SAKARYA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ DERGİSİ

Sakarya University Journal of Science
SAUJS

ISSN 1301-4048 e-ISSN 2147-835X Period Bimonthly Founded 1997 Publisher Sakarya University
http://www.saujs.sakarya.edu.tr/

Title: Assessment of the Usability of A Composite Containing Boron Carbide for Shielding the Gamma Rays

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Recieved: 2022-06-07 00:00:00

Accepted: 2022-12-14 00:00:00

Article Type: Research Article

Volume: 27
Issue: 1
Month: February
Year: 2023
Pages: 159-167

How to cite
Urkiye AKAR TARIM; (2023), Assessment of the Usability of A Composite Containing Boron Carbide for Shielding the Gamma Rays. Sakarya University Journal of Science, 27(1), 159-167, DOI: 10.16984/saufenbilder.1127260
Access link
https://dergipark.org.tr/en/pub/saufenbilder/issue/75859/1127260

Sakarya University Journal of Science 27(1), 159-167, 2023

SAKARYA ÜNİVERSİTESİ

Assessment of the Usability of a Composite Containing Boron Carbide for Shielding the Gamma Rays

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Abstract

Considering the negative effects on the environment and toxicity of lead, which has been widely used for gamma shielding for a long time in nuclear technology, studies have been focused on the development of various materials that can be used as an alternative to lead in gamma radiation shielding. In this research, a composite material containing magnetite and boron carbide (epoxy/magnetite/boron carbide) and gamma transmission technique which is emphasized in nuclear applications have been used for the study of gamma ray shielding. The radiation sources considered for this technique are the radioisotopes Am-241, Cs-137, Na-22 and Co-60, which are important in nuclear technology. The interactions between the composite material and gammas with 59.5, 511, 661.6, 1173.2, 1274.5 and 1332.5 keV energies were investigated separately by the Monte Carlo method, and the ability of the material to shield the radiations at these energies was investigated. Gamma rays, one by one, followed by using cross sections and determining the probability of interaction with the composite from the point they are emitted until they leave the system (through escaping or absorption from the system) in the Monte Carlo code, which is written to determine the linear attenuation coefficient, mean free path, half value layer and tenth value layer, among the radiation shielding parameters of the composite under investigation. The shielding parameters calculated using the simulation results were also calculated using the data obtained from the XCOM software, and the results were found to be compatible with each other. On the other hand, in order to better evaluate the usability of the composite as an alternative shielding material for nuclear applications in the studied energy range, a comparison was made with the shielding parameters of various materials available in the literature.

Keywords: Radiation, gamma ray, shielding, boron carbide, Monte Carlo method

1. INTRODUCTION

Gamma rays are type of electromagnetic radiations which have high frequency i.e. higher energy or shortest wavelength. Interaction of these rays cannot be compared with those of charged particles because gamma rays are uncharged particles with zero mass due to which it has the large penetrating power [1]. They can easily entire and penetrate through the human body and may caus harm on living cells by transposing its energy to ambient cells [2]. Therefore, attenuation or shielding of this electromagnetic radiation by an appropriate material is important and necessary to keep

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safe human and the environment from the damaging effects of them.

Decrease in intensity of gamma rays occurs due to the interaction of them with matter. The grade of this decreasement depends on the energy of incident gamma ray, atomic number and density of constituent elements in the shielding material, and the thickness of material. For sampling and assigning the most convenient shielding, the cost, weight, chemical and physical durability of the materials are main parameters taken into account. Materials with high density and high atomic number provide superior attenuation to low density and low atomic number materials. Lead, bismuth, tungsten, iron and steel, water, borated paraffin or polyethylene are some of the materials commonly utilized to shield gamma rays by several researchers. These listed materials can be employed solo, blended into a structural material or into a polymer, or layered to maximize the effectiveness of shielding for several sources of radiation [3]. The widespread use of lead which is a toxic heavy metal generates several serious effects on health and environment in the long-term [2]. Thus, it incentives to find non-toxic, light, flexible and low-cost gamma ray shielding materials to supply as a substitute for lead [2, 4]. Most of the recent research works focus on composites that feature gamma ray shielding [5-17].

