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Multilayer Shielding Design and Analysis of Optimal Thickness for the Storage of Highly Radioactive Sources Concerning Environmental Safety

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Abstract

As a kind of radiological protection, multilayer shielding is superior to a single-layer shield in terms of blocking off radiation. This study examined a multilayer shielding strategy to protect employees from potentially harmful gamma radiation from highly radioactive sources such as ^{60}Co. This paper presents a novel strategy for cost-effective and environmentally safe radiation protection by aligning expensive and heavy materials such as W and Pb to improve their effectiveness and limit exposure below the occupational dose. The largely unpublished set of final exposure rates for the W–Pb–Fe combination was calculated by the numerical interpolation method in MATLAB software. Attention has been given to frequently neglected processes such as mean free path, source strength, and weight-to-cost ratio. The total optimal thicknesses and costs were found to be 33 cm at $5478.65 (USD), and 38 cm at $5831.14 for ^{60}Co energies at 1.17 MeV and 1.33 MeV, respectively. The thickness was found in a successive manner that was verified with the theoretical data group. This method, procedure, and calculation are planned to be used for the storage of new or used fuel in a nuclear power plant.

Keywords: Multilayer radiation shielding, mass attenuation coefficient, linear attenuation coefficient, exposure rate, cost-effective ratio, buildup factor

DOI:

1. Introduction

In many industries, including medical, industrial, and military, radiation exposure is a major concern. Radiation can have a negative effect on health in a variety of ways, from small skin irritations to serious conditions such as cancer. Therefore, having strong shielding materials is essential for radiation protection. According to the International Commission of Radiation Protection, shielding is the most common protection method rather than maintaining distance and limiting the operation time [1]. Radiation shielding research includes engineering science, medical physics, and high-energy physics accelerator equipment. In comparison with single-layer shields, multilayer shielding is a viable method for offering higher radiation attenuation. A multilayer shield is homogenous material layers that eliminate pinholes and reduce radiation intensity as it travels through each layer. As a result, the effectiveness of the shielding capacity is enhanced compared with a single-layer shield. The shielding efficacy depends on the materials and their configuration [2]. Thus, choosing W–Pb–Fe for the first time in a shielding analysis, as well as an emphasis on reducing Pb thickness, marks a new era in the concept of the environmentally conscious radiation shield.

The purpose of this study was to investigate the shielding effectiveness of three materials and their multilayer configuration, with a special emphasis on the environmental impact of using Pb. Following the ALARA (as low as reasonably achievable) approach, shielding can limit gamma ray intensity and radiation employee exposure [3]. This study aimed to find the minimum thickness of the radiation resistance material with the lowest weight-to-cost ratio for industrial and research purposes.

Multilayer shielding is an effective method for reducing the intensity of radiation, especially ionizing radiation [4]. Ionizing radiation is a type of radiation that can ionize atoms and molecules, harming living things. Ionizing radiation often takes the form of alpha, beta, neutron, and gamma rays. These include uncharged particles like neutrons and gamma rays, which have a high penetration rate and cannot be prevented by electric forces alone [5]. Multilayer shielding absorbs radiation using several shielding materials and can protect against radiation more effectively than single layers. Inner shielding layers absorb radiation, whereas outer layers reduce it.

The study considers three materials—namely, W, Pb, and Fe—and analyzes the mass attenuation coefficient and exposure buildup factor for each material. The isotope ^{60}Co, a highly radioactive source used in nuclear research and medical treatment, is one of the variables in this study, which takes into account 1.17 and 1.33 MeV energies with 100 Ci activity. The radiation-shielding properties of W are novel compared with Pb and Fe. However, the cost of W is a limiting factor for its extensive use, which is why it is used cost-effectively. The second and third layers are made of Pb and Fe, which are common shielding materials. This study considered the environmental implications of using Pb in the inner layer to prevent direct environmental pollution [6].

