A computational study of the mass attenuation coefficients of gamma rays using the mixing rule and the XCOM program and parameters of design(HVL and MFP)

Wafaa N. Jasim*,iD , https://orcid.org/0000-0001-9318-9671iD

Department of Physics, College of Education for Women, University of Kufa, Najaf,Iraq

https://orcid.org/0000-0001-9318-9671

Abstract :

In this research, the mass attenuation coefficient (μ/ρ) for gamma rays in a quaternary alloy composed which were aluminum (Al), copper (Cu), zinc (Zn), and lead (Pb) was calculated using two different methods. In the first method, the weight fraction rule was applied based on elemental data extracted from the XCOM program. This rule was programmed in MATLAB to obtain theoretical values. In the second method, the XCOM program was used directly from the mixture field to calculate the mass attenuation coefficient for the alloy as a whole. Based on the values calculated using the mixing rule, the linear attenuation coefficient (μ_l) was calculated, from which the half-value layer (HVL) and mean-free path (MFP) values were obtained. A comparison between the two methods showed good convergence in the values of mass attenuation coefficient, confirming the accuracy of the mixing rule in characterizing the radiation properties of multi-element alloys. The results indicate that the studied alloy could be a promising candidate for radiation protection applications, particularly in the fields of medical physics and nuclear engineering.

Keywords: The mass attenuation coefficient, mixing rule,Half-value layer, Mean-free path, XCOM **.**

1- Background

Mixing elements with high-Z with elements with low-Z and vice-versa this amends the exposure build-up factors because of alteration in equivalent atomic numbers . An element with high atomic number provides effective X and gamma ray shielding. To get goodness shielding must be used alloys consisted of several elements or compounds [1]. Because of the increasing the use of this rays due to technology and development of science various industries [2]. Ionization can cause by Electromagnetic radiation for example gamma rays and x-rays which dangerous on human health when they exposed to this radiation from the several source that are found in , medical diagnostic centers, nuclear research establishments and nuclear weapon development facilities for that personal protect and sensitive electronic equipment are necessary [3]. The attenuation and scattering happens because of the interaction happen betwen electromagnetic radiation with matter Therefore , the attenuation, scattering , absorption coefficients and cross sections are very important in the explanation the interaction the electromagnetic radiation with matter[4]. To study the penetration and the energy deposition by photons (x-ray, γ-ray, bremsstrahlung) in shielding, biological and other materials we must used quantitiessuch as The mass attenuation coefficient, μ/ρ, and the mass energy-absorption coefficient, $\mu en/\rho$, [5].

To understand interaction mechanisms of this radiation must be know that photons are not subject to any of the Coulomb forces or the nuclear force as well, due to the concentration of their interactions over a short distance, the beam intensity decreases when it flow during the material and photons are removed from it, but the energy of the individual photons that do not participate in the interaction is not affected. The three ways in which photons interact with matter: the photoelectric effect, Compton scattering, and pair production, in addition to the possible interaction mechanism at energies less than 1000 keV, which is Rayleigh scattering[6,7]. Each of these interaction methods has different energy thresholds and cross sections depending on the type of material [7]. When gamma rays passes through a given material, the photons of this ray either exit without interaction or are completely displaced from the beam by scattering or absorption. If a beam intensity (I) is incident on a sample of thickness (x), the intensity of the beam (I) transmitted through the sample is given by the following Lambert-Beer relation:

$$I = I_{\circ} e^{-\mu_l x} \ldots\ldots (1)$$

I and $I_{\circ}$ are the photon beam intensity without the sample and with the sample present, respectively, calculated over a certain period of time at a thickness of x. Whereas the linear attenuation coefficient (μ_l) is the number of photons that are displaced or blocked from the beam per unit distance.. This coefficient is measured in units of (cm^{-1}). It is one of the most important coefficients that show the process of penetration of shields by gamma rays. It depends on the incident photons energy of gamma rays and the atomic number or the effective atomic number of the target material on which it falls. (μ/ρ) of metals is more important and is defined as the rate of photon interactions per unit mass per unit area (g/cm^2). It is given by the following equation[8]:

$$\frac{\mu}{\rho} = \frac{\mu_l}{\rho} \ldots\ldots(2)$$

Where ρ: the absorbent material density measured in g/cm^2 .

