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Comparison of Gamma Radiation Shielding Parameters of Lead, Rhenium, and Elgiloy Alloy in Radiation Practices Using Geant4 Simulation Code

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Keywords

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Abstract

This study compares the gamma radiation shielding performance of Rhenium (Re) and Elgiloy alloy with Lead (Pb) using the Geant4 Monte Carlo simulation code. LAC and HVL values of the materials were calculated and compared against the library data. Ten different energy levels which are ranging from 59.5 keV to 2.754 MeV were analyzed to represent the various radiation practices and interaction modes. Results indicate that Rhenium has better shielding performance than Lead mostly due to its higher density, and its Half-Value Layer (HVL) is approximately 40% lower than Lead at 662 keV. Although the Elgiloy alloy's shielding performance is weaker than Lead, there are some studies demonstrating that it has some remarkable physical properties such as ultimate tensile strength and corrosion resistance. Thus, Elgiloy can be used as a structural component in radiation applications due to its physical strength and resistance. This study suggests that Rhenium can be a better shielding alternative to Lead. Especially in some medical and industrial practices where low volume and temperature resistance are main constraints. Additionally, Elgiloy can be considered as a supportive element in the structural body and as a complementary shielding layer under extreme environmental conditions.

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1. INTRODUCTION

The fundamental safety objective in radiation protection is to protect individuals, society, and the environment from the harmful effects of ionizing radiation (IAEA, 2006). For achieving this objective, effective radiation shielding has a critical role since selecting appropriate shielding materials can minimize dose exposure in medical and industrial radiation practices. Despite the fact that Lead is a toxic metal and contains risk for the environment, it is used extensively for shielding purpose for radiation applications (Flora et al., 2012; AbuAlRoos et al., 2019; Safari et al., 2024). In addition, Lead's low thermal properties and poor mechanical strength limit the functionality of the material, especially in industrial practices (Haynes, 2014). In order to avoid and overcome negative effects of Lead, new approaches are required. These hazards and limitations open a new area of research and development for alternative shielding materials.

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In this study, Rhenium is chosen as an alternative to Lead for its shielding capability and Elgiloy alloy is selected in terms of physical strength and corrosion resistance. Rhenium is one of the elements with the highest density and has a very high melting point. Therefore, Rhenium is an excellent alternative for environments where both high temperatures and radiation are present together. Rhenium generally alloyed with tungsten and molybdenum to improve the material properties (Georg Nadler, 2000). Elgiloy is a superalloy with a main composition is Co (40%), Cr (20%), Fe (16%), Ni (15%), Mo (7%), Mn (2%). It was first produced as a corrosion-resistant watch spring material and later became widespread in some other fields due to its physical properties. Ultimate tensile strength exceeds 1700 MPa with cold working and age hardening (Zhang et al., 2011). When compared to Lead, which has a tensile strength of 12-17 MPa and a melting point of 327 °C (the recommended limit for Elgiloy is 454 °C), Elgiloy exhibits notable properties as a structural material. Studies have been conducted on its use in aerospace missions involving radiation and high temperature differences (Balat-Pichelin et al., 2017). Also, a recent study by Akman et al. (2024) has shown that Elgiloy has greater radiation shielding performance when compared to stainless steel, nitinol, and beta-titanium. In addition, Elgiloy's non-magnetic structure and mechanical stability make it a candidate for shielding alternative for industrial practices (Elgiloy Specialty Metals, n.d.). Comparison data regarding the general mechanical properties of materials are presented in Table 1.

Table 1. *General Mechanical Properties of Materials*

Parameter	Elgiloy	Lead	Rhenium
Tensile Strength (MPa)	1724–2413	12-17	1070–1130
Modulus of Elasticity (GPa)	221	14	469
Melting Point (°C)	454	327	3186

In radiation shielding studies, the Beer-Lambert Law defines the gamma radiation attenuation capability of a material. According to this law, the attenuation of the intensity of mono-energetic gamma rays which are passing through a material in a narrow beam geometry is calculated using the following formula (Knoll, 2010):

$$I = I_0 e^{-\mu x} \tag{1}$$

Here, I represents the transmitted radiation intensity, I_0 is the incident radiation intensity, x is the material thickness (cm), and μ is the Linear Attenuation Coefficient (LAC) of the material (cm^{-1}).