2. Literature Review

A variety of prior studies have been conducted to evaluate the effectiveness of various shielding materials and configurations. However, cost-effective and environmentally friendly shielding solutions need more research. Muhammad et al. [7] review multilayer radiation shielding and describe the shielding equations. The commutative property of multiplication and the buildup factor formula for each atomic number were used to generate the beginning and final intensity equations. The authors lined up the previous materials that were used for shielding. Using point kernel codes, Suteau et al. [8] formulated an iterative method that can calculate the gamma-ray buildup factor for the *N*-layer in comparison with a double-layer shield. This formula was applied only for the buildup factor calculation. Geant4-based simulation tools were implemented by Lei et al. [9] for multilayer shielding to calculate radiation fluence, dose, and effect analysis. The authors developed MULASSIS software as a general tool within the European Space Agency (ESA). The software is accessible over the World Wide Web, but it should not be used for mass storage or shielding against highly radioactive sources. Radiation shields against mixed neutrons and gamma rays were examined by Guang et al. [10]. For verification, they designed and compared experimental data. Their work did not address multilayer concepts. Applying polymers to observe shielding response mixtures for high-frequency electromagnetic interference was established by Jao et al. [11]. The work was further organized and developed by Lee et al. [12] for polyaniline mixtures and multilayer films. Both works were done for particulate radiation using polymer composition instead of focusing on hard metals and radioactive sources with high intensity. Kim et al. [13] built a multilayer structure for x-ray shielding. The composite films were thinned by the authors using non-Pb metal. Gamma rays, on the other hand, have greater penetration than x-rays. As a result, applying the x-ray idea to gamma radiation is inconvenient. The work on multilayer, waterborne, polyurethane, conductive composites was done by Sheng et al. [14] for the same electromagnetic interference. They built up an absorption-dominated shielding material for the next generation of smart electronic devices. The experiment on shielding for normal, underground, low-background radiation was done by Stewart et al. [15]. This concept could be used as a data source for the background radiation, but it did not cover the minimum thickness of the shielding materials.

All writers computed the buildup factor or developed multilayer shielding, but they did not optimize the thickness of each material for radiation shielding or consider environmental safety, weight, and cost-effectiveness. Therefore, a more accurate thickness was obtained by the double interpolation method, which adds novelty to this research. Several works exist on single- and double-layer shields. For example, Abbas et al. [16] used water–Pb, Kuspa et al. [17] used Al–Pb, and Arif et al. [18] imposed an Al–Fe–Pb combination for stopping the radiation. However, a W–Pb–Fe shielding and composition sequence has not yet been studied.

3. Methodology

The multilayer shielding calculation was based on the thickness of each layer. The ultimate goal was to find the optimal thickness and exposure rate, which should be below the desired level [19]. The highly radioactive source, ^{60}Co (100 Ci), emits the equivalent of 3.7×10^{12} gamma rays per second. To calculate the intensity or initial flux ($Ø_0$, gamma rays/[cm^2·s]), the source activity was converted to decays per second.

The formula for flux is

$$\text{Ø}_o = \frac{S}{4\pi r^2}. \tag{1}$$

Here, S is the strength of ^{60}Co, and r is the distance from the source to the shielding. When a photon interacts with the matter after shielding, the uncollided flux is written as

$$\text{Ø}_u = \text{Ø}_o \mathrm{e}^{-(\mu_1 d_1 + \mu_2 d_2 + \mu_3 d_3)}. \tag{2}$$

In this equation, μ_1, μ_2, and μ_3 are the linear attenuation coefficients, and d_1, d_2, and d_3 are the thicknesses of W, Pb, and Fe, respectively. The buildup factor is an important parameter for multilayer shielding calculations. Thus, the buildup flux including the buildup factor is

$$\text{Ø}_b = \text{Ø}_u B_m(\mu a), \tag{3}$$

where $B_m(\mu a)$ is called the exposure buildup factor, and it is a continuous function of the atomic number and depends on the energy of the materials. Because $\mu a = a/\lambda$, where λ is the photon mean free path, μa is equal to the thickness of the shield in mean free paths computed at the energy of the incident photons [20].