In the present work, Monte Carlo simulation which is an alternative method to the experiment due to its advantages [18, 19], was applied for the research on shielding effectiveness of a composite material containing magnetite and boron carbide [20]. A modified code, reliability and validation of it tested previously was used to get the data essential in determining the linear attenuation coefficient (μ), mean free path (MFP), half value layer (HVL) and tenth value layer (TVL) thicknesses, which are among the radiation shielding parameters for gamma rays with 59.5, 511, 661.6, 1173.2, 1274.5 ve 1332.5 keV energies. Results for radiation shielding efficiency of boron carbide composite approximate those of lead at medium gamma ray energies. On the other hand, studied composite has better shielding properties from compared composite and concrete samples. The conclusion can be drawn from this study is also that the written code is suitable to be used for preliminary work before expensive and difficult experiments for desinging a shielding material.

2. MATERIAL AND METHOD

Three types of shielding materials required for radiation workers can be described, these are namely structural shield, optically transparent shield, and flexible shield [21]. Recently, it is an important subject to obtain the composite with high attenuation properties and thereby to replace lead. Polymer composites are considered a good choice due to the advantages of them like flexibility, light weight, non-toxic, and non-corrosiveness. The concerned polymeric composite is a robust epoxy/magnetite/boron carbide (EP/Mag/B4C) composite. The constituents where: Epoxy=15%, magnetite=75% and boron carbide 10% [20]. Here, for proper assessment of shielding properties of this suggested formulation, in addition to this filled composition, EP/Mag/B_4C, epoxy blank composition has also been concerned. The detailed elemental compositions and densities of the studied materials [20] are given in Table 1.

Table 1 Elemental compositions and densities of the materials investigated in the present study

Sample	Density (g cm^{-3})	H	B	C	N	O	Na	Mg	Si	K	Ca	Fe
EP	1.16	0.066		0.6745	0.0285	0.2310						
EP/Mag/B_4C	2.995	0.012170	0.077010	0.128500	0.004050	0.276409	0.007300	0.002300	0.057990	0.000561	0.047310	0.386400

Experiments for such researches are often costly and time comsuming. For this reason Monte Carlo is an alternative method used in recent years safely. Also, it can be applied for testing before practical implementations. In the application of this method for selection a suitable shielding material, knowledge of the type of incident radiation, the type of interaction it undergoes with the shield, and the secondary radiation that is produced is fundamental. In the present study, a simulation code for the geometry given schematically in Figure 1, based on Monte Carlo, has been written to deal gamma ray attenuation by discussed material and to decrease the uncertainty in estimations in this simulation, a large number of incident gamma rays were used, set at 10^7.

As a preliminary, parameters for the attenuation data for each absorber specimen are derived from the XCOM database developed by Berger et al. [22]. The fitted equation to these data for the energy values in the range of 10–2000 keV is given in Eq. (1), where x is the natural logarithm of energy value of tracked gamma ray.

$$\mu = \exp\left(p_1 + p_2 x + p_3 x^2 + p_4 x^3 + p_5 x^4\right) \quad (1)$$

For each sample, the parameters (p_1, p_2, p_3, p_4 and p_5) in the equation were obtained for both Photoelectric absorption and Incoherent attenuation and presented in Table 2.

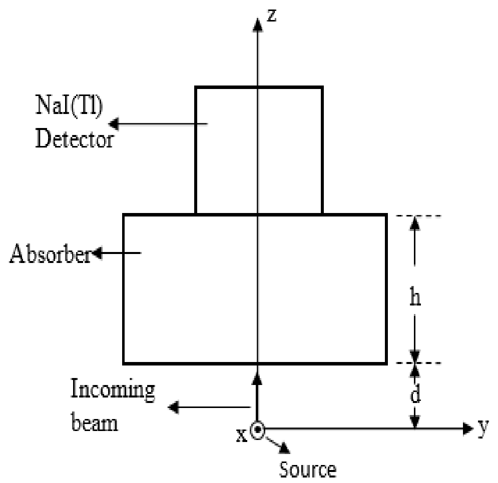

Figure 1 The scheme of the geometry used in Monte Carlo simulation

Table 2 Parameters of the fitted equation for the cross section data

	Photoelectric absorption		Incohorent scattering	
	EP	EP/Mag/B_4C	EP	EP/Mag/B_4C
p_1	8.67725751	11.5389782	-3.51042698	-3.23289350
p_2	-3.56588436	-2.86845988	1.29263358	1.52263871
p_3	0.26850526	0.22922942	-0.27432453	-0.29858612
p_4	-7.29802732 10^{-2}	-7.65192335 10^{-2}	2.01071793 10^{-2}	1.97501435 10^{-2}
p_5	6.21446394 10^{-3}	6.49829807 10^{-3}	-6.59699882 10^{-4}	-5.40090027 10^{-4}

