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Development of Transparent Epoxy Resin–Bi_2O_3 Composites as Alternative Radiation Shielding Materials for Optical Shielding

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ABSTRACT

Scattered radiation exposure during radiology procedures can reach the head and eye lenses of personnel, requiring eye protection with good radiation attenuation capabilities without compromising comfort. Conventional lead-based radiation protection materials have high density, making them heavy and less ergonomic for long-term use. This study aims to evaluate the X-ray attenuation capability of a transparent epoxy resin–bismuth oxide (Bi_2O_3) composite as a candidate optical shielding material for radiation glasses based on the Half Value Layer (HVL) parameter. The composite was made using epoxy resin as a matrix and Bi_2O_3 as a high atomic number filler, with a mass ratio of 5:1 and a thickness of 0.5 mm and 1.0 mm. Measurements were performed using a diagnostic X-ray machine at voltages of 40 kV and 45 kV with an ionization dosimeter detector. The HVL value was calculated based on the linear attenuation coefficient (μ), and the data were analyzed using the Shapiro–Wilk normality test and Spearman's correlation. The results showed that an increase in composite thickness resulted in an increase in the HVL value, and there was a significant positive correlation between thickness and HVL ($r = 0.681$; $p < 0.01$). The epoxy resin–Bi_2O_3 composite showed effective attenuation at thin thicknesses with optical transparency characteristics, making it a potential lead-free optical shielding material for radiation glasses. These findings demonstrate that Bi_2O_3--epoxy resin composites are promising candidates for developing lightweight, transparent, and effective radiation protective eyewear.

***Keywords**: HVL; Optical Shielding; Radiation Protection; Scattered Radiation; X-ray Attenuation*

INTRODUCTION

X-rays are high-energy electromagnetic waves with very short wavelengths so that they are able to penetrate body tissues and various solid materials. Since its discovery by Wilhelm Conrad Röntgen in 1895, X-rays have been a key technology in radiodiagnostics and a wide range of medical applications (Ratnawati, 2014). In radiology practice, exposure to scattered radiation (Scatter Radiation) potentially reach the eye lens of a medical officer, which is a very Radiosensitive with a low dose tolerance threshold. Repeated exposure, even at low doses, can increase the risk of cataracts (Moriarty et al., 2022). The use of protective glasses has been shown to reduce the radiation dose in the eye's lens by up to 90% during the fluoroscopy procedure (Burns et al., 2013). This is in line with the policy International Commission on Radiological Protection (ICRP) which lowers the lens equivalent dose limit to 20 mSv/year (International Commission on Radiological Protection, 2018), as well as the principle of ALARA (As Low As Reasonably Achievable) which emphasizes the use of personal protective equipment (Endo et al., 2021). ALARA is a radiation protection principle that emphasizes that radiation exposure must be kept as low as possible reasonably by considering technical, economic, and social aspects. Without compromising medical purposes, through timing, distance, and radiation shielding (International Commission on Radiological Protection, 2018).

However, most conventional protective glasses still use heavy, uncomfortable high-density materials. Therefore, alternative materials were developed that are lighter, ergonomic, and remain transparent (Haraldosson & Mielcarek, 2024; Mariani & Malucelli, 2022; Pandit, Goswami, Holkar, & Pinjari, 2025). Epoxy resin is widely used as a composite matrix because it is stable, strong, easy to process, and can be made transparent (Aygün, 2022), while polymer composite materials weigh 30–50% lighter than conventional shields Cao et al., 2024). Effectiveness Shielding can be improved with the addition of filler high atomic number such as bismuth oxide (Bi_2O_3) (Munhoz et al., 2023; Sayyed et al., 2021) that has a probability of interaction Photoelectric high against X-rays (Mahmoud et al., 2023). This strategy is commonly used in material development Shielding Lead-free (Darwesh et al., 2023).

