Abstract: Epoxy resins with varying amounts of MoO$_3$ were theoretically investigated for their radiation shielding ability at low energies (between 0.0395 and 0.344 MeV). The quantity of MoO$_3$ varied from 0 to 30%, and relevant shielding parameters were obtained and analyzed from Phy-X software. The half value layer (HVL) of the resins demonstrated that increasing MoO$_3$ content improved the space-efficiency of the prepared samples at all tested energies, leading to the Mo4 sample, the epoxy resin with the greatest MoO$_3$ content having the smallest HVL. Additionally, the mean free path of the materials has an inverse relationship with their density, which increased with additional MoO$_3$. The tenth value layer ratio between Mo1 and Mo4 illustrated how the introduction of Mo has a much greater effect on thickness reduction at lower energies than at higher energies due to photoelectric phenomena. The Z$_{eff}$ and N$_{eff}$ parameters showed how the epoxy samples benefited from the introduction of MoO$_3$ at different energies.

Keywords: epoxy resin, MoO$_3$, radiation protection, Phy-X software

1 Introduction

The application of ionizing radiations is expanding at a rapid rate in a wide variety of sectors. In light of this, the concept of developing novel nuclear-protecting technologies that have multiple functions has garnered an increasing amount of attention in recent years [1–3]. Evidently, random exposure to gamma radiation creates major health concerns such as cancer and cell mutation. In contrast to increasing the distance from the radiation source and decreasing the amount of time spent exposed to the radiation, selecting an appropriate shield is the most successful method of protecting humans from the dangers caused by gamma rays [4–6]. The use of typical lead and lead composites as a nuclear radiation shield imposes certain constraints on the design of the shield. Lead has several drawbacks, including a low melting point, limited mechanical strength, poisonous properties, and heavy weight. As a result, the development of a new shield and the replacement of the conventional shielding materials that are presently in use with materials that are both harmless and inexpensive are becoming increasingly important [7–10]. In recent years, data on the interactions of gamma radiation with some materials, including glasses, polymers, ceramics, and epoxy resin composites, have been documented [11–16].

Due to their interesting qualities, polymers like epoxy resin are used in radiation protection. As a result, they are beneficial for medical imaging and dosimetry applications. Epoxy resins are a good choice in the field of radiation protection since they are also inexpensive, flexible, and simple to make in large quantities [17,18].

In the literature, different works reported epoxy resin as shielding material. In brief, we will discuss some previous works that reported the epoxy resin as a potential candidate for radiation shielding applications and their features, and performance compared to other traditional materials. The epoxy resin with micro and nano Bi$_2$O$_3$ and WO$_3$ particles for shielding applications was studied by Karabul and Iceli [19] against gamma radiation. The samples with the greatest amounts of these heavy metal oxides were found to have the best abilities to shield against harmful ionizing gamma-ray radiation. Zhang et al. [20] fabricated Bi$_2$O$_3$–Ti$_3$C$_2$T$_x$ hybrids to reinforce epoxy composites in gamma ray shielding applications. They found that the Bi$_2$O$_3$ NPs uniformly anchored onto the surface of the Ti$_3$C$_2$T$_x$ layers through chemical bonding,
supporting against the layers from collapsing while limiting the agglomeration of the nanoparticles in the epoxy resin. The synergistic characteristics of the resulting mixture led to the agglomeration of the nanoparticles in the epoxy resin. Meanwhile, Aldhuibaibat et al. [21] evaluated the effective atomic number, as well as other related parameters, of pure epoxy, Al2O3-epoxy, and Fe2O3-epoxy at various mid-to-high gamma-ray energies. The metal oxides were found to improve upon these shielding parameters, reinforcing the use of epoxy nanocomposites for gamma-radiation shielding. Polymer matrix composites can also be enhanced by blending high atomic number metallic fillers into the system to improve their shielding capability. Li et al. [22] introduced basalt fiber into an epoxy resin matrix containing varying amounts of tungsten and erbium oxide fillers. These fillers were found to have a great positive correlation with the mass attenuation coefficient of the basalt fiber composite, especially at lower energies. Therefore, adding these heavy metal and rare earth fillers into the reinforced polymer composites improved the shielding ability of the material. Liu et al. [23] instead focused on epoxy resin matrices containing micro-fillers of WO3 and boron carbide and studied the effect of the size of the filler, the uniformity of dispersion, and the types of fillers and fiber, on the radiation attenuation capabilities of the prepared materials. The mass attenuation coefficient of the fibers was found to be proportional to the density of the fiber, independent of the material that it was composed of, while the mass attenuation coefficient decreased significantly with large filler size and uneven dispersion at low energies. A polycarbonate-bismuth oxide composite (PC-Bi2O3) was prepared by Mehrara et al. [24] using a mixed-solution method to find the thermal and radiation shielding properties of the samples. Increasing the concentrations of the Bi2O3 fillers in the polycarbonate matrix was observed to increase the attenuation coefficients of the composites significantly, especially compared to pure polycarbonate. Additionally, El-Khatib et al. [25] investigated the effect of particle size of CdO particles on the photon shielding ability of high-density polyethylene with CdO particles in different concentrations. Introducing the micro and nano CdO particles was found to greatly increase the shielding abilities of the composites at low gamma-ray energies, with the nano-CdO particles having the greatest effect. These earlier studies show that various research teams attempted to examine the radiation attenuation capabilities of epoxy resin using various fillers. To establish the ideal filler concentration and investigate its effective use in actual radiation shielding situations, more research is required. The purpose of our research was to determine how the radiation-shielding capabilities of epoxy resin would be affected by the addition of MoO3. Our research advances the field of materials science and has potential applications in industries including nuclear energy, diagnostic imaging, and radiation shielding.