The formula for buildup is

$$B_m = B_{\mathrm{W}}(\mu_1 a_1) B_{\mathrm{Pb}}(\mu_2 a_2) B_{\mathrm{Fe}}(\mu_3 a_3). \tag{4}$$

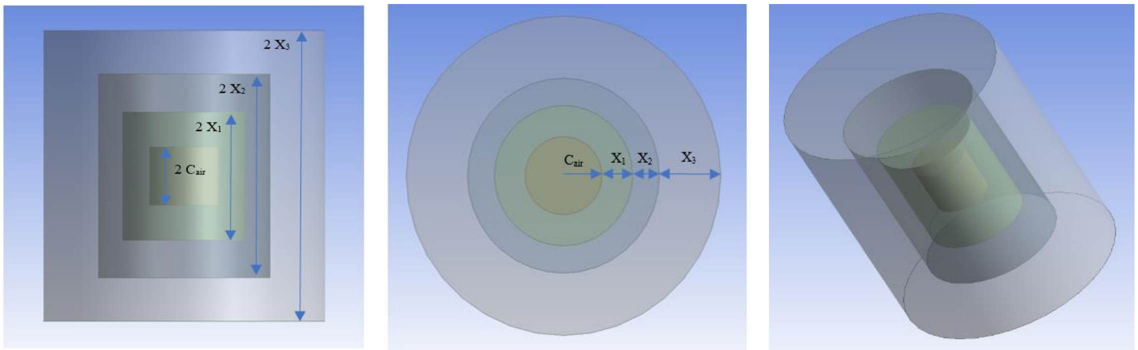
The final exposure rate [21] is

$$\dot{X} = 0.0659 E_o \left(\mu \frac{a}{\rho}\right)^{\mathrm{air}} \text{Ø}_b \ \mathrm{mR/h}. \tag{5}$$

This study aimed to calculate the optimal thickness for radiation shielding because the safety of radioactive sources depends on the shielding. The exposure rate was minimized to 20 mSv/year, which is used for radiation workers. The thickness of each layer was calculated by the linear interpolation method through MATLAB software [22, 23].

a. Design and Algorithm

The schematic representation with dimensions of a cylindrical-shape radiation protection container is visualized in Figure 1. The variables x_1, x_2, and x_3 are the thicknesses of W, Pb, and Fe, respectively, and the gap (i.e., inner radius) of the container is denoted by c_{air}.



(a) Front view (b) Top view (c) Side view

Figure 1. Different views of a cylindrical-shape radiation shielding design.

Figure 2 shows the algorithms by which the output was extracted from the MATLAB software. The ^{60}Co energy (*E* = 1.17 or 1.33 MeV) and density (W = material #1, Pb = material #2, and Fe = material #3) were imported as input variables into MATLAB. The flowchart (Figure 2) also shows that the so-called *double interpolation method* was used to calculate the mass and linear attenuation coefficient, mean free path, and exposure buildup factor using Equations (4) and (5).