The attenuation coefficients of any chemical compound or homogeneous mixture And reaction coefficients (weight fractions or partial density) used as protective materials are theoretically calculated as the weight sum of the identical coefficients of the elements. The mass attenuation coefficient (μ/ρ) can be calculated by adding the weight as follows: [9]:

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \ldots\ldots (3)$$

w_i and $\left(\frac{\mu}{\rho}\right)_i$ are the fraction by weight (Weight percentage) and mass attenuation coefficient of *ith* component, respectively [5,7,9]. The half-value layer (HVL) is the One of the important parameters in designing a suitable radiation shielding material which is the thickness of the material make the intensity of the incident radiation to half its value by attenuate and reduce it. It is given by the following relationship:

$$HVL = \frac{ln2}{\mu_l} \ldots\ldots(4)$$

In adition to the half-value layer (HVL) there are importance parameter designing a suitable radiation shielding material which itis called mean free path (MFP)which is The average distance a photon travels along the path inside a material before being absorbed .the mean free path (MFP) given by the following relationship [8,10,11]:

$$MFP = \frac{1}{\mu_l} \ldots\ldots (5)$$

2- Results and Discussion:

The mass attenuation coefficient tells us how the photon interacting with matter per unit mass. In addition, it measures the ability of a material to attenuate (shield) X-rays and gamma rays (μ/ρ)[12,13] therefore at measure and study it for 5 alloys from Al-Cu-Zn-Pb alloys which have applications in radiation shielding because their tunable density, good strength, and ability to attenuate high-energy photons such as gamma rays and X-rays, they are candidates for use in nuclear physics, medical imaging, and industrial radiation shielding. They can be used in X-ray rooms and radiotherapy centers as an alternative to shielding made of pure lead, reducing lead toxicity while maintaining attenuation efficiency. In this research we use XCOM program which it is an electronic program used on websites to calculate the mass attenuation coefficients (μ/ρ) or cross-section of various elements, compounds, or mixtures theoretically in the range of the energy range (1 keV-100 GeV). First, we calculate the mass attenuation coefficient for each element of the alloy components using the XCOM program. According to what is in the program interface, we choose an element and each element of the sample alloy components and enter the energy range, which is (0.06-1.5MeV). The program calculates it , uploads it and calls the text file using the code used which it in the form of a txt file so that the code used in the MATLAB program reads the values from it and calculates the mass absorption coefficient for each alloy after inserting the required variables in the code, which includes the density and the weight fraction wi of each element of the alloy components and the energy range used. Using the mixing rule shown in equation (3), we calculate the mass absorption coefficient of the gamma rays incident on each alloy. At the same time, we calculate the mass absorption coefficient of the gamma rays, assuming that the sample is a mixture. From the XCOM program interface, we choose a mixture and follow the instructions requested by the program, which is to enter the weight fraction of each element of the alloy and the incident gamma rays energy of, to obtain the mass absorption coefficient for the alloy as a whole. We compare it with the results we obtained from the mixing rule in equation (3) and as shown in the attached code for calculating the gamma ray absorption coefficient for the first alloy, and we compare the results. The half value layer (HVL) for the five alloys was also calculated using equation (4) in two ways: the first was using the attenuation coefficient obtained from the mixing rule, and the second was using the attenuation coefficient obtained from the results of the XCOM program, assuming the sample alloy was a mixture. We compared the two results and also performed the calculations in MATLAB. To calculate the mean free path (MFP) using the MATLAB program, we extract the value of the linear absorption coefficient (μ_l) for each of the five alloys from the mass absorption coefficient extracted from the mixing rule. In another way, from the results we obtained from the Xcom program, we use the equation (2)and by using the density for each alloy, which was calculated for each alloy from the inverse mixing rule shown in the following equation[14] :

$$\rho_{Alloy} = \frac{1}{\sum_i w_i/\rho_i} \ldots\ldots (6)$$

ρ_{Alloy} and ρ_i are the density of alloy and density of any element in the alloy respectively . ρ_i of alloy elements Al,Cu,Zn and Pb are 2.7 g/cm³, 8.933 g/cm³, 7.134 g/cm³, 11.342 g/cm³ respectively[15].

Table 1 shows the alloying elements, the weight fraction of the element in the alloy, and the density of the sample alloy used in the research, calculated by Equation(6) .

Table 1: Shows the alloying elements, weight fraction, mass, and density of the samples used in the study.