2 Materials and methods

2.1 Samples preparation

This study employed a two-part epoxy thermosetting resin, where component A represents the epoxy resin and component B is the curing agent. The density of the undiluted epoxy resin used in this research was 1.10 g/cm³ after 24 h of solidification. The samples were fabricated according to the manufacturer’s guidelines by using a weight ratio of 2:1 (epoxy to curing agent). The current radiation shielding materials were prepared by incorporating different percentages of MoO3 oxide (Sigma-Aldrich, purity of >99%) as doping agents. The molding and curing process was used to create four distinct sample compositions. The MoO3 contents varied from 0 to 30 wt% (Table 1). After measuring the epoxy matrix, the necessary quantity of MoO3 doping compounds is incorporated. The combination is thoroughly blended under magnetic stirring for 10 min to guarantee that the particles are uniformly distributed throughout the matrix. The mixture was well agitated before being placed into a circular mold. It was then allowed to cure undisturbed for 24 h before being removed from the mold. Figure 1 illustrates a photograph of the fabricated composites. The composition of the newly developed composites is summarized in Table 1, where we designated Mo1, Mo2, Mo3, and Mo4 as codes for these composites.

Utilizing an analytical balance, we determined the mass of the sample in ethanol and the air, and then, using the Archimedes principle (equation (1)), we calculated the density of the newly Mo1, Mo2, Mo3, and Mo4 composites.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Epoxy</th>
<th>MoO3</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo1</td>
<td>100</td>
<td>0</td>
<td>1.13</td>
</tr>
<tr>
<td>Mo2</td>
<td>90</td>
<td>10</td>
<td>1.21</td>
</tr>
<tr>
<td>Mo3</td>
<td>80</td>
<td>20</td>
<td>1.35</td>
</tr>
<tr>
<td>Mo4</td>
<td>70</td>
<td>30</td>
<td>1.39</td>
</tr>
</tbody>
</table>
In the above equation, the $\rho_e$ is 0.789 g/cm$^3$.

### 2.2 Radiation shielding parameters

The mass attenuation coefficients (MAC) are a quantity that is connected to the photon energy as well as the chemical components of a substance and the likelihood of interactions between material and radiation. Mathematically, it is defined as:

$$\text{MAC} = \left(\frac{-1}{\rho t}\right) \ln \frac{N}{N_0},$$

where $t$ is the thickness of the absorber, $N$ and $N_0$ represent the intensity with and without the absorber.

From the MAC, we can derive a density-dependence parameter known as the linear attenuation coefficients (LAC). Simply, the LAC is the product of the MAC with the density of the absorber.

Half value layer (HVL) is a shorthand way of describing the efficacy of shielding provided by an absorber. The HVL is a useful quantity that reveals the absorber’s capacity for shielding electromagnetic radiation. The thickness of any particular material at which half of the incoming energy has been absorbed is known as the HVL. Mathematically, it is defined as:

$$\text{HVL} = \frac{0.693}{\text{LAC}}.$$

The LAC not only helps to derive the HVL of the absorber, but also helps in determining the mean free path (MFP), namely:

$$\text{MFP} = \frac{1}{\text{LAC}}.$$

To evaluate the efficacy of a substance’s shielding, the terminology effective atomic number ($Z_{\text{eff}}$) is frequently utilized. It specifies the percentage of the number of electrons in a shielding material that is involved in photon–atom interactions. Mathematically, it is defined as:

$$Z_{\text{eff}} = \frac{\sigma_a}{\sigma_e}.$$

The numerator of equation (4) is called the total cross-section, while the denominator is the total electronic cross section.