Previous research has shown that increased Bi_2O_3 thickness in epoxy resin is able to improve attenuation coefficient and efficiency Shielding significantly (Li et al., 2022; Munhoz et al., 2023). In addition, the use of Bi_2O_3 nanoparticles and the combination of particle sizes resulted in better attenuation values as well as lowering half value layer (HVL) (Elsafi et al., 2023; Hedaya et al., 2024; Mehrara et al., 2021; Muthamma et al., 2021). Modifications and combinations filler, As with graphene oxide and other materials, it is also proven to improve performance Shielding without compromising the mechanical stability of the material (Khalil et al., 2024; Moonkum et al., 2025). Nonetheless, most research still focuses on panels that are 1–2 mm thick, while eyeglass lens applications require transparent materials with a thin thickness of about 0.5–2 mm (Yusof et al., 2025). Capability evaluation Shielding generally use the parameters of protection effectiveness and HVL (Sayyed et al., 2021).

Based on this, this study aims to analyze the X-ray attenuation ability of epoxy–Bi_2O_3 resin composites with thicknesses of 0.5 mm and 1.0 mm. The novelty of this research lies in the development of a thin (0.5--1.0 mm) transparent epoxy-Bi_2O_3 composite specifically designed for optical shielding applications in radiation protective eyewear, an area that remains underexplored as most previous studies have focused on thicker shielding panels for general radiation protection. By evaluating both HVL parameters and protection effectiveness at diagnostic energy levels (40--45 kV), this study provides comprehensive insight into the material's potential as a lightweight, lead-free alternative for eye lens protection. The results of this study are expected to be the basis for the development of lighter, more transparent, and more effective radiation protective glasses.

METHOD

This research was a laboratory experimental study carried out at the Radiology Laboratory of the University of Muhammadiyah Purwokerto in May-June 2025. The study aimed to analyze the effect of variations in the thickness of Bi_2O_3 resin composites on the X-ray attenuation ability based on HVL values and protection effectiveness. The material consists of epoxy resin, catalysts, and Bi_2O_3 powder as *high-Z filler*. The tools used include precision glass molds (0.5 mm and 1.0 mm), mechanical mixers, digital scales (Nankai 177-21), ionization dosimeters, and X-ray aircraft operated at 40 kV and 45 kV. The voltage range was chosen because it represents the ideal low energy for the characterization of protective materials, as per previous research recommendations (Hedaya, Elsafi, Al-Saleh, & Saleh, 2024; Li, Peng, Zhao, & Chen, 2022).

The composite is made by mixing epoxy resin and Bi_2O_3 in a mass ratio of 5:1, then adding a catalyst (2:1 of the resin volume). The mixture is homogenized, poured into the mold, and left to curing 8–10 hours. The hardened sample is then removed, cleaned, and polished until the surface is flat. Measurements are made by placing the sample between the X-ray source and the detector; the intensity without the sample was recorded as I_0 and the intensity after passing the sample as I. Each condition was tested three times at a combination of thickness of 0.5 mm and

1.0 mm and voltage of 40 kV and 45 kV. The linear attenuation coefficient (μ) is calculated from the ratio of radiation intensity before and after it passes through the material, as shown in equation (1). Furthermore, the HVL value is determined based on the linear attenuation coefficient according to equation (2).

The value of the linear attenuation coefficient (μ) is calculated using the equation:

Linear Attenuation Coefficient (μ)

$$\mu = -\frac{\ln(I/Io)}{\chi} \qquad (1)$$

Half-Value Layer (HVL)

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

With I_0 the radiation intensity without shielding, I is the radiation intensity after passing through the apron with a thickness x (mm). HVL analysis was performed to evaluate the efficiency of radiation absorption by the prototype at voltage variations. Data were obtained from direct measurements of radiation intensity before and after passing through protective materials.

$$Efektivitas\ Proteksi(\%) = \left(\frac{I_O - I}{I}\right) \times 100 \quad (3)$$

with I_0 being the radiation intensity without the sample and I being the intensity after passing through the sample. The effectiveness value is used as a supporting parameter of HVL to describe the ability of materials to reduce radiation. Data were analyzed using descriptive and inferential statistics. Statistical analysis includes descriptive statistics to illustrate the distribution of HVL values and effectiveness in each group. The Spearman Correlation test is used because the data is not normally distributed, making it more suitable for assessing the monotonic relationship between thickness and HVL.