In practical use, there is another indicator for the shielding performance known as Half-Value Layer (HVL). HVL is defined as the material thickness that reduces the incident radiation intensity by half, and it is calculated using the LAC value as follows:

$$HVL = \frac{\ln(2)}{LAC} \approx \frac{0.693}{LAC} \tag{2}$$

In terms of radiation interaction of gamma rays with matter, there are three fundamental modes which are known as the photoelectric effect, Compton scattering, and pair production. The photoelectric effect is the interaction of low-energy photons with orbital electrons, resulting in energy transfer from photons to the electrons and it is strongly dependent on the atomic number of the element. The Compton scattering is dominant for the intermediate energy levels of the gamma rays and involves the transfer of a part of the photon's energy to the electrons. Despite the changes in the photon's energy and direction of travel, the cross-sectional area of interaction is directly proportional to the electron density of the material. Pair production is the transformation of photons into an electron-positron pair with energies above a threshold of 1.022 MeV, due to the electromagnetic field interaction while passing near an atomic nucleus or electrons (Knoll, 2010). These three interactions are the main mechanisms used in the Geant4 simulation.

In addition to these three primary interaction mechanisms, Rayleigh scattering (coherent scattering) was also integrated into the Geant4 simulation calculations. The Rayleigh scattering involves no energy loss but it changes the photon's trajectory. Thus, it has a crucial role in narrow-beam geometry experiment. This deviation causes photons to scatter away, and they cannot reach the detector volume, resulting in the decrease in photon counts. Therefore, Rayleigh scattering has also been included in the Physics List of the Geant4 to facilitate valid methodological comparison and achieve a high degree of consistency with Geant4 database library.

The main objective of this study is to evaluate and compare the Linear Attenuation Coefficient (LAC) and Half-Value Layer (HVL) values of Rhenium, Lead and Elgiloy alloy. This comparison was performed using the Geant4 Monte Carlo simulation code at ten different gamma energy levels. These energy levels are specifically determined to represent common industrial and medical practices. Simulation results are compared with generic Geant4 library data.

In this context, it is expected that Rhenium will demonstrate better attenuation properties compared to Lead due to its higher density and similarly high atomic number. For this reason, it can be used in compact shielding designs. On the other hand, Elgiloy alloy is not expected to have better attenuation efficiency of Rhenium and Lead. Nevertheless, the assessment of its usefulness for structural integrity as well as additional shielding is still significant. The purpose of this study is to establish that Rhenium and Elgiloy alloy could have benefits over the standard Lead shielding.

2. MATERIAL AND METHOD

2.1. Geant4 Simulation Code and Geometry Modelling

Geant4 (Geometry and Tracking) is a software that based on Monte Carlo algorithm and developed by European Organization for Nuclear Research (CERN) designed to simulate the interaction of particles with matter (Agostinelli et al., 2003). Geant4 has a vast range of use in particle physics and also can be implemented for the different radiation shielding applications (Allison et al. 2016; Mahmoud et al., 2022; Paul et al., 2023; Yaghi et al., 2026). In this frame of the study, in order to evaluate the gamma shielding performance of

Rhenium, Lead, and Elgiloy, fixed number of mono-energetic photons were used in each simulation. This fixed number corresponds to the incident (I_0) photons. After the interactions with the shielding material, photons reaching successfully to the detector utilized as the transmitted intensity (I) values. These values are required for the Beer-Lambert law. After obtaining the transmitted intensity values from each simulation, the LAC value can be calculated from the law based on the constant thickness and number of incident photons.

In the design phase of the simulation geometry, specific arrangements of the materials were carried out to represent a more realistic experimental configuration and to achieve results that are in line with database values. A point source was used to simplify the process and emitted photons (one-directional on the z axis) initially pass through a cylindrical lead collimator with an aperture diameter of 1 cm and a length of 10 cm. After that they reached to the 0.2 cm thick shielding sample, the photons experience various radiation interactions and therefore either they are absorbed or their energy and momentum change. Subsequently, the photons pass through a secondary collimator which has 1 cm aperture diameter and 5 cm length. This configuration was arranged to get minimal build-up effect within the material and to attain the narrow-beam geometry and thus enhance the precision and quality of the detector count. Finally, counting of photons was performed using a detector modelled as a NaI crystal, with both a diameter and height of 3 inches. A visual representation of the simulation geometry is shown in Figure 1.