Sample code of alloy	Base material	weight fraction	Alloying element	weight fraction	Alloying Element	weight fraction	Alloying element	weight fraction	Alloy density (gm/cm^3)
A1	Al	0. 6	Cu	0.3	Zn	0.015	Pb	0.085	3.767
A2	Al	0. 6	Cu	0.3	Zn	0.02	Pb	0.08	3.764
A3	Al	0. 6	Cu	0.3	Zn	0.025	Pb	0.075	3.760
A4	Al	0. 6	Cu	0.3	Zn	0.03	Pb	0.07	3.756
A5	Al	0. 6	Cu	0.3	Zn	0.035	Pb	0.065	3.753

Table .2 shows the values of the mass attenuation coefficient μ/ρ for the five alloys for the gamma ray energy range (60-1500KeV), which was calculated as we explained previously, first by the mixing method shown in Equation (3) by substituting the values of the attenuation coefficient that were calculated by the XCOM program for each element of the alloy, and the other method by the XCOM program directly. The results showed that the mass attenuation coefficient with highest value for gamma rays at energy 60 KeV was in alloy A1 because it contains the highest percentage of lead and is equal to 1.09768 cm^2/g using the mixing method and 1.098 cm^2/g from the XCOM program, while the lowest value was equal to 1.03248 cm^2/g using the mixing method and 1.032 cm^2/g from the XCOM program, and it is for alloy A5 because it contains the lowest percentage of lead, meaning that high-energy gamma rays can penetrate an alloy with a low percentage of lead, as lead has a high density, which makes it absorb gamma rays than other elements witch is appearance in the figure1. figures 2-6 show the relation between the gamma ray attenuation coefficient and the energy of the gamma rays incident on each alloy by this two methods which are show good agree between them .

Table .2: Shows the values of the mass attenuation coefficient μ/ρ(cm^2/g) for the five alloys (A1,A2,A3,A4 and A5) for the gamma ray energy range (60-1500KeV).

	A1		A2		A3		A4		A5	
E(eV)	μ/ρ(cm^2/g) by mixing method	μ/ρ(cm^2/g) by XCOM	μ/ρ(cm^2/g) by mixing method	μ/ρ(cm^2/g) by XCOM	μ/ρ(cm^2/g) by mixing method	μ/ρ(cm^2/g) by XCOM	μ/ρ(cm^2/g) by mixing method	μ/ρ(cm^2/g) by XCOM	μ/ρ(cm^2/g) by mixing method	μ/ρ(cm^2/g) by XCOM
60	1.097	1.098	1.081	1.081	1.065	1.065	1.048	1.049	1.032	1.032
80	0.568	0.568	0.560	0.560	0.552	0.552	0.544	0.544	0.536	0.53
100	0.7189	0.718	0.6936	0.693	0.668	0.668	0.643	0.643	0.617	0.617
150	0.323	0.324	0.3150	0.315	0.306	0.306	0.297	0.297	0.288	0.288
200	0.207	0.207	0.203	0.203	0.199	0.199	0.194	0.194	0.190	0.190
300	0.132	0.132	0.130	0.130	0.129	0.129	0.127	0.127	0.126	0.126
400	0.105	0.105	0.104	0.104	0.103	0.103	0.103	0.103	0.102	0.102
500	0.090	0.090	0.090	0.090	0.089	0.089	0.089	0.089	0.089	0.089
600	0.081	0.081	0.081	0.081	0.080	0.080	0.080	0.080	0.080	0.080
800	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.068	0.068
1000	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061
1022	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060
1250	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
1500	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049

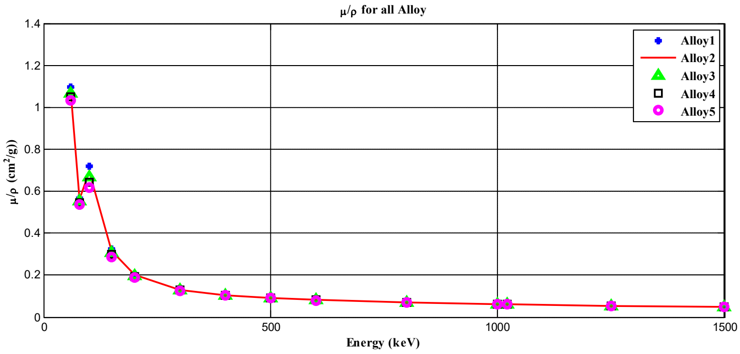

Fig.1: The relationship between the gamma ray attenuation coefficient and the energy in all alloys (A1,A2,A3,A4 and A5).