The difference in effectiveness between the four groups of thickness and stress combinations was analyzed using the Kruskal–Wallis test, which is a non-parametric alternative when the data do not meet the assumption of normality. Next, the Mann–Whitney test was performed to compare the effectiveness between thicknesses at the same stress, as this test was effective for two independent groups with a non-parametric data scale. This test aims to determine the significance of the effect of thickness on the protective ability of X-ray radiation in epoxy–Bi_2O_3 resin composites.

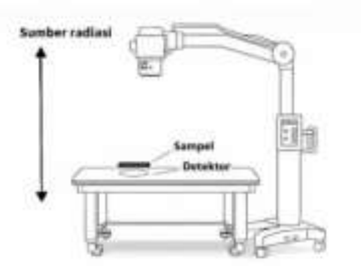

Figure 1. Testing of the apron prototype against X-rays
Source: Research documentation, 2025

Figure 1 shows the configuration of the device during the test, with an X-ray plane as the source of radiation, a prototype of radiation glasses as a test material placed on the radiation beam path, and a detector as an intensity measuring device. This illustration illustrates the orientation and spacing between components to ensure measurements are made consistently and accurately.

RESULTS AND DISCUSSION

The prototype of radiation glasses is carried out as an initial stage to provide test samples that are in accordance with the research design. Two prototypes made of epoxy resin and Bi_2O_3 It is manufactured using two thickness variations namely 0.5 mm, and 1 mm. Prototype documentation is shown on Figure 2 which shows the top and side appearance as a verification of the final shape before radiation testing is carried out.

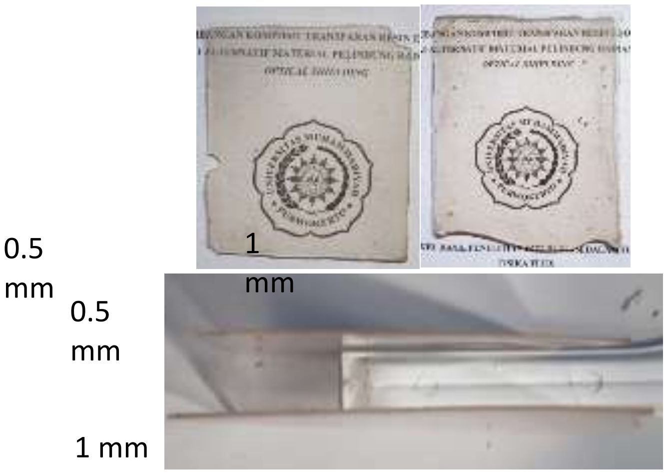

Figure 2. Apron Prototype Results: a) top view, b) side view with 0.5 mm and 1 mm Thickness Variation

Source: Research documentation, 2025

The purpose of this study is to calculate HVL and effectiveness in thickness variations of Bi_2O_3-based Pb glasses in combination with Epoxy Resin as a binder. The test was conducted on two thickness variations, namely 0.5 mm, and 1 mm, with an X-ray voltage variation of 40 kV, and 45 kV at a current of 4.0 mA. Initial radiation intensity (*baseline*) without the use of aprons was measured at 0.009 mGy for a voltage of 40 kV, and 0.013 mGy for 45 kV, respectively. The results of the calculation of the average absorbed dose after penetration on Table 1.

Table 1. Average dose absorbed after penetrating the apron

Thickness (mm)	Average dose absorbed after penetrating the apron (mGy)	
	40 Kv	45 kv
0.5	0.0016 ± 0.0008	0.0039± 0.00164
1.0	0.0012 ± 0.0004	0.0027± 0.00064

Source: Primary data, 2025

Next, the calculation of HVL is carried out The calculation results shown on Table 2 indicates that HVL values increase as thickness increases at both voltages, indicating that thickness variations of 0.5 mm and 1.0 mm provide different attenuation responses to radiant energy.