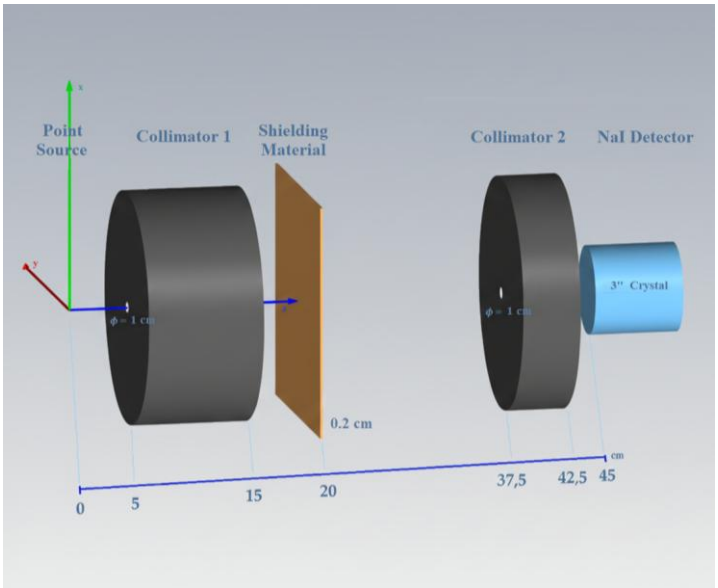


Figure 1. *Geometry Setup for the Geant4 Simulation*

In this work, the photon counts recorded by the detector correspond to the materials' transmitted intensity (I) in the Beer-Lambert equation. To reduce the error rate of statistical uncertainty values comes with the Monte Carlo algorithm, the incident photon count (I_0) was determined as 10^6. Additionally, independent simulations were carried out for each sample at different reference energy levels. The thickness for the sample materials was standardized at 0.2 cm to comply with general application standards. The Geant4 library data used for the comparative analysis of the obtained simulation values of HVL and LAC were provided directly within the Geant4 simulation. Specified data regarding the materials and simulation parameters are presented in Table 2.

Table 2. *General Parameters of Materials and Geant4 Simulation*

Parameter	Elgiloy	Lead	Rhenium
Density (g/cm^3)	8.3	11.35	21.02
Composition	Co (40%), Cr (20%), Fe (16%), Ni (15%), Mo (7%), Mn (2%)	Pb (100%)	Re (100%)
Shielding Material Dimensions	10 cm x 10 cm		
Shielding Thickness	0.2 cm		
Simulation Counts	10^6 photons for each energy and each material		
Geant4 Physics List	Shielding (Standard)		
Data Set	G4EMLOW v8.6.1		
Calculator	G4EmCalculator		
Geant4 Version	Geant4-11.3.2		

2.2. Energy Spectrum

To assess the potential usability of the selected materials, ten different gamma energies ranging from 59.5 keV to 2.754 MeV which belong to typical isotopes used in various radiation practices were selected. The biggest benefit provided by this energy spectrum is that it allows for a detailed analysis at low, medium and high energy ranges. Also, this broad spectrum reflects the variations in the shielding behavior due to the dominance of different mechanisms in different intervals. The selected energies and their corresponding radiation practices and purpose are presented in Table 3 (IAEA, 2011; 2018).

Table 3. *Selected Energy Levels and Their Corresponding Fields of Application*

Energy Value	Isotope	Radiation Practices / Purpose
59.5 keV	Am-241	Thickness gauges, smoke detectors
122 keV	Co-57	Nuclear medicine equipment calibration
140 keV	Tc-99m	Nuclear Medicine (Scintigraphy / SPECT)
364 keV	I-131	Thyroid therapy
511 keV	Na-22	Positron Emission Tomography (PET)
662 keV	Cs-137	Level measurement gauges
835 keV	Mn-54	Industrial radiation monitoring
1.25 MeV	Co-60	Irradiation facilities, teletherapy, industrial radiography
1.46 MeV	K-40	Geological sampling and environmental monitoring
2.754 MeV	Na-24	High-energy industrial practices

3. RESULTS AND DISCUSSION

Based on the geometry and parameters described in Section 2, the radiation transmission, LAC, and HVL values for the Rhenium, Lead and Elgiloy were obtained. Illustrations of Geant4 simulations correspond to low, medium, and high energy levels and effect of different photon counts with Elgiloy are presented in Figure 2.