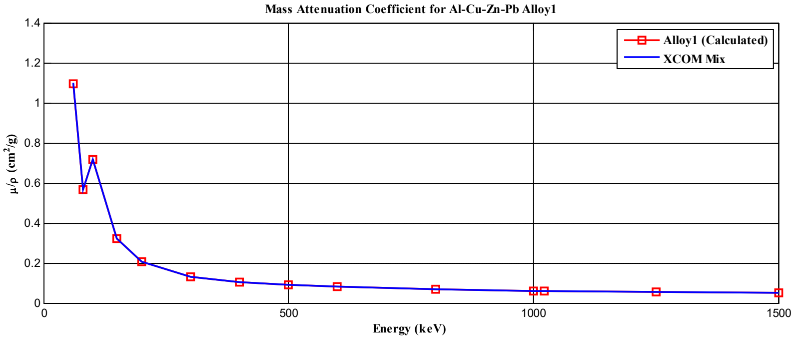

Fig.2: The relationship between the gamma ray attenuation coefficient and the energy in alloy A1

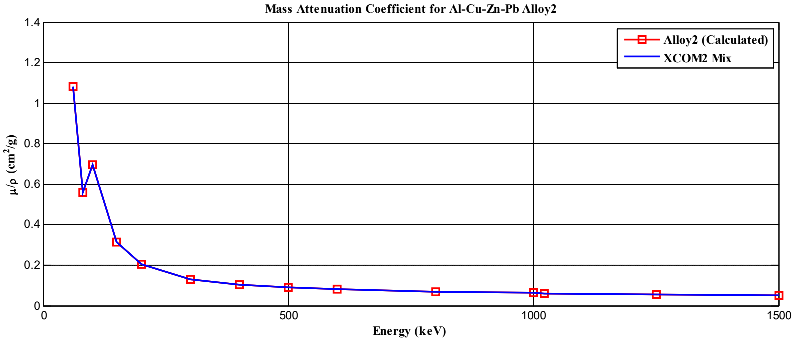

Fig.3: The relationship between the gamma ray attenuation coefficient and the energy in alloy A2

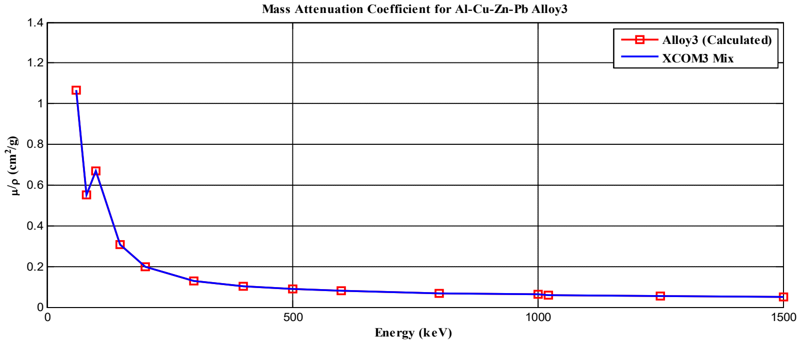

Fig.4: The relationship between the gamma ray attenuation coefficient and the energy in alloy A3

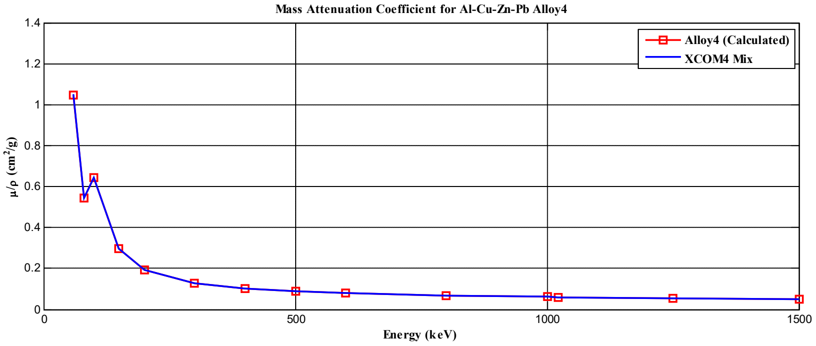

Fig.5: The relationship between the gamma ray attenuation coefficient and the energy in alloy A4