These two parameters are defined as:

$$\sigma_a = \frac{1}{N_i} \sum_j f_j A_i \text{(MAC)},$$

$$\sigma_e = \frac{1}{N_i} \sum_j f_j A_i \text{(MAC)}.$$

For the determination of the above parameters, we can use a theoretical approach. The ability to model the performance of various shielding materials and geometries prior to them being constructed and verified makes theoretical studies to play an important function in radiation shielding. This makes it possible to choose the best materials and geometries for a desired purpose and can reduce the expense and length of time associated with testing. Phy-X software is important software that can theoretically calculate different radiation shielding parameters [26]. It is essential to perform calculations involving radiation physics using Phy-X software for a number of reasons. Complex calculations can be automated using Phy-X Software, which can save a lot of effort and time compared to manually conducting the same calculations. High-accuracy computations may be made with Phy-X Software, which is crucial in the study of radiation physics because even tiny inaccuracies in calculations can have big effects. Moreover, it is simple to repeat tests and simulations since Phy-X Software can store and recreate earlier calculations. This is especially helpful when attempting to duplicate or verify earlier findings. Most importantly, the Phy-X software package is user-friendly, making it simple to use for researchers and academics of all levels of experience.
3 Results and discussion

We calculated the MAC for the investigated samples using Phy-X between 0.0395 and 0.344 MeV. Figure 2 represents the variation in the theoretical values of MAC of the Mo1, Mo2, Mo3, and Mo4 shielding composites in the range of 0.0395–0.344 MeV. These MAC values were acquired using the Phy-X theoretical approach, as we indicated in subsection 2.2. The Mo1-Mo3 composites’ MAC exhibits a general declining tendency as energy is increased. Significantly, as energy increased from 0.0395 to 0.344 MeV, the MAC curve in the chosen energy range abruptly decreased. Mo4 was chosen to examine the mechanism of the produced epoxy resin composites’ radiation-shielding capabilities. According to the selected energies in this work, the entire MAC value of these composites can be separated into two components based on the interaction of matter and incident photons: the Photoelectric effect (PE) and the Compton scattering (CS) (Figure 3). According to Figure 3, where photon energies range from 0.0395 to 0.122 MeV, the PE effect predominates in the low-energy area. The MAC value in this region gradually declines as photon energy rises. For Mo4, the MAC decreases from 2.973 to 0.260 cm²/g in this area. This is explained by the PE cross-section being inversely related to the energy (i.e., with $E^{-3.5}$) and proportionate to the atomic number $Z^{4-5}$. The second region is between 0.245 and 0.344 MeV, when the PE effect becomes less significant and the CS effect takes over. In this region, where the MAC for Mo4 falls from 0.133 to 0.110 cm²/g, we can observe that the MAC reduces gradually.

As shown in Figure 2, the lowest MACs were observed in the pure epoxy matrix sample. This was owing to the low Z atomic numbers of the constituent components of the epoxy, which were found in the sample. As is common knowledge, epoxy is predominantly made up of carbon and also contains nitrogen, oxygen, hydrogen, and chlorine in varying quantities. However, it has been shown that the radiation shielding capability of the epoxy matrix improves as a result of an increase in the quantity of the MoO₃ additives. The Mo4 composite has been successful in achieving the greatest MAC values, which is an indication of the greatest radiation shielding efficiency.

The LAC is a significant variable that is utilized in a broad variety of fields, including radiation protection. Calculating the amount of radiation absorbed by a material using LAC is one of the steps involved in radiation physics. This step is important because it can help identify the radiation-shielding qualities of the material. Since it is an important factor, we reported the LAC for the Mo1–Mo4 composites, and we presented the results in Figure 4. Before discussing the results, it is important to mention that when the LAC is higher, it indicates that the medium absorbs or scatters radiation to a greater extent. From Figure 4, we found that the process of attenuation is affected by the energy of the radiation in some way. This is because the LAC is high at low energy, and then, it decreases and attained the minimum value at 0.344 MeV. On the other words, the lower the energy of the photons, the greater the likelihood that the radiation will be absorbed or scattered by the present composites; as a result, the LAC value will be larger. Numerically, the LAC (in units of cm⁻¹) for Mo2 is 1.484 at 0.0395 MeV, 1.052 at 0.0459 MeV, 0.153 at 0.245 MeV, and 0.131 at 0.344 MeV. We can observe that the LAC tends the order: Mo4 > Mo3 > Mo2 > Mo1. From this...
result, when there is a greater amount of MoO$_3$ present in an epoxy resin, the LAC has a greater propensity to go up. This is because MoO$_3$ is a compound with a high atomic number ($Z$), and its presence in the composite contributes to an increase in the $Z$ as well as the density of the composite as a whole. Since they are better at absorbing radiation, high-density composites typically have higher LAC values. As the MoO$_3$ concentration rises, the likelihood of radiation interaction with the composite also rises. Thus, more photons are absorbed and scattered, raising the LAC value. For the Mo$_1$ (free MoO$_3$), the LAC is 0.395 cm$^{-1}$ at 0.0395 MeV, while it is 4.132 cm$^{-1}$ for the composite with 30% of MoO$_3$.