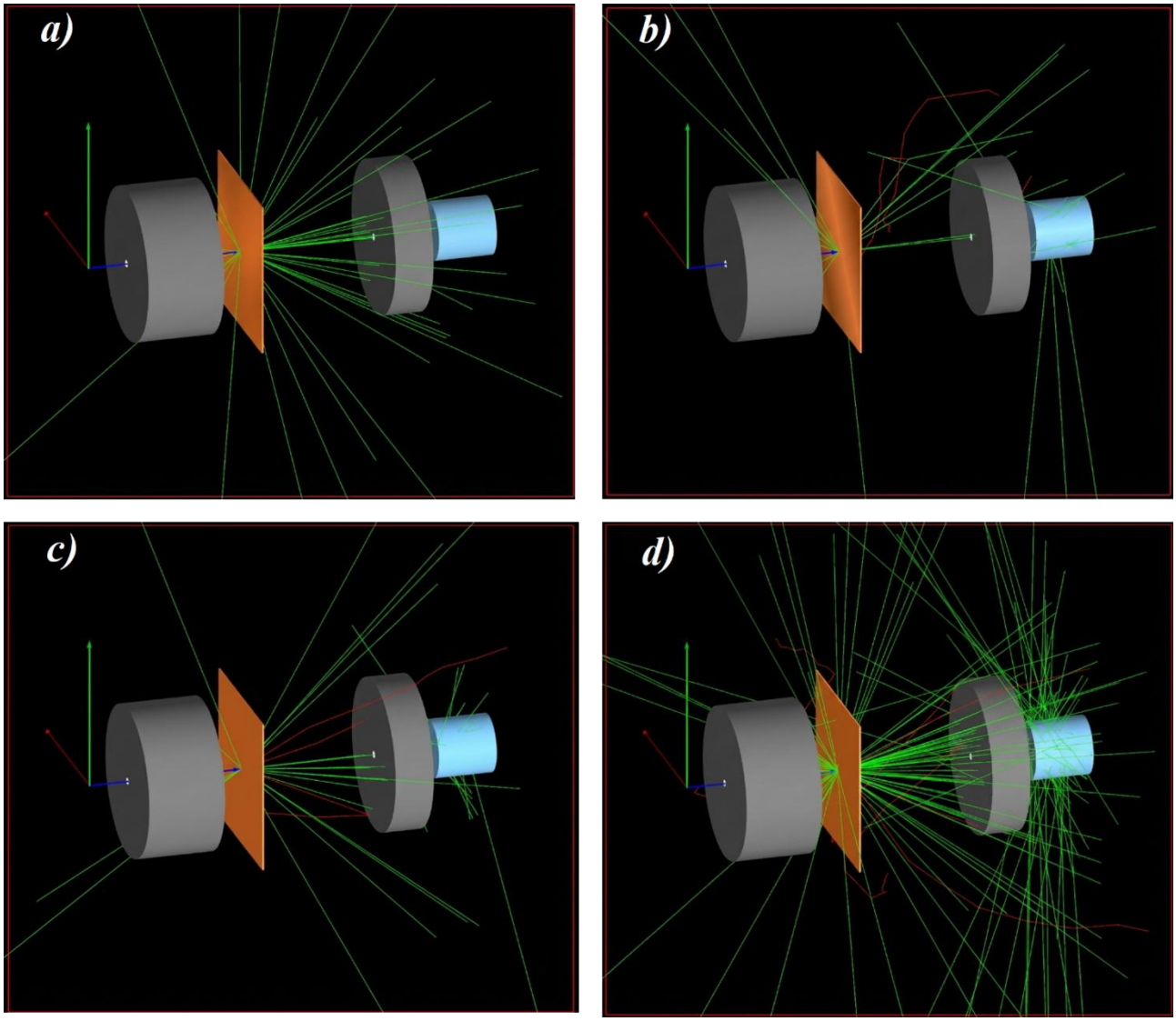


Figure 2. *Geant4 Shielding Simulations[1] of Elgiloy with* ***a)*** *200 photons at 122 keV,* ***b)*** *200 photons at 662 keV* ***c)*** *200 photons at 1250 keV,* ***d)*** *1000 photons at 1250 keV*

3.1. Radiation Transmission

Gamma radiation transmission ratio (I/I_0) percentage over 10^6 photons for each simulation presented in Figure 3. Results show an inverse relationship between photon energy and shielding efficiency in all simulation cases.

[1] *Low photon numbers (N) were used in order to make a clear visual demonstration. Additionally, Figures c) and d) represent the difference of the photon number increment between the same simulation parameters.*

In the low-energy region, both Rhenium and Lead demonstrated greater radiation attenuation. It is important to note that almost no photons were detected for Rhenium and Lead at 59.5 keV 122 keV and 140 keV. At these energies, the shield thickness is significantly higher than the HVL thickness of these materials. Because of this, a substantial decrease is observed in the number of photons reaching the detector (at 59.5-122-140 keV for Rhenium 0, 13, and 272; for Lead 14, 461, 4077 photons, respectively). The low number of photons also introduces statistical uncertainty to the simulation results. On the other hand, more efficient results were obtained at 364 keV energy, where the dominant radiation interaction mechanism starts shifting from the photoelectric effect to Compton scattering (at 364 keV the number of photons for Elgiloy, Lead and Rhenium were 845916, 531172 and 373198, respectively). Along with these, throughout the entire energy spectrum, Rhenium consistently exhibited the best shielding performance among the materials and it is followed by Lead and Elgiloy, respectively. This result aligns with the physical densities of the materials, as the density increases probability of interaction per unit volume also increases.