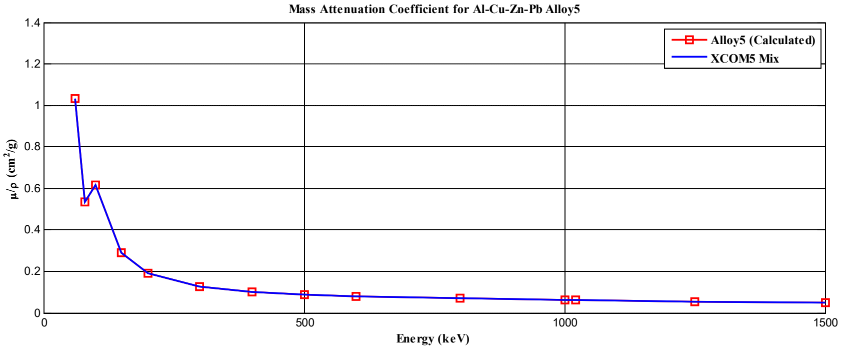

Fig.6: The relationship between the gamma ray attenuation coefficient and the energy in alloy A5

Table .3 shows the half value layer HVL for the five alloys . From it, we note that the highest value of the half-value layer was for alloy A5 and equaled 0.178874079210401 cm at energy 1500KeV, while the lowest value for the gamma ray intensity to become half of what it was equaled 0.167592516794850 cm at energy 60KeV. The higher the energy of the incident gamma ray, the greater the thickness required to reduce its intensity to half its value. That is, the relationship between gamma ray energy and HVL. is a direct relationship, and Figure (7) shows this relationship between HVL with the range of energy used.

Table 3: Shows the values of The half value layer (HVL) cm for the five alloys (A1,A2,A3,A4 and A5) for the gamma ray energy range (60-1500KeV).

E(eV)	HVL forA1(cm)	HVL forA2(cm)	HVL forA3(cm)	HVL forA4(cm)	HVL forA5(cm)
60	0.167	0.170	0.173	0.175	0.178
80	0.323	0.328	0.333	0.338	0.344
100	0.255	0.265	0.275	0.286	0.298
150	0.567	0.584	0.602	0.620	0.640
200	0.886	0.905	0.925	0.946	0.968
300	1.392	1.409	1.426	1.444	1.462
400	1.750	1.764	1.777	1.790	1.804
500	2.027	2.038	2.048	2.059	2.070
600	2.258	2.267	2.276	2.285	2.294
800	2.650	2.657	2.664	2.671	2.678
1000	2.990	2.996	3.002	3.008	3.014
1022	3.026	3.032	3.038	3.043	3.049
1250	3.372	3.377	3.382	3.387	3.392
1500	3.708	3.713	3.718	3.723	3.728

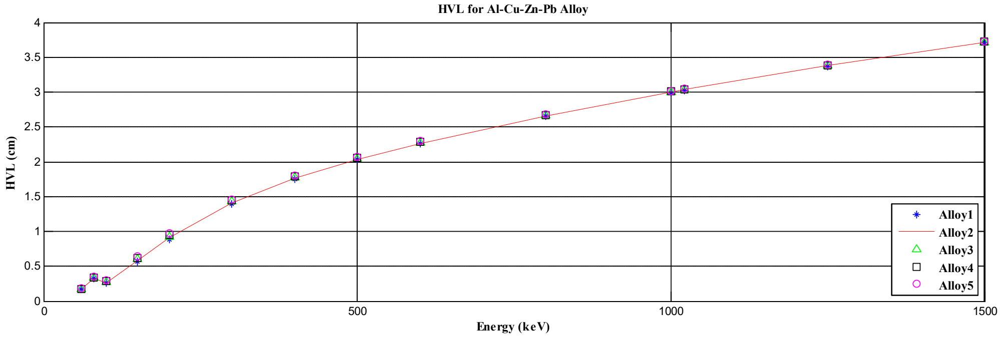

Fig. (7) :The relationship between HVL(cm) with energy of gamma rays in the five alloys (A1,A2,A3,A4 and A5).