In the form of written code, it is assumed that the setup is in vacuum and the gamma rays interact only in the polymeric absorbers and detector system, i.e., the runaway gamma rays travel towards the vacuum or optical couplant are left unfollowed. All the incident gamma rays (I_0) are directed toward the absorbing material. In tracing procedure, the coordinates of the gamma rays go into the sample are appointed; the free path length is sampled by random sampling from the exponential distribution; coordinates of the interaction point of gamma ray are established. If the interaction point of localized gamma is in the absorber, the simulation is continued according to the type of the interaction. Two main interactions of gammas with media are considered, namely Photoelectric absorption and Compton scattering. If the interaction point is not in the absorber, it is checked whether the gamma ray arrives to the detector system. The gamma rays that arrive to the detector system are counted to determine the transmitted intensity (I). In addition to these, it is assumed that the energy of electrons that are arised from interactions is deposited locally. By plotting the natural logarithm of (I_0/I) ratio versus absorber thickness (t) as shown in Figure 2, the slope is calculated and this obtained value defines the linear attenuation coefficient, as it is clear from Eq. (2).

$$\mu = \frac{1}{t}\ln\left(\frac{I_0}{I}\right) \quad (2)$$

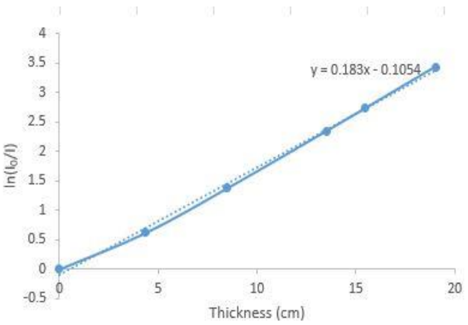

Figure 2 Plotting of ln(I_0/I) values versus attenuator medium thickness (for epoxy at energy of 59.5 keV)

Two of important quantities for gamma ray shielding, the half value layer (HVL) and tenth value layer (TVL) were worked out to assess the absorbing ability of studied materials against gamma rays with several energies.
Half value layer is the appropriate thickness of material to reduce the intensity of radiation to one half of its original intensity (provides 50% attenuation) and tenth value layer is the appropriate thickness of material to reduce the intensity of radiation to one tenth of its original intensity (provides 90% attenuation) [3]. These shielding parameters are expressed mathematically as follows, respectively:

$$HVL = \frac{\ln 2}{\mu} \quad (3)$$

$$TVL = \frac{\ln 10}{\mu} \quad (4)$$

Another essential quantity, the mean free path (MFP), is defined as the average distance of consecutive interaction points of a gamma ray photon and computed from following equation

$$MFP = \frac{1}{\mu} \quad (5)$$

3. RESULTS AND DISCUSSION

Appointing the most suitable shielding material for a given gamma ray source requires knowledge of the energy of gamma ray, application of attenuation data from available resources and understanding of the basic principles of gamma ray interactions with matter. In the present study, radiation attenuation simulations were performed to determine the shielding efficiency of the designed attenuator material (EP/Mag/B4C), formulated by Gheith et al. [20]. Here, a Monte Carlo code has been written out and all the presented results were computed based on repeated random sampling and statistical analysis.

For research the effect of high-density magnetite and boron carbide content to the shielding efficiency, gamma ray transmission simulations were performed for epoxy blank samples with thicknesses of 0(bare)-4.36-8.50-13.49-15.45-19.02 cm; then repeated for epoxy/magnetite/boron carbide composite samples with thicknesses of 0(bare)-4.30-8.56-13.48-15.53-20.56 cm. By using the code output, ie transmitted intensity of gamma rays, linear attenuation coefficients of both materials were determined for gamma rays with 59.5, 511, 661.6, 1173.2, 1274.5 and 1332.5 keV energies and tabulated (Table 3). The validation of written Monte Carlo code for the investigation of shielding parameters for composite structures has been reported by comparison simulated data with theoretical ones [22].