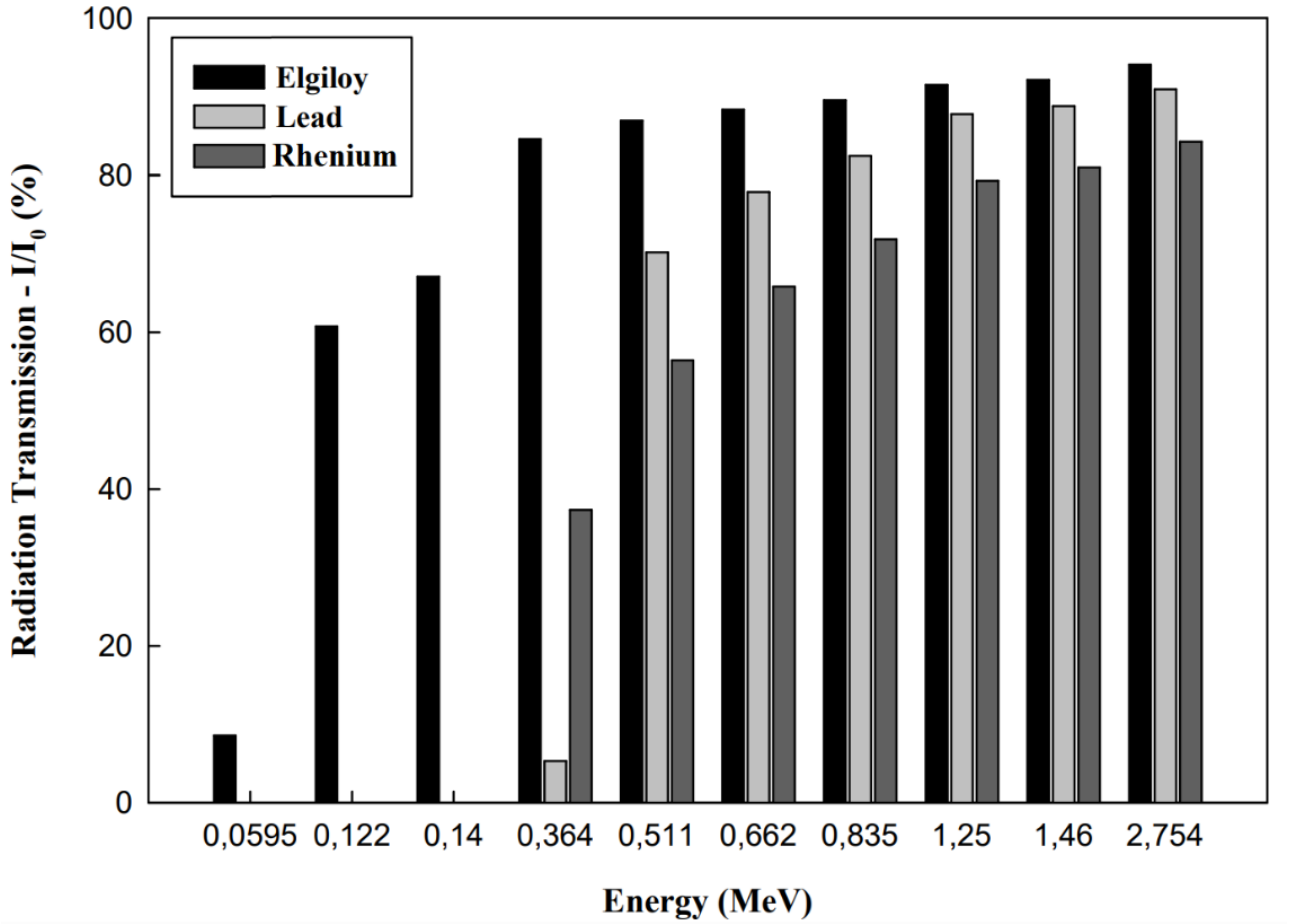


Figure 3. *Radiation Transmission Ratio of the Shielding Materials at Different Energies*

3.2. Half Value Layer and Linear Attenuation Coefficients

Results presented in Figure 4 show strong correlation between photon energy and HVL. Rhenium consistently exhibited the lowest HVL values and so greater shielding efficiency for the entire spectrum. Of particular significance is the performance at 662 keV, one of the common reference energies for industrial radiography.

Rhenium has approximately 40% lower HVL value than that of Lead at this level. Since the higher density of Rhenium also leads to a higher electron density, Compton Scattering is stronger at this intermediate energy level. This substantial reduction in HVL demonstrates that Rhenium can provide an equivalent level of protection with significantly reduced material thickness. The similarly high atomic number and the greater density of Rhenium play a significant role in this result and Rhenium can be a good candidate for radiation practices that the mass, area or volume is an important concern. Similar high-Z elements like Tungsten (W) have also shown attenuation properties comparable to Lead in theoretical studies (Büyük & Tuğrul, 2014). Also, recent studies have demonstrated the effectiveness of shielding properties of Tungsten-based composites, further validating the potential for use of high-Z materials (Das et al., 2023).