Table 2. HVLe Calculation Results

Thickness (mm)	Average HVL (mm)	
	40 kV	**45 kV**
0.5	0.02037± 0.00625	0.03028± 0.01083
1.0	0.03444± 0.00581	0.04431± 0.00682

Source: Primary data, 2025

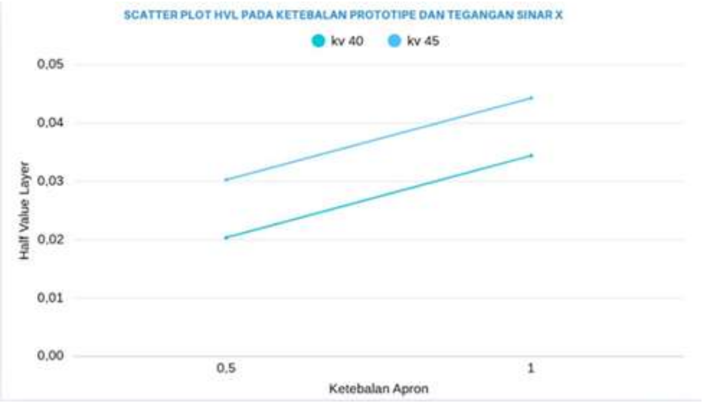

Figure 3 HVL Value Thickness Relationship Graph on Beam Voltage Variation

Source: Primary data, 2025

The HVL value increases with the increase in material thickness, both at 40 kV and 45 kV as shown in Figure 3. An increase in HVL indicates that thicker materials require additional thickness to reduce radiation intensity by half, due to the build-up effect (*build-up effect*) and more complex photon energy distribution. At higher voltages (45 kV), HVL values also increase compared to 40 kV, which indicates that X-rays with higher energy have greater penetration. Thus, a thicker protective layer is required to achieve the same damping. The results of the data analysis shown in Figure 3.

Table 3. Shapiro–Wilk normality test results for HVL

Voltage	Statistics	Sig. (p)
40	827	002
45	819	002

Remarks: HVL data is not normally distributed because the p value < 0.05.

Source: Primary data, 2025

The value of p-*Value* at both voltages (40 kV and 45 kV) < 0.05, so the HVL data is not normally distributed. Therefore, the analysis of the relationship between variables was continued using the non-parametric method on Table 4.

Table 4. Spearman's correlation between thickness and HVL

Variable	Spearman's rho correlation	Sig. (2-tailed)	N
Thickness vs HVL	0,681	0,000	40

Remarks: Composite thickness had a strong and significant positive relationship with HVL (p < 0.01).

Source: Primary data, 2025

The correlation coefficient value of r = 0.681 (p < 0.01) showed a strong and significant positive relationship between material thickness and HVL value. This means that the thicker the protective material, the higher the HVL value produced. Physically, an increase in HVL indicates an increase in X-ray penetrability due to increased energy or thickness of the material being tested. Furthermore, an effectiveness analysis was carried out to evaluate the ability of the material to reduce the intensity of radiation directly on the Table 5.

Table 5. Radiation effectiveness of Bi_2O_3–epoxy resin composite (%)

Thickness (mm)	Average Effectiveness	
	40 kV	**45 kV**
0.5	82,222± 9,3697	70,000± 13,298
1.0	86,666± 4,6848	79,230± 5,1919

Source: Primary data, 2025

The effectiveness at 40 kV is higher than at 45 kV for the entire thickness, suggesting that the photoelectric mechanism is more dominant at low energy. Under this condition, Bi_2O_3 particles with a high atomic number ($Z = 83$) increase the probability of photon absorption thereby improving shielding performance. A thickness of 1 mm indicates the highest effectiveness value, while a thickness of 0.5 mm at 45 kV indicates the lowest value. Next, a normality test of effectiveness was carried out using Shapiro–Wilk on Table 6.

Table 6. Shapiro–Wilk normality test results for effectiveness

Voltage	Statistics	Sig. (p)
40	0.717	001
45	0.842	047

Remarks: Effectiveness data are not normally distributed because the p value < 0.05.

Source: Primary data, 2025

The p-value at both voltages (40 kV and 45 kV) < 0.05, so the effectiveness data is not normally distributed. Analysis of differences between groups was continued using Kruskal–Wallis, a non-parametric method Table 7 display the results of the Kruskal–Wallis test.

Table 7. Kruskal–Wallis test results effectiveness

Statistic	Value
p-value	0,001

Source: Primary data, 2025

The significant difference in effectiveness is reinforced by the mean rank value as shown in Table 8.