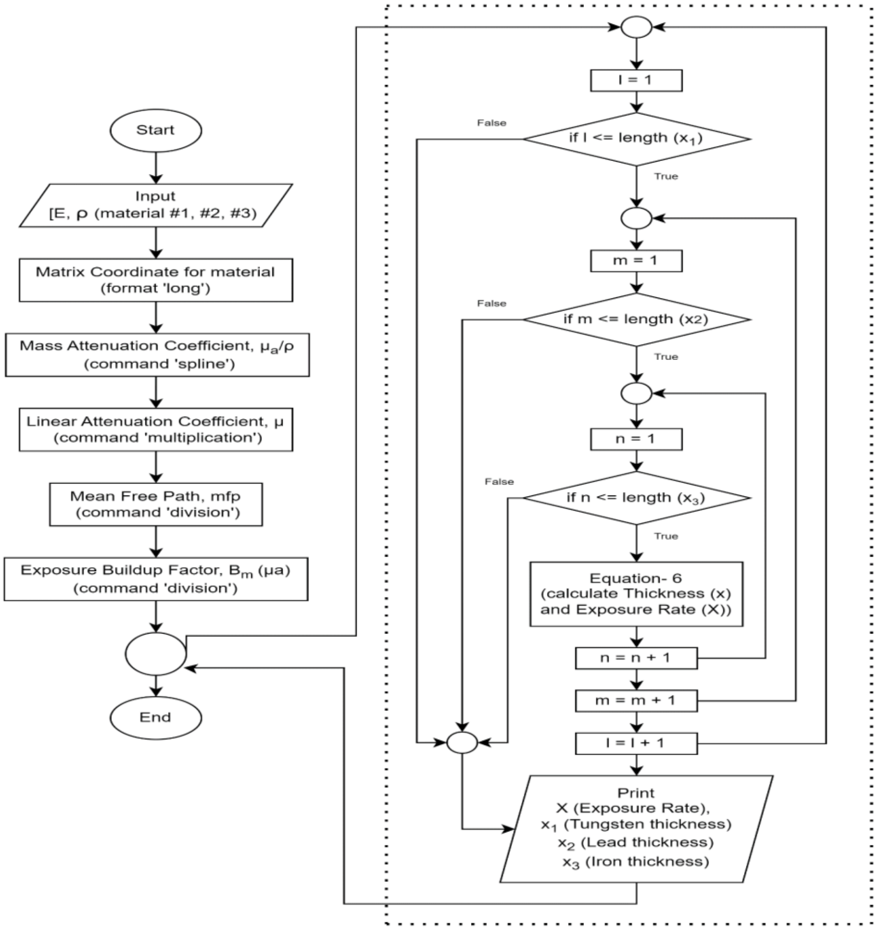


Figure 2. Overview flowchart of calculating shielding thickness for expected exposure rate for radiation workers.

4. Weight and Cost

The weight vs. cost ratio should remain at a small value to implement it in a real-life scenario. Equation (6) is used to calculate the weight of the container in kilograms, and Equation (7) is used to measure the cost of that container [23].

$$\begin{aligned}\frac{2\pi}{1000}\{\rho_{\text{air}}c_{\text{air}}{}^3 &+ \rho_1[(x_1+c_{\text{air}})^3 - c^3{}_{\text{air}}] \\ &+ \rho_2[(x_1+x_2+c_{\text{air}})^3 - (x_1+x_2+c_{\text{air}})^3] \\ &+ \rho_3[(x_1+x_2+x_3+c_{\text{air}})^3 - (x_1+x_2+c_{\text{air}})^3],\end{aligned} \tag{6}$$

where ρ_{air} is the air density of the inner part of the container, and ρ_1, ρ_2, and ρ_3 are the densities of W, Pb, and Fe, respectively.

$$\begin{aligned}\frac{4.4\pi}{1000}\{A_1\rho_1[(x_1+c_{\text{air}})^3 - c^3{}_{\text{air}}] + A_2\rho_2[(x_1+x_2+c_{\text{air}})^3 - (x_1+x_2+c_{\text{air}})^3] \\ + A_3\rho_3[(x_1+x_2+x_3+c_{\text{air}})^3 - (x_1+x_2+c_{\text{air}})^3]\},\end{aligned} \tag{7}$$

where A_1, A_2, and A_3 are the costs of W at $3.25/lb, Pb at $0.44/lb, and Fe at $0.07/lb, respectively [24].

5. Results and Discussion

a. Mass Attenuation Coefficient Analysis

Table 1 represents the mass attenuation coefficient and exposure buildup factors for energies at 1.17 and 1.33 MeV. The shielding attenuation formula yielded the mass attenuation coefficient, which correlates with density in Table 1. The calculation used the iteration method with National Institute of Standards and Technology and ANS-6.4.3 experimental data [25, 26]. The buildup factor was inversely proportional to the radiation-resistant material’s mean free path. Thus, the buildup factor was low for highly dense materials and decreased with increasing photon energy. The buildup factor was greater than unity, indicating that absorption was dominant and validating theoretical theories.

Table 1. Calculated Mass attenuation coefficient and exposure buildup factor for 1.17 and 1.33 MeV.