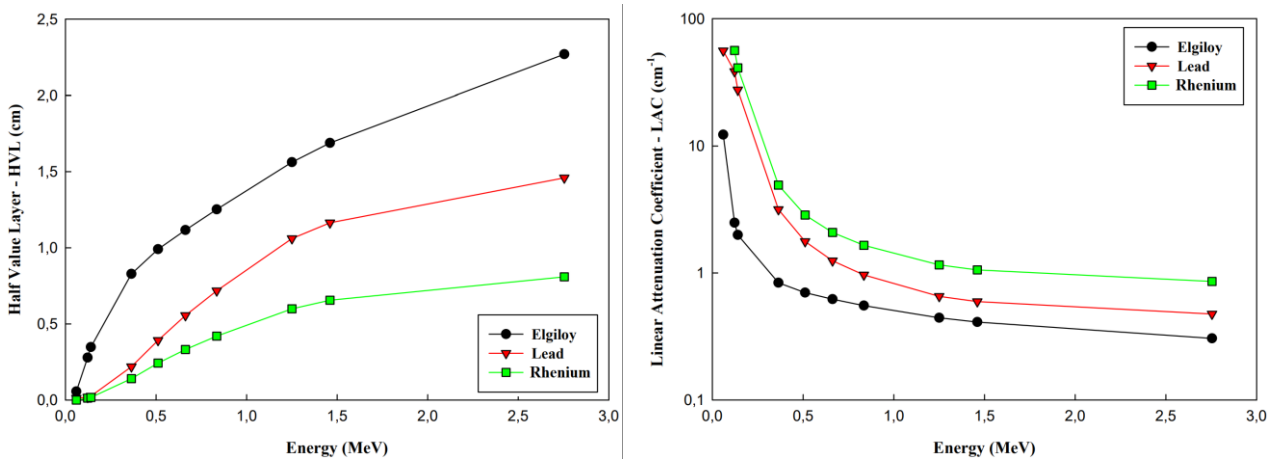


Figure 4. a) *Half Value Layer and* ***b)*** *Linear Attenuation Coefficient Comparison of Materials*

Results regarding the LAC values demonstrate a substantial decrease for all materials as photon energy increases. This behavior is mainly due to the increased penetration of radiation parallel with the increase in energy. In addition, the transition in the dominant interaction mechanism affects the rate of decrease in LAC values. While the photoelectric effect causes total photon absorption in the low-energy region, Compton scattering and pair production become dominant at higher energies and the primary interaction mode changes into the scattering and pair production. As a result, Rhenium has higher LAC values compared to both Lead and Elgiloy throughout the entire energy spectrum, in line with theoretical expectations.

3.3. Comparing with Reference Library Data

The values for HVL are provided in Table 4, which shows that Elgiloy alloy has the highest values for HVL for the entire range of energies. The reason for this is the low density of the material compared with others. Another material that stands out, with the highest efficiency for shielding, is Rhenium, which requires the least thickness.

The uncertainty value provided together with the HVL simulation results corresponds to the standard deviations. The basis for calculating this value lies in the fact that radiation interactions have a Poisson distribution (Knoll, 2010). Based on the photons counted by the detector (I), LAC values were calculated using

the Beer-Lambert law. In accordance with this, the standard deviation values of HVL values were obtained. The formulas of the calculations performed, along with the using the equations (1) and (2), for error propagation are given in equations (3), (4), and (5).

Table 4. *Half Value Layers of Materials with Statistical Uncertainty and Percentage Difference*

Energy (MeV)	Elgiloy			Lead			Rhenium		
	HVL (cm)		Diff. (%)	HVL (cm)		Diff. (%)	HVL (cm)		Diff. (%)
	Library	Simulation ± σ		Library	Simulation ± σ		Library	Simulation ± σ	
0.0595	0.0565	0.0564 ± 0.0001	0.20	0.0120	0.0124 ± 0.0003	3.31	0.0085	Not Detected[2]	
0.1220	0.2824	0.2783 ± 0.0007	1.42	0.0181	0.0180 ± 0.0001	0.31	0.0120	0.0123 ± 0.0003	2.66
0.1400	0.3529	0.3474 ± 0.0011	1.55	0.0255	0.0252 ± 0.0001	1.38	0.0169	0.0169 ± 0.0001	0.37
0.3640	0.8392	0.8285 ± 0.0054	1.28	0.2213	0.2191 ± 0.0005	0.99	0.1423	0.1407 ± 0.0002	1.17
0.5110	0.9981	0.9902 ± 0.0076	0.79	0.3899	0.3920 ± 0.0013	0.55	0.2402	0.2423 ± 0.0006	0.88
0.6620	1.1320	1.1166 ± 0.0096	1.36	0.5512	0.5554 ± 0.0025	0.76	0.3291	0.3318 ± 0.0010	0.81
0.8350	1.2691	1.2528 ± 0.0120	1.28	0.7145	0.7178 ± 0.0041	0.46	0.4163	0.4200 ± 0.0015	0.88
1.2500	1.5606	1.5628 ± 0.0184	0.14	1.0308	1.0606 ± 0.0087	2.89	0.5811	0.5989 ± 0.0029	3.06
1.4600	1.6896	1.6886 ± 0.0214	0.06	1.1453	1.1647 ± 0.0104	1.69	0.6407	0.6557 ± 0.0034	2.34
2.7540	2.2460	2.2699 ± 0.0383	1.06	1.4334	1.4594 ± 0.0161	1.81	0.7966	0.8092 ± 0.0051	1.58