Table 3 Monte Carlo calculated linear attenuation coefficients (μ) for the investigated materials

Radioisotope	Gamma-ray energy (keV)	Linear attenuation coefficient (cm^{-1})	
		EP	EP/Mag/B_4C
Am-241	59.5	0.1830 (XCOM [22]:0.2075)	1.6263 (XCOM [22]:1.7312)
Cs-137	661.6	0.0892 (XCOM [22]:0.0957)	0.2116 (XCOM [22]:0.2281)
Co-60	1173.2	0.0676 (XCOM [22]:0.0728)	0.1604 (XCOM [22]:0.1731)
	1332.5	0.0632 (XCOM [22]:0.0682)	0.1533 (XCOM [22]:0.1623)
Na-22	511	0.0975 (XCOM [22]:0.1066)	0.2325 (XCOM [22]:0.2547)
	1274.5	0.0648 (XCOM [22]:0.0697)	0.1570 (XCOM [22]:0.1657)

The linear attenuation coefficient depends on the incident gamma ray energy and the chemical composition of the absorbing composite material. It is to be remarked from Table 3 that, for gamma ray energy values in a range from 59.5 keV to 1332.5 keV the values of linear attenuation coefficient increase remarkably with addition the magnetite and boron carbide and decrease in a sharp manner as the gamma ray energy increases in this range. EP/Mag/B_4C always have higher linear attenuation coefficients than EP at all the studied gamma ray energies.

Tables 4-6 show the values of other dealed shielding parameters, MFP, HVL and TVL for each gamma ray energy studied. These results can be used to estimate the thickness of these shielding materials required to achieve a desired level of attenuation. This is clearly seen in these tables; the MFP, HVL and TVL values of the concerned composite are much lower than pure epoxy especially at all studied energies of gamma rays and filled formulation leads better shielding properties versus pure epoxy.

Table 4 Mean free path (MFP) values calculated by using Monte Carlo simulation data

Radioisotope	Gamma-ray energy (keV)	Mean free path (cm)	
		EP	EP/Mag/B_4C
Am-241	59.5	5.4645	0.6149
Cs-137	661.6	11.2108	4.7259
Co-60	1173.2	14.7929	6.2344
	1332.5	15.8228	6.5232
Na-22	511	10.2564	4.3011
	1274.5	15.4321	6.3694

Table 5 Half value layers (HVL) calculated by using Monte Carlo simulation data

Radioisotope	Gamma-ray energy (keV)	Half value layer (cm)	
		EP	EP/Mag/B_4C
Am-241	59.5	3.7877	0.4262
Cs-137	661.6	7.7707	3.2757
Co-60	1173.2	10.2537	4.3214
	1332.5	10.9675	4.5215
Na-22	511	7.1092	2.9813
	1274.5	10.6967	4.4150

Table 6 Tenth value layers (TVL) calculated by using Monte Carlo simulation data

Radioisotope	Gamma-ray energy (keV)	Tenth value layer (cm)	
		EP	EP/Mag/B_4C
Am-241	59.5	12.5824	1.4158
Cs-137	661.6	25.8137	10.8818
Co-60	1173.2	34.0619	14.3553
	1332.5	36.4333	15.0201
Na-22	511	23.6163	9.9036
	1274.5	35.5337	14.6661

Definition of the tabulated values could be that, constituents in the polymeric composite increase the shielding properties owing to the mangetite (F_3O_4) and boron carbure (B_4C) that have strong gamma radiation absorption capability. Also it is apparent that, increase in the gamma ray energy causes an increase in the HVL and TVL thicknesses where more thickness of the absorber is necessary to reduce the intensity of the incident gamma ray to one half and one tenth of its initial value, respectively. All the dailed shielding parameters showed that, lower density of epoxy blank requires thicker shielding as an expected result and as seen in the literature [3, 23, 24].

Furthermore, the shielding performance of the studied formulation has been evaluated by comparison of selected attenuation parameter, HVL, with values for commonly used shielding materials that are existing in many references. Figure 3 depicts the HVL of epoxy/magnetite/boron carbide composite together with the materials frequently used for gamma ray shield such as lead and concrete [25] and some polymeric composites [6, 26] for pointing out of similarities/differences of these materials at gamma ray energies of 59.5 keV, 661.6 keV and 1332.5 keV.

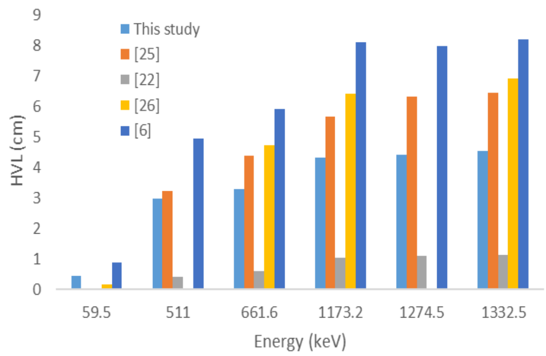

Figure 3 Comparison with literature

It is obvious that 0.4262 cm of epoxy/magnetite/boron carbide composite is equivalent to 0.0132 cm of lead shield at 59.5 keV which is 32.29 times the thickness of lead. However, at higher energy of 1332.5 keV, 4.5215 cm of this composite is equivalent to 1.1228 cm of lead which is only 4.03 times the thickness of lead. Therefore, this simulation work supports that this composite is encouraging to be utilized as absorber for medium energy gamma rays.