Material	**Density (g/cm^3)**	**Mass attenuation coefficient (1.17 MeV)**	**Mass attenuation coefficient (1.33 MeV)**	**Buildup factor (1.17 MeV)**	**Buildup factor (1.33 MeV)**
W	19.3	0.0603	0.0551	1.3928	1.4349
Pb	11.29	0.0626	0.0560	1.4607	1.5443
Fe	7.874	0.0554	0.0518	3.1973	3.4791

b. Optimal Thickness Calculation

The final exposure rate was found to be inversely proportional to the thickness of the material, which indicated the absorption and penetration power of the highly dense material when using a maximum thickness of W. Using the Figure 1 algorithm, the thickness was calculated by the linear and bilinear interpolation methods in MATLAB software. The optimum thickness was found to be 33 cm for energy at 1.17 MeV and 38 cm for energy at 1.33 MeV considering the weight and cost of the material.

In the case of 1.17 MeV energy, the total thickness was 33 cm, where the thicknesses of W, Pb, and Fe were sequentially 8, 5, and 20 cm, respectively. This combination is perfect, not only considering exposure rate but also focusing on cost and weight. The container's weight and cost were 2460.74 kg and $5478.65, respectively. This cost was the lowest among others, which is beneficial for industrial purposes, as well. The occupational exposure rate was 15.86 mSv/year, which is safe for the workers (Table 2).

Table 2. Weight and cost of the container for the optimal solution by MATLAB (1.17 MeV).

W (cm)	Pb (cm)	Fe (cm)	Total thickness (cm)	Exposure	Weight (kg)	Cost (USD)
9	5	17	31	18.310226	2134.66	6706.36
8	6	18	32	18.634055	2291.48	5610.76
8	5	20	33	15.86073	2460.74	5478.65
9	5	20	34	4.950565	2696.14	6886.03
9	4	20	35	2.431903	2924.88	7168.77

For the energy of 1.33 MeV, 38 cm was selected for the total thickness, and the combinations were 8, 5, and 25 cm for W, Pb, and Fe, respectively, where the exposure rate was 13.87 mSv/year. For this combination, weight and cost were found to be 3562.28 kg and $5831.14, respectively (Table 3).

Table 3. Weight and cost of the container for the optimal solution by MATLAB (1.33 MeV).

W (cm)	Pb (cm)	Fe (cm)	Total thickness (cm)	Exposure	Weight (kg)	Cost (USD)
9	6	20	35	19.49	2924.88	7168.77
9	3	25	37	17.06	3322.97	6735.95
8	5	25	38	13.87	3562.28	5831.14
8	6	25	39	7.35	3835.70	6104.92
9	6	25	40	2.53	4143.67	7472.99

c. Exposure Rate vs. Thickness

The thickness was optimized and ranged from 32 to 40 cm for 1.33 MeV of energy, which is safe for radiation workers. Figures 3 and 4 show the exposure rate against different thicknesses for two energies of ^{60}Co. These figures show that the final exposure rate decreased with increased thickness.

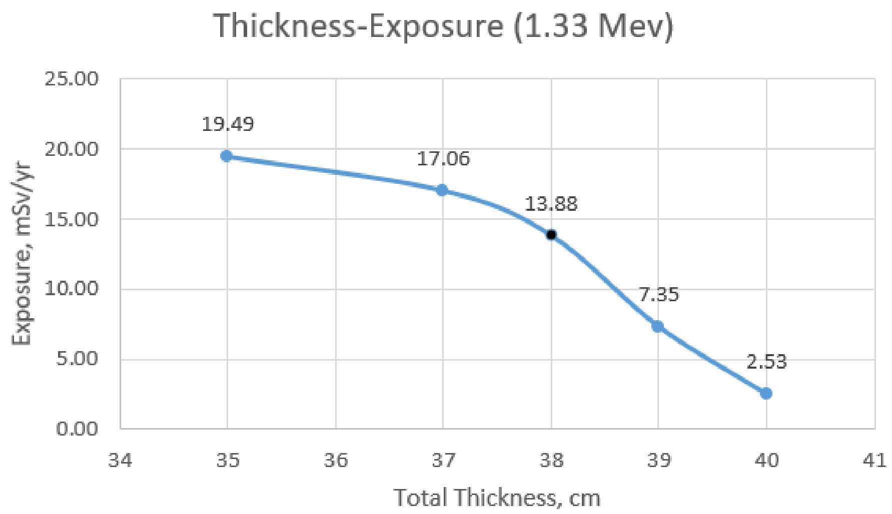


Figure 3. Graph for the total thickness vs. exposure for ^{60}Co (1.33 MeV).