$$\sigma_I = \sqrt{I} \tag{3}$$

$$\sigma_{LAC} = -\frac{1}{x\sqrt{I}} \tag{4}$$

$$\sigma_{HVL} = \frac{HVL}{\sqrt{I}\,|\ln(I/I_0)|} \tag{5}$$

Notably, at the 59.5 keV energy level, a specific HVL value for Rhenium was undefined due to the total absorption of the photons caused by the excessive shielding thickness. As shown in Table 3, corresponding HVL value of library data at 59.5 keV is hundreds of times less than the thickness of the modelled sample. Particularly for Rhenium and Lead, the insufficient number of photons count at low energies reduces the reliability of the HVL values. These photon counts have a high fractional standard deviation. In order to calculate a reliable HVL value at these energy levels, it is necessary to use more simulation histories or to work with thinner shielding materials. In this study, these methods were not preferred to compare the shielding performance of materials under equal conditions, while also considering the uncertainties they would cause.

[2] The HVL value and its relative error at 59.5 keV could not be calculated from the simulation, since none of the 59.5 keV photons reached the detector. Also, the similar low photon counts observed for Lead and Rhenium at 122 keV and 140 keV. Uncertainty introduced by low photon counts are analyzed further in the section.

On the other hand, consistency of the simulation geometry is supported by the minimal percentage difference (remains mostly below 3%) and when compared to reference data. The percentage difference was based on the Geant4 library values provided in Table 4 and calculation formula given in equation (6). Despite all these, high degree of consistency is also supported by the comparative analysis of each material presented in Figure 5.

$$Percentage\ Diff.= \left|\frac{HVL_{Library} - HVL_{Simulation}}{HVL_{Library}}\right| x\ 100 \quad (6)$$

Although the direct experimental validation was not performed in this specific study, the reliability of the simulation tools and theoretical values has been demonstrated in the literature. A recent comparative study conducted an experiment to validate Geant4 simulation for Mercury (Hg, Z=80) which is an element adjacent to Lead (Z=82) and Rhenium (Z=75) in periodic table, with a discrepancy of less than 5% (Mokhtari Dorostkar & Abdi Saray, 2025).