Table 8. *Mean rank* Effectiveness based on thickness and tension

Groups	*Mean rank*
40 kV – 1.0 mm	30.00
40 kV – 0.5 mm	24.70
45 kV – 1.0 mm	15.95
45 kV – 0.5 mm	11.05

Remarks: A higher mean rank indicates greater effectiveness.

Source: Primary data, 2025

Value *Mean Rank* on Table 8 shows that the effectiveness of protection tends to be higher at a thickness of 1 mm compared to 0.5 mm, and more optimal at a voltage of 40 kV compared to 45 kV. To directly compare the two thicknesses, the Mann–Whitney test was performed Table 9.

Table 9. Man Whitney Test

Parameters	kV 40	kV 45
Mean rank 0.5 mm	9.30	8.65
Mean rank 1 mm	11.70	12.35
p-value	0.260	0.143

Remarks: The mean rank of the apron was 1 mm higher at both voltages, but there was no significant difference (p > 0.05)

Source: Primary data, 2025

The results showed that at low energy of 40–45 kV, both composite thicknesses (0.5 mm and 1 mm) still provided relatively similar protection performance, although the 1 mm thickness trend still showed higher effectiveness. At 40 kV, the effectiveness of 1 mm was slightly greater than that of 0.5 mm, but the difference was not statistically significant ($p = 0.144$). At 45 kV, the effectiveness decreases across the entire thickness due to increased scattering *Compton*.

Variations in the thickness and voltage of X-rays affect the attenuation characteristics of the material. The radiation dose passed decreases with increasing thickness, while HVL values increase both due to increased thickness and voltage. This trend is in line with the theory that higher-energy photons require a greater protective thickness to achieve a 50% reduction. The Spearman correlation reinforces the findings through a strong positive relationship between thickness and HVL ($r = 0.681$; $p < 0.01$).

The protection effectiveness is higher at 40 kV than at 45 kV due to the dominance of photoelectric interactions which is closely related to the high atomic number of bismuth ($Z = 83$). In contrast, at 45 kV, the increased contribution of the Compton scattering causes more photons to be passed on. The Kruskal–Wallis test showed a significant difference between the thickness–stress combination ($p = 0.001$), although the Mann–Whitney test indicated that the difference in effectiveness between 0.5 mm and 1 mm was not significant.

The integration of HVL results and effectiveness showed that although HVL increased, the amount of radiation passed on continued decreased as thickness increased, so protection continued to increase. This confirms that HVL does not directly reflect effectiveness *shielding,* rather, it is the characteristics of radiation interactions at certain energies. These findings are consistent with previous studies that reported that the addition of Bi_2O_3 to epoxy resins increases the attenuation coefficient and material protective ability in diagnostic energy (Hedaya et al., 2024; Li et al., 2022; Munhoz et al., 2023). With a thickness of only 0.5–1 mm, the Bi_2O_3–resin composite remains high in effectiveness and low HVL, making it potentially used as a lighter but still efficient protective eyewear material.

This section presents the results of the research. The results of the research can be supplemented with tables, graphs (images), and/or charts. The discussion section explains the results of data processing, interprets the findings logically, and relates to relevant reference sources.

CONCLUSION

This study showed that the variation in the thickness of Bi_2O_3–epoxy resin composites has an effect on radiation attenuation ability. The 1 mm thickness results in a higher HVL value as well as a lower penetration dose compared to the 0.5 mm thickness, thus providing performance

Shielding which is better at both voltages tested. The results of the effectiveness test also showed that a thickness of 1 mm had the highest damping effectiveness, especially at a voltage of 40 kV. Overall, the combination of HVL test results and effectiveness confirms that materials with greater thickness provide more optimal radiation protection, although the difference between 0.5 mm and 1 mm is not statistically significant. With a thickness of 0.5–1 mm, Bi_2O_3–epoxy resin composites have been shown to provide adequate radiation protection over the diagnostic energy range and have the potential to be used as an alternative material for radiation protective glasses. Future research is recommended to explore higher thickness variations, evaluate optical transparency quantitatively, and conduct mechanical strength testing to support practical application in radiation eyewear.

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