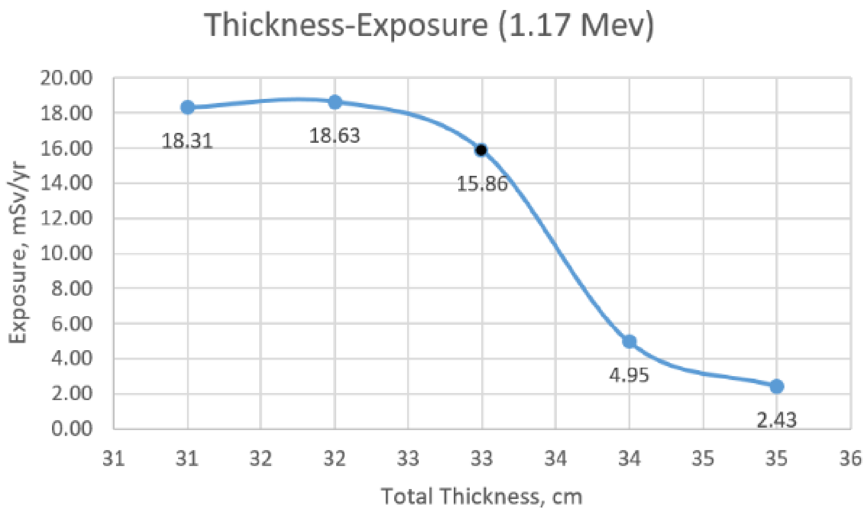


Figure 4. Graph for the total thickness vs. exposure for ^{60}Co (1.17 MeV).

Figure 3 plots ^{60}Co energy at 1.33 MeV, which was the maximum peak energy. Because of this highest gamma-ray energy, the thickness needed to be designed in such a way that it could reduce the intensity of the gamma rays. The intensity and exposure rate would both decrease while passing through the multilayer shield. The maximum and minimum exposures were 19.49 mSv/year and 2.53 mSv/year, respectively. Because of some constraints, 38 cm was selected as an optimal thickness (8 cm W, 5 cm Pb, and 25 cm Fe). But in the case of 1.17 MeV, the graph is not gradually decreasing because in a 32 cm combination, the Pb was considered to be 3 cm. High-density material had a great effect on reducing the exposure, but low-density material needed a higher thickness and consumed more space. In the next combination with increased Pb thickness, the exposure again decreased.

d. Weight vs. Cost

Increased shielding thickness would increase weight and expense. Figures 5 and 6 show the weight and cost calculation graphs for different energies. Usually, the cost would increase with the weight. However, the graphs do not show any linear behaviors. The costs (at the starting point) for both graphs are higher because of the thicknesses of W and Pb (highly dense material and per unit mass is very high). However, for the next point, the cost was reduced because the width of W and Pb were decreased. In total, for W, $5831.14 for 3562.27945 kg and $5478.65 for 2460.74 kg were finalized for 1.33 MeV and 1.17 MeV sequentially. The weight-to-cost ratio played a vital role in finding the minimal width as well as an essential parameter in mass production for industrial purposes. In this study, W was used well to reduce exposure and expense while keeping radiation workers safe. Additionally, this research used no more than 6 cm of Pb, reducing environmental contamination.