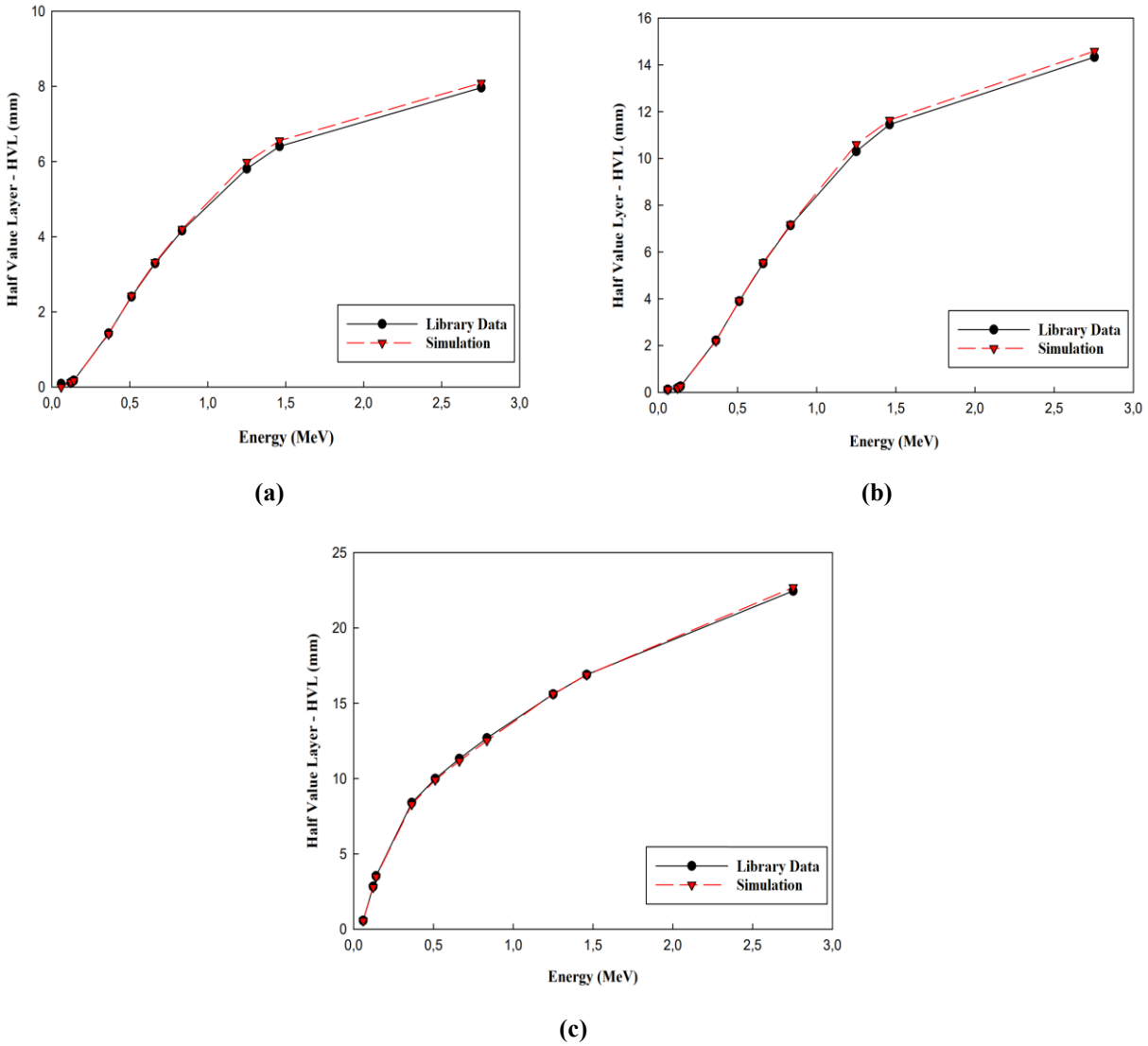


Figure 5. *Half Value Layer Comparison of Geant4 Simulation and Library Data* ***a)*** *for Rhenium;* ***b)*** *for Lead;* ***c)*** *for Elgiloy*

4. CONCLUSION

This study aims to evaluate and compare the gamma radiation shielding effectiveness of Rhenium and Elgiloy alloy against the conventional standard Lead. The simulation results of the shielding capability using the Geant4 Monte Carlo code have been compared with the generic data and uncertainty evaluation. The results show that Rhenium has the greatest Linear Attenuation Coefficient (LAC) cross-section and the thinnest Half Value Layer (HVL) for all selected energies. The most significant result is that the HVL of Rhenium was approximately 40% lower than Lead at 662 keV. This potential of Rhenium can provide an equivalent level of protection with a significantly thinner layer for radiation practices which has volume constraints. Therefore, its implementation in radiation practices can be more feasible where minimizing volume and weight is more important than material cost, such as in specialized compact medical devices or in aerospace technologies.

While Lead is the second-most effective shielding material throughout the spectrum, environmental and health hazards of Lead are main problems. On the other hand, Elgiloy alloy's shielding performance did not reach the level of Rhenium or Lead. But evaluation of its gamma radiation performance at broad energy intervals reveals a critical potential. In this study, Elgiloy is indicated as a notable candidate for structural components in some radiation practices due to its physical strength and resistance. As a result, this study suggests that Rhenium can be a better shielding alternative to Lead. Especially in some medical and industrial practices where low volume and temperature resistance are main constraints. Additionally, Elgiloy can be used as a supportive element in the structural body and as a complementary shielding layer in radiation practices under extreme environmental conditions. Results from the Geant4 Monte Carlo simulation study are considered to be a useful basis for further experimental and theoretical studies in this

AUTHOR CONTRIBUTIONS

Conceptualization, M.E.O., S.Ç and S.B.O.; methodology, S.B.O.; software, M.E.O.; validation, M.E.O.; formal analysis, M.E.O. and S.Ç.; research, M.E.O. and S.Ç.; sources, M.E.O., S.Ç and S.B.O.; manuscript-original draft, M.E.O. and S.Ç.; manuscript-review and editing, M.E.O., S.Ç, and S.B.O., visualization, M.E.O.; supervision, S.B.O. All authors have read and legally accepted the final version of the article published in the journal.

AI Exclusion: AI tools are strictly prohibited from being listed as authors.

Legal Consent: All human authors confirm they have reviewed and legally accepted the final version under the **CC BY-SA 4.0** framework.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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