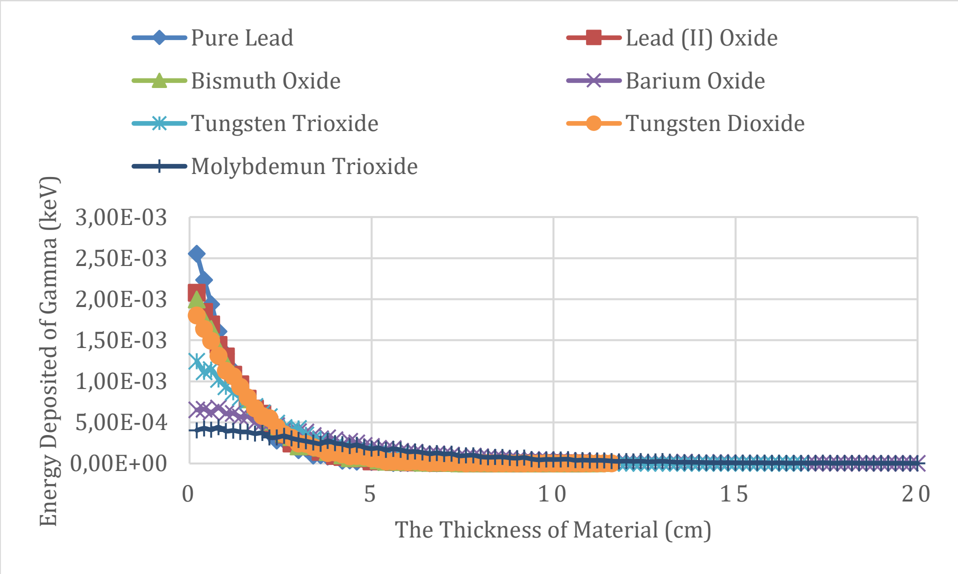

Fig. 5. Energy deposition stored in every 2 mm cylinder of various materials

Based on the fitting result, non-lead materials with the most effective attenuation coefficient are Bi_2O_3 and WO_2, with values of 0.710 and 0.715 respectively. Coefficient attenuation and HVL obtained from simulation analysis are listed in Table 3.

Table 3. List of coefficient attenuation value and HVL for various materials

Material	Coefficient Attenuation	Half Value Layer (mm^{-1})
Pure Pb	0.902	0.768
PbO	0.747	0.927
Bi_2O_3	0.710	0.976
BaO	0.342	2.026
WO_3	0.491	1.411
WO_2	0.715	0.969
MoO_3	0.283	2.448

The use of exponential fitting to determine the attenuation coefficient and HVL is a common and valid approach. This analysis methods helps quantify how effectively different materials can attenuate gamma radiation. The finding of Bi_2O_3 and WO_2 as substitutes for lead shielding is significant and promising choices for radiation shielding applications, particularly when lead-free alternatives are preferred.

5. CONCLUSION

Given the potential hazards associated with lead due to its toxicity, there is a preference for alternative radiation shielding materials. The results of this study indicate that among the simulated materials, the closest alternatives to Pb and PbO are Bi_2O_3 and WO_3, both exhibiting an attenuation coefficient of 0.71 mm^{-1}. This simulation underscores the potential of Bi_2O_3 and WO_2 as alternatives for non-lead radiation shielding materials.

ACKNOWLEDGMENT

We would like to express our sincere gratitude to the developers and contibutors of the Particle and Heavy Ion Transport code System (PHITS) for providing the valuable software used in our research. PHITS played a crucial role in our work study and the generation of important data for this study.

AUTHOR CONTRIBUTION

G.A. Urfa conducted simulations, designed the research, and drafted the manuscript. T.N Manik and T. Wianto contributed significantly to manuscript writing and data interpretation. A.V. Nasrulloh served as editors, providing critical feedback, refining the manuscript, and ensuring it met academic standards. All authors approved the final version for publication.

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