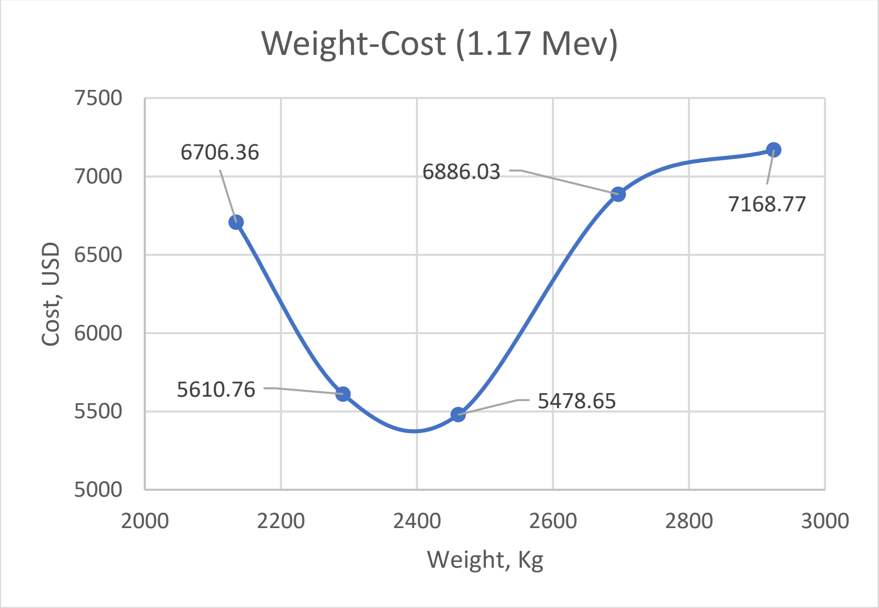


Figure 5. Weight vs. cost for ^{60}Co energy at 1.17 MeV.

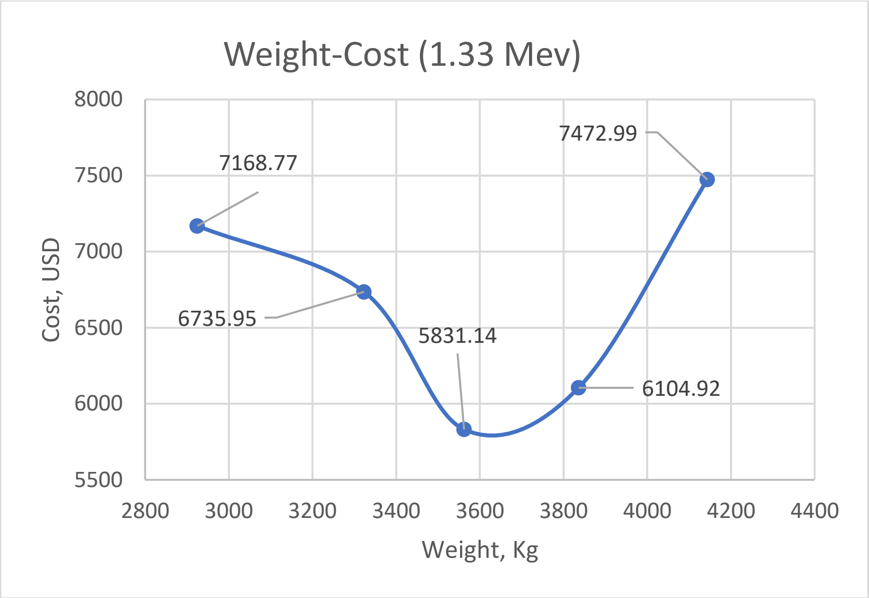


Figure 6. Weight vs. cost for ^{60}Co energy at 1.33 MeV.

e. Mean Free Path vs. Buildup Factor

Dense materials had a small value for the mean free path, which indicated the stopping power of any irradiation. Figure 7 shows that the high-density material W had the minimal exposure buildup factor but Fe, the lowest-density material among those tested had the highest buildup factor. For both energies, the graph shows the same nature, although the buildup factor for 1.17 MeV is slightly higher than that of 1.33 MeV because the average distance of the gamma ray for energy at 1.17 MeV travels more before interacting.