4. CONCLUSION

Attenuation or shielding of gamma radiation is one of the most important component of radiation safety [3] and it has become important to develop portable, cheap and lead-free shielding material that will provide as much protection as lead. The main goal of this research is to evaluate the effectiveness of a polymeric composite, EP/Mag/B_4C, as new lead-free gamma ray shielding material by considering the attenuation properties in datail with Monte Carlo method as a cheap and fast way. As evident from the data presented in tables and figures of this paper, the shielding performance of filled formulation, EP/Mag/B_4C, for gamma sources with different energies is better than that of blank, EP, with the same thickness; and even from concrete, polymer composites reinforced with $BaTiO_3$ and $CaWO_4$ compounds and CdO/HDPE composites. Among the materials compared, shielding values closest to lead were found for EP/Mag/B_4C at medium gamma ray energies.

Acknowledgments
The author would like to thank Prof. Dr. Orhan GURLER and Prof. Dr. Emin N. OZMUTLU for their contributions.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declare that she comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that she does not make any falsification on the data collected. In addition, she declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

REFERENCES

[1] J. K. Chahal, “Dependence of Resolution and Efficiency of NaI(Tl) on Various Parameters,” M.S. Dissertation, Thapar Institute of Engineering and Technology, Punjab, India, 2020.

[2] N. J. AbuAlRoos, M. N. Azman, N. A. B. Amin, R. Zainon, “ Tungsten-based Material as Promising New Lead-free Gamma Radiation Shielding Material in Nuclear Medicine,” Physica Medica, vol. 78, pp. 48-57, 2020.

[3] D. R. McAlister, “Gamma Ray Attenuation Properties of Common Shielding Materials,” Ph.D. Dissertation, University Lane Lisle, IL, USA, 2018.

[4] N. J. Abualroos, R. Zainon, “Fabrication of New Non-hazardous Tungsten Carbide Epoxy Resin Bricks for Low Energy Gamma Shielding in Nuclear Medicine,” Journal of Physics Communications, vol. 5, no. 9, p. 095014, 2021.

[5] B. Aygün, E. Şakar, V. P. Singh, M. I. Sayyed, T. Korkut, A. Karabulut, “Experimental and Monte Carlo Simulation Study on Potential New Composite Materials to Moderate Neutron-gamma Radiation,” Progress in Nuclear Energy, vol. 130, p. 103538, 2020.

[6] F. Akman, M. R. Kaçal, N. Almousa, M. I. Sayyed, H. Polat, “Gamma-ray Attenuation Parameters for Polymer Composites Reinforced with $BaTiO_3$ and $CaWO_4$ Compounds,” Progress in Nuclear Energy, vol. 121, p. 103257, 2020.

[7] B. Ahmed, G. B. Shah, A. H. Malik, Aurangzeb, M. Rizwan, “Gamma-ray Shielding Characteristics of Flexible Silicone Tungsten Composites,” Applied Radiation and Isotopes, vol. 155, p. 108901, 2020.

[8] M. C. M. Higgins, N. A. Radcliffe, M. Toro-Gonzalez, J. V. Rojas, “Gamma ray Attenuation of Hafnium dioxide- and Tungsten trioxide-epoxy resin Composites,” Journal of Radioanalytical and Nuclear

Chemistry, vol. 322, pp. 707–716, 2019.

[9] T. Özdemir, A. Güngör, I. K. Akbay, H. Uzun, Y. Pabucçuoglu, “Nano lead oxide and Epdm Composite for Development of Polymer Based Radiation Shielding Material: Gamma Irradiation and Attenuation Tests,” Radiation Physics and Chemistry, vol. 144, pp. 248-255, 2018.

[10] N. I. Cherkashina, V. I. Pavlenko, A. V. Noskov, “Radiation Shielding Properties of Polyimide Composite Materials,” Radiation Physics and Chemistry, vol. 159, pp. 111-117, 2019.