Figure 5 plots the HVL of the prepared epoxy resins. The minimum HVL occurs at 0.0395 MeV, while the highest HVL occurs at 0.3443 MeV. Between these two energies, HVL increases as energy increases. For instance, Mo$_1$ has an HVL of 1.753 cm at 0.0395 MeV, which increases to 1.793 cm at 0.0401 MeV, 3.909 cm at 0.1218 MeV, 4.995 cm at 0.2647 MeV, 5.359 cm at 0.2959 MeV, and 5.680 cm at 0.3443 MeV. Meanwhile, Mo$_3$'s HVL values are equal to 0.244, 0.254, 2.273, 3.959, 4.372, 4.705 cm for the same respective energies. Because HVL increases with energy, a thicker epoxy resin is needed to attenuate half of the incoming photons if they have more energy, while a thinner shield is needed if they have less energy. Additionally, the HVL values follow the order of Mo$_1$ > Mo$_2$ > Mo$_3$ > Mo$_4$. At 0.0459 MeV; they are equal to 2.135, 0.659, 0.354, and 0.246 cm for Mo$_1$-4, respectively, while at 0.2835 MeV they are equal to 5.273, 4.848, 4.279, and 4.093 cm for the same respective epoxies. These results indicate that introducing additional MoO$_3$ into the epoxy resin leads to a lower HVL, making the shield more space efficient for radiation shielding applications.

The ratio between the tenth value layer (TVL) for Mo$_1$ and Mo$_4$, the samples with the lowest and highest MoO$_3$ content respectively, is graphed in Figure 6. At all tested energies, the ratio is greater than 1, which means that Mo$_1$'s TVL is higher than Mo$_4$. In other words, the addition of MoO$_3$ leads to a reduction in TVL, improving space efficiency. In the photoelectric effect region, the ratio is at its highest, between 8 and 10, which means that the impact of MoO$_3$ on the TVL values is very high at low energies. This effect occurs because the photoelectric effect highly depends on the atomic number of the absorber. As

![Figure 4: LAC of the Mo1–Mo4 epoxy resin composites.](image)

![Figure 5: Relationship between HVL and the energy.](image)

![Figure 6: Ratio between the TVL for Mo1 and Mo4.](image)
energy increases into the Compton scattering area, the ratio decreases to around 1.2–1.3, which means that the impact of MoO₃ on the TVL is small for energies greater than 0.245 MeV. This effect, meanwhile, occurs because the Compton scattering effect has a small dependence on the atomic number of the absorber.

The relationship between MFP and the density of the prepared epoxy resins is shown in Figure 7. As the density of the epoxy matrix increases, at all tested energies MFP decreases. At 0.0459 MeV, the resin has an MFP of 3.080 cm at a density of 1.13 g/cm³ but drops to 0.951 cm when density increases to 1.21 g/cm³, 0.511 cm at 1.35 g/cm³, and 0.355 cm at 1.39 g/cm³. At a higher energy such as 0.2959 MeV, this drop is still observed, as the MFP values are equal to 7.731, 7.127, 6.307, and 6.050 cm for the same respective energies. Because of the inverse relationship that density has with MFP, adding more MoO₃ into the epoxy resin improves the distance between subsequent collisions within the sample, leading to a more effective shield. Therefore, it is important to try to increase the density of the samples as much as possible to maximize attenuation.