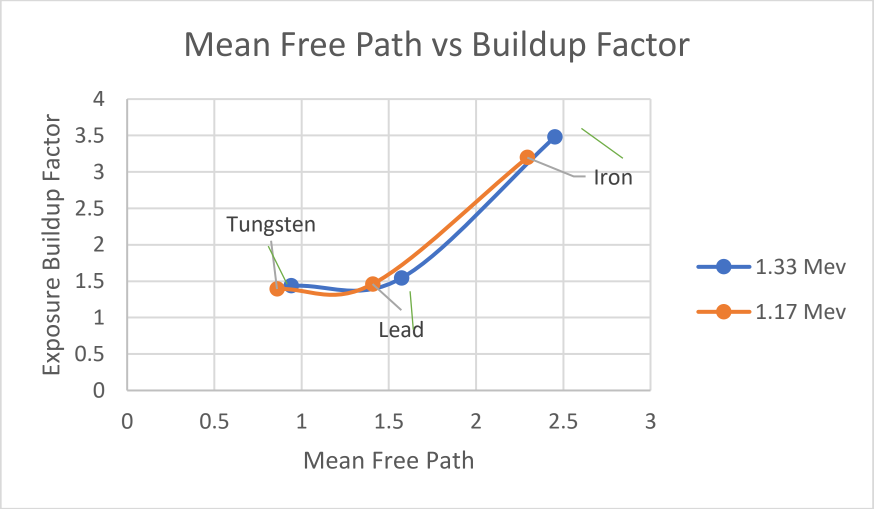


Figure 7. Exposure buildup factor vs. mean free path.

f. Monetary Value and Radiation Protection

The radiation protection calculation must maintain a particular value to obtain the safety limit. The monetary value of radiation is a measurement of the protection of radiation workers to a specified range. To compare the benefit of a radiation protection option (averted exposure) with its cost, the International Commission on Radiological Protection developed the reference monetary value of the man Sievert. The value was obtained using Equation (8):

$$Y = \alpha S_E. \tag{8}$$

Considering the cost of health detriment (according to the US), Y is \$11,582 [27]. From Table 1 and Figure 1, the optimized exposure rate was found to be 13.88 mSv/year. Consider a group of 100 workers and the sum of all individual effective doses. The monetary value was found to be \$8.344/(man·mSv). Usually, less than \$45/(man·mSv) is considered a good investment [28].

The values of the exposure rate, weight, and cost according to its thickness are similar to the theoretical and experimental values [23]. The data from the attenuation coefficient for the buildup factor were also validated with the benchmark analysis problem [29]. The effectiveness of the single-layer shield was optimized by implementing a multilayer concept (W–Pb–Fe).

6. Conclusion

From the present investigation, W–Pb–Fe was found to be the best combination of shielding materials because of its higher values for the attenuation coefficient and lowest value for buildup factor. This effective configuration of shielding was better than a homogenous single-layer shield. This study showed that 33 and 38 cm are in good agreement for ^{60}Co energies at 1.17 and 1.33 MeV, respectively. This shielding was used for medical and industrial purposes. Thus, the design of this multilayer shielding was done in such a way that it could limit the exposure rate below 20 mSv/year. By implementing this approach, workers can be assured of their safety while working with radioactive materials. Additionally, the environment will be protected from harmful radiation exposure, and heavy metals as dense material are placed in the first two layers, which prevents direct contamination. The iterative method for calculating buildup factors was based on the product of the buildup factors of each material that consists of the shield. If the order of the materials is changed, the values (e.g., thickness, cost, weight, etc.) will also change. A dependency of the mean free path on the attenuation coefficient, as well as the consequences of the density of each metal, were observed. The output value of the theoretical calculation seemed to be validated with the expected data group; the monetary value was calculated to be \$8.344/(man·mSv).

The proposed method ensures that the shielding is both efficient and secure, reducing the risk of radiation leaks and other hazards. As such, it has the potential to revolutionize radiological protection in various industries. With its application, companies can guarantee the safety of their workers and protect the environment in the long term. Overall, this study provided a promising solution to the growing need for effective radiological protection.

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