Table. 4 shows the calculated MFP values for the five alloys used. It is clear from Table (4) that the higher the ratio of lead in the alloy and the lower the energy of the incident gamma rays, the lower the mean free path rate. The lowest value of the MFP rate was in alloy A1 0.241784892870030 cm at an energy of 60 keV, which contains the highest percentage of lead, and the highest value of the mean free path rate was equal5.37928740033854 cm at an energy of 1500 KeV in alloy A5, which has the lowest percentage of lead. Figure (8) shows the nature of the relation which related between the energy of the incident gamma rays and the MFP in the alloys.

Table 4: Shows the values of the mean free path (MFP) cm for the five alloys (A1,A2,A3,A4 and A5) for the gamma ray energy range (60-1500KeV).

E(eV)	MFP forA1(cm)	MFP forA2(cm)	MFP forA3(cm)	MFP forA4(cm)	MFP forA5(cm)
60	0.241	0.245	0.249	0.253	0.258
80	0.467	0.474	0.481	0.488	0.496
100	0.369	0.382	0.397	0.413	0.431
150	0.819	0.843	0.868	0.895	0.923
200	1.279	1.306	1.335	1.365	1.397
300	2.009	2.033	2.058	2.083	2.109
400	2.525	2.544	2.564	2.583	2.603
500	2.924	2.940	2.955	2.971	2.986
600	3.258	3.271	3.284	3.297	3.310
800	3.824	3.834	3.843	3.853	3.863
1000	4.315	4.323	4.331	4.339	4.348
1022	4.366	4.374	4.382	4.391	4.399
1250	4.865	4.872	4.880	4.887	4.895
1500	5.349	5.357	5.364	5.371	5.379

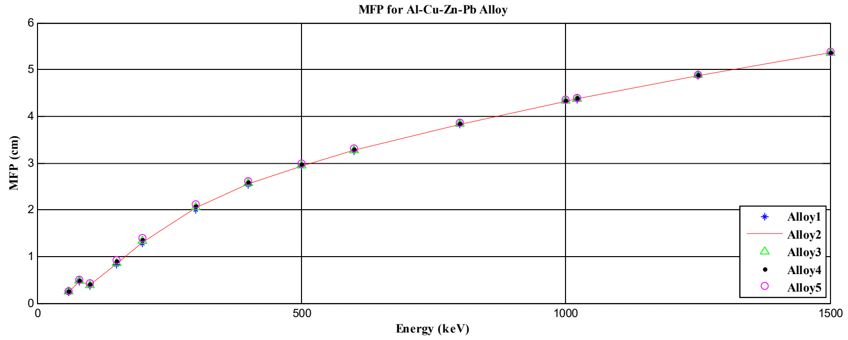

Fig. (8): The relationship between MFP(cm) with energy of gamma rays in the five alloys (A1,A2,A3,A4 and A5).

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3- Conclusion:

From the results and calculations, we obtained for the mass attenuation coefficient of gamma rays, we concluded that decreasing this coefficient with increasing its energy of gamma rays, as shown in the figures and tables that shown the relationship between the mass attenuation coefficient and the gamma ray energy for the five selected alloys. The the attenuation coefficient with highest value of at energy 60KeV was 1.09768 cm^2/g for alloy A1, while at energy 1500KeV it was 0.0496088 cm^2/g for the same alloy, which contains the highest percentage of lead, which means that when the lead percentage in the alloy decreases, the attenuation coefficient decreases. While the half value layer with highest value required to reduce gamma rays to half their value was at energy 1500KeV for alloy A5, and it equals 3.72863789496630 cm , as it contains the lowest percentage of lead, while the relation between the free path rate and the energy of the incident gamma rays showed that the free path rate is directly proportional to the energy of the gamma rays, as the highest value appeared The free path rate at energy 1500KeV for alloy A5 was 5.37928740033854 cm. The reason is that this alloy contains the lowest percentage of lead, meaning the path rate of the rays through it is greater due to its ease of penetration. The edge appearing in the MFP and HVL curves at energies below 500 keV is caused by the absorption edges of the alloy elements, where the material's ability to absorb photons suddenly increases due to the activation of the photoelectric effect. This leads to a higher attenuation coefficient and, consequently, a sudden drop in both MFP and HVL values. This edge reflects a change in the interaction mechanism between photons and the material and is an accurate indicator of the critical energies for internal absorption. Thus, through the studied protection properties (mass absorption coefficient, half-value layer, and free path rate) of this alloy, it appeared that alloy A1 is the best in radiation protection.

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