[11] H. Alavian, H. Tavakoli-Anbaran, “Study on Gamma Shielding Polymer Composites Reinforced with Different Sizes and Proportions of Tungsten Particles Using MCNP code,” Progress in Nuclear Energy, vol. 115, pp. 91-98, 2019.

[12] V. I. Pavlenko, N. I. Cherkashina, R. N. Yastrebinsky, “Synthesis and Radiation Shielding Properties of Polyimide/Bi2O3 Composites,” Heliyon, vol. 5, p. e01703, 2019.

[13] S. Atef, D. E. El-Nashar, A. H. Ashour, S. El-Fiki, S. U. El-Kameesy, M. Medhat, “Effect of Gamma Irradiation and Lead Content on the Physical and Shielding Properties of PVC/NBR Polymer Blends,” Polymer Bulletin, vol. 77, pp. 5423–5438, 2020.

[14] A. Sharma, B. Singh, B. S. Sandhu, “Investigation of Photon Interaction Parameters of Polymeric Materials Using Monte Carlo Simulation,” Chinese Journal of Physics, vol. 60, pp. 709-719, 2019.

[15] C. Eke, “A Study on the Gamma-ray Attenuation Parameters of Some Commercial Salt Samples,” Sakarya University Journal of Science, vol. 24, pp. 412-423, 2020.

[16] B. Kanberoğlu, A. Y. Teşneli, “Shielding Performance of Composite Materials Used in Air Vehicles,” Sakarya University Journal of Science, vol. 25, pp. 554–562, 2021.

[17] U. Akar Tarım, O. Gürler, “Application of Monte Carlo Method for Gamma ray Attenuation Properties of Lead Zinc Borate Glasses,” Sakarya University Journal of Science, vol. 22, pp. 1848-1852, 2018.

[18] T. F. Çavuş, E. Yanıkoğlu, “Karmaşık Sistemlerin Monte Carlo Yöntemi ile Güvenilirlik Analizi,” Sakarya University Journal of Science, vol. 7, pp. 99-102, 2003. (In Turkish)

[19] U. Akar Tarım, “Monte Carlo Simulation of Multiple Scattering of Medium-energy Gamma Rays,” Ph.D. Dissertation, Bursa Uludag University, Bursa, Turkey, 2014.

[20] A. T. Gheith, M. A. El-Sarraf, I. E. Hasan, N. L. Helal, R. A. Rizk, A. A. El-Sawy, A. El-Sayed Abdo, “Assessment of a Polymeric Composite as a Radiation Attenuator and a Restoration Mortar for Cracking in Biological Shields,” Nuclear Physics and Atomic Energy, vol. 21, pp. 361-368, 2020.

[21] A. Bijanu, R. Arya, V. Agrawal, A. S. Tomar, V. S. Gowri, S. K. Sanghi, D. Mishra, S. T. Salammal, “Metal-polymer Composites for Radiation Protection: A Review,” Journal of Polymer Research, vol. 28, p. 392, 2021.

[22] M. J. Berger, J. H. Hubbell, S. M. Seltzer, J. Chang, J. S. Coursey, R. Sukumar, D. S. Zucker, K. Olsen, "XCOM: photoncrosssectionsdatabase, NIST standard reference database 8 (XGAM)" February, 18, 2022 [Online]. Available : http://www.nist.gov/pml/data/xcom/index.cfm/

[23] M. D. M. Ali, M. E. M. Eisa, J. A. Mars, K. E. M. Mohamadain, A. E. El faki, A. Hamed, K. J. Cloete, A. A. Beineen, "Study of gamma rays shielding parameters of some building materials used in Sudan," International Journal of Radiation Research, vol. 19, pp. 191-196, 2021.

[24] N. J. AbuAlRoos, M. N. Azman, N. A. B. Amin, R. Zainon, "Tungsten-based material as promising new lead-free gamma radiation shielding material in nuclear medicine," Physica Medica, vol. 78, pp. 48-57, 2020.

[25] O. Gurler, U. Akar Tarim, "Potential Use of Concretes for Gamma-Ray Shielding," Fresenius Environmental Bulletin, vol. 28, pp. 10029-10034, 2019.

[26] A. M. El-Khatib, M. I. Abbas, M. A. Elzaher, M. S. Badawi, M. T. Alabsy, G. A. Alharshan, D. A. Aloraini, "Gamma Attenuation Coefficients of Nano Cadmium Oxide/High density Polyethylene Composites," Scientific Reports, vol. 9, p. 16012, 2019.