Figure 8 illustrates the $Z_{\text{eff}}$ of the epoxy resin samples as a function of energy. The $Z_{\text{eff}}$ for Mo1, the epoxy with no MoO₃, is almost constant, varying between 5.87 and 4.02. However, when introducing MoO₃ into the epoxy composite (in other words for Mo2, Mo3, and Mo4), a great increase in $Z_{\text{eff}}$ occurs, especially in the low energy region. At 0.0395 MeV, the $Z_{\text{eff}}$ for Mo2, Mo3, and Mo4 are 16.11, 22.67, and 27.24, respectively, which means that adding 30% MoO₃ causes $Z_{\text{eff}}$ to increase by 4.6 times at this energy. At 0.0459 MeV, introducing 30% MoO3 raises $Z_{\text{eff}}$ by 4.56 and at 0.0470 MeV, it increases by 1.99 times.

At energies higher than 0.245 MeV, the increase in $Z_{\text{eff}}$ due to adding more MoO₃ is smaller than at low energies. For example, at 0.296 MeV, the $Z_{\text{eff}}$ increases by 1.35 times. Nevertheless, introducing more MoO₃ raises $Z_{\text{eff}}$ at all tested energies.

The effective electron density, or $N_{\text{eff}}$, is graphed against energy in Figure 9. $N_{\text{eff}}$ has the same trend with increasing energy as $Z_{\text{eff}}$. Because high $N_{\text{eff}}$ values indicate a high number of electrons per unit mass, an increase in $N_{\text{eff}}$ corresponds to an increased probability for a photon to interact with electrons in the radiation-shielding material. For the prepared samples, the highest effective electron densities occur at 0.0395 MeV for all the samples. In addition, introducing MoO₃ into the epoxy
matrix gradually increases the $N_{\text{eff}}$ values, leading to the maximum value occurring for Mo4 at 0.0395 MeV, equal to $1.65 \times 10^{24}$ electron/g.

Figures 10 and 11 demonstrate how exposure buildup factor (EBF) changes with increasing energy at different mfp values for Mo1 and Mo4, respectively. For both Mo1 and Mo4, the lowest EBF values occur at 1 mfp, the lowest penetration level, while EBF increases with increasing mfp at all energies. For example, at 0.150 MeV, Mo1’s EBF increases from 3.40 to 116.67 from 1 to 10 mfp, to 633.0 at 20 mfp, and to 5157.3 at 40 mfp, while Mo4’s EBF is equal to 1.72, 5.88, 10.03, and 17.27 for the same respective penetration depths. For both Mo1 and Mo4, their EBF values start at their lowest for all mfp values, then increase to their maximum near 0.150 MeV, and then decrease as energy increases past this point. For example, Mo1’s EBF at 15 mfp starts at 1.35 and increases to 14.92, 185.84, and 302.66, and then decreases to 135.53, 55.83, 10.41, and 4.00. The maximum values occur in the intermediate energy region because this is the region where the Compton scattering effect is the dominant photon interaction phenomenon. The figures also demonstrate that the EBF values decrease when adding MoO₃ into the samples. Specifically, Mo1’s EBF is equal to 77.65 at 0.300 MeV and 10 mfp, while Mo4’s EBF is equal to 15.03 at 0.300 MeV and 10 mfp. Because of this, the Mo4 resin has the lowest EBF values out of the tested samples.

### 4 Conclusion

In this work, the radiation-shielding capabilities of epoxy resin with varying amounts of MoO₃ were analyzed at a wide range of energies. The HVL of the samples showed that introducing more MoO₃ into the epoxy matrix leads to an improvement in the thickness needed for the shield due to the increased absorption ability of the material. The TVL ratio between Mo1 and Mo4 demonstrates that at low energies, the addition of MoO₃ has a tremendous effect on the shielding ability of the epoxy, with the ratio varying around 8–10. Meanwhile, at higher energies, this effect is still observed, although to a lesser degree, as the ratio lies between 1.2 and 1.3. Due to the inverse relationship between MFP and density, to ensure the highest number of collisions within the sample, density should be increased as much as possible. Adding 30% MoO₃ into the composites led to $Z_{\text{eff}}$ increasing by 4.6 times at 0.0395 MeV, and 1.99 times at 0.0470 MeV. The highest $N_{\text{eff}}$ values occur at 0.0395 MeV, which means that this energy has the highest probability for the incoming radiation to interact with the electrons in the material. At all tested energies, the Mo1 sample had the highest EBF values, while the Mo4 samples had the lowest.

**Acknowledgements:** The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through project number RI-44-0089.

**Funding information:** The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through project number RI-44-0089.

**Author contributions:** D. A. A and A. H. A.: supervision, funding acquisition; software. M. I. A.: writing – original
draft preparation; methodology; software. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Ethical approval: The conducted research is not related to either human or animal use.

Data availability statement: The data presented in this study are available on request from the corresponding author.

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