Monte Carlo assessment of gamma ray attenuation properties for MCP-96 alloy using transmission technique

تخمين مونت كارلو لخصائص السبيكة MCP-96 لتوهين أشعة كاما بإستخدام تقنية النفاذ

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Abstract

The photon attenuation properties of a material can be evaluated using the linear attenuation coefficients (μ_l), mass attenuation coefficients (μ_m) and related parameters such as mean free path (*mfp*) and half and tenth values thickness (*HVT*) , (*TVT*) respectively etc.

In present work, a new procedure of computer simulation program based on Monte Carlo method and photon attenuation technique was designed and written to be as virtual experimental system, instead of the real experimental system, concerning evaluation of attenuation properties for materials. The attenuation coefficients, as well as several other properties, were determined for MCP-96 alloy to assess its use in radiation applications. The density of alloy, also, was calculated. These provide followed the histories of numerous emitted photons from radioactive source. These photons with varying energies will pass through various thicknesses of MCP-96 alloy. The count rate for the beam of incident photons, after that the attenuation within the alloy was took place, was determined for each varying thickness of the alloy. Plotting the thickness of the alloy versus the corresponding logarithmic count rate of the beam will allow calculation of the attenuation properties. Counted photons were treated by means of correction factor. This factor gave present simulated results good agreement with XCOM program output and published experimental results. Contributing the porosity in the error percentage of simulated density value was discussed. Our simulation results are useful for training and development of human resources, staff and students, in the field of application of nuclear techniques, particularly, in radiation shielding protection.

الخلاصة :

يمكن تقييم خصائص المواد لتوهين الفوتونات بإستخدام كلاً من معاملات التوهين الخطية (μ_l) والكتلية (μ_m)والمعاملات المرتبطة بها مثل معدل المسار الحر (*mfp*) وسمكي النصف (*HVT*) والعشر (*TVT*) .

في البحث الحالي، تم وبإسلوب جديد تصميم وكتابة برنامج محاكاة حاسوبي بالإستناد الى طريقة مونت كارلو وتقنية توهين الفوتونات ليكون بمثابة منظومة عملية إفتراضية عوضاً عن المنظومة العملية الحقيقية المتعلقة بتقييم خصائص التوهين للمواد. حيث تم حساب معاملات التوهين، إضافة الى خصائص أخرى، لسبيكة MCP-96 لتقييم استخدامها في التطبيقات الإشعاعية. كذلك تم حساب كثافة السبيكة. وهذا يتطلب متابعة تواريخ عدد من الفوتونات المنبعثة من المصادر المشعة. هذه الفوتونات ذات الطاقات المختلفة ستمر من خلال السبيكة MCP-96 ولقيم سمك مختلفة. بعد حدوث التوهين ضمن مادة السبيكة، تم تحديد نسبة العد لفوتونات الحزمة الساقطة. يسمح التمثيل البياني للقيم اللوغاريتمية لنسبة العد بالنسبة لقيم السمك المناظرة في تحديد خواص التوهين. تم معالجة الفوتونات المعدودة بوساطة معامل تصحيح. يعطي هذا المعامل للنتائج المحاكاة الحالية توافقا جيداً مع مخرجات البرنامج XCOM والنتائج العملية المنشورة. لقد تم مناقشة مساهمة المسامية في نسبة الخطأ المئوية في قيمة الكثافة المحسوبة. يمكن الإستفادة من المحاكاة في البحث الحالي في تدريب وتطوير الموارد البشرية، طلاباً وفنيين، في مجال تطبيقات التقنيات النووية، خصوصاً، في مجال الوقاية من الإشعاع.

Keywords: gamma attenuation coefficients, MCP-96 alloy, Monte Carlo method, transmission method.

1. Introduction

Exposure to gamma rays can occur in a range of nuclear research establishments, medical diagnostic centers, industries, nuclear reactors and nuclear weapons. Since the energetic gamma rays are hazardous for organisms, particularly the humans, the needed precautions must be taken by shielding the radiations.

MCP alloys are low melting point alloys, or fusible alloys, specially built for radiation shielding protection and tissue compensating purposes [1, 2].The low melting point allows for easier shaping of the metal for specific shapes often needed in radiation therapy. They can reproduce very fine details and are reusable [3]. Unlike alloys with similar characteristics, MCP-96 is free of the known carcinogen cadmium. Cadmium exposure most often occurs in the manufacturing of products containing cadmium and causes lung damage, cancer, and fragile bones [4]. MCP-96 is not classified as dangerous for either transportation or storage. It is easy to handle, and quite safe when the rules for normal handling are observed.

The linear attenuation coefficient is a few of the important characteristics that need to be studied and determined prior to using a material in radiation applications. Since, the accurate attenuation coefficient values of materials are a very essential parameter in nuclear and radiation physics, radiation dosimetry, radiography, spectrometry, crystallography, biological, medical, agricultural, environmental and industrial.

Computer simulation can be broadly defined as: 'Using a computer to imitate the operations of real world process or facility according to appropriately developed assumption taking the form of logical, statistical, or mathematical relationships which are developed and shaped into a model' [5].The results can be manipulated by varying a set of input parameters to help an analyst understand the underlying system's dynamics. The model typically is evaluated numerically over a simulated period of time and data is gathered to estimate real world system characteristics. Generally, the collected data is interpreted with statistics like any experiment. So, we can say, a simulation is an experiment [6], or as computer experiments because they share much in common with laboratory experiments.

The Monte Carlo method is a stochastic numerical simulation method that takes into account all the physical and geometrical aspects of the problem. This method is used in radiation transport studies for simulating the transport of neutrons, photons and electrons, particularly in irregular geometries. In the Monte Carlo approach, individual particle transport histories are generated by randomly sampling particles as they travel through the geometry. These transport histories are then analyzed to provide information on quantities of interest, such as particle fluence or detector response. The Monte Carlo method is most effective in solving problems that are difficult to simulate with common deterministic methods. This method also provides an answer with a statistical uncertainty associated with it, so that a confidence level in the results can be established.

The attenuation or transition method is simply the measurement of the change in detected count rate from a source when a material, under study with particular thickness, is introduced in between.

In present work, a new procedure of computer simulation program based on Monte Carlo method and photon attenuation technique was designed and written to be as virtual experimental system, instead of the real experimental system, concerning evaluation of attenuation properties for materials. The linear attenuation coefficient, as well as several other properties, will be determined for MCP-96 alloy to assess its use in radiation applications. These provide followed the history of numerous emitted photons from radioactive source. These photons with varying energies will pass through various thicknesses of MCP-96 alloy. The count rate for the beam of incident photons, after that the attenuation was took place, will be determined for each varying thickness of the alloy. Plotting the thickness of the alloy versus the corresponding logarithmic count rate of the beam will allow calculation of the attenuation properties.

2. The history of simulated photons:

The proposed configuration for the present simulation is shown in Fig.1 including a radio-active source, a NaI(Tl) detector and a MCP-96 alloy as specimen with various thickness values. The distance between the source-alloy and the alloy-detector can be changed. Based on the proposed configuration, we have developed Monte Carlo simulation to describe the interaction processes occurred when the photon beam coming in the alloy, the results of which are that only the photons that are transmitted within a solid angle covered by the detector are to be registered (counted). These registered events allowed then us to study "virtually" the characteristics of the experimental system concerned geometrical characteristics of system or/and, characteristics of the alloy to determine the needed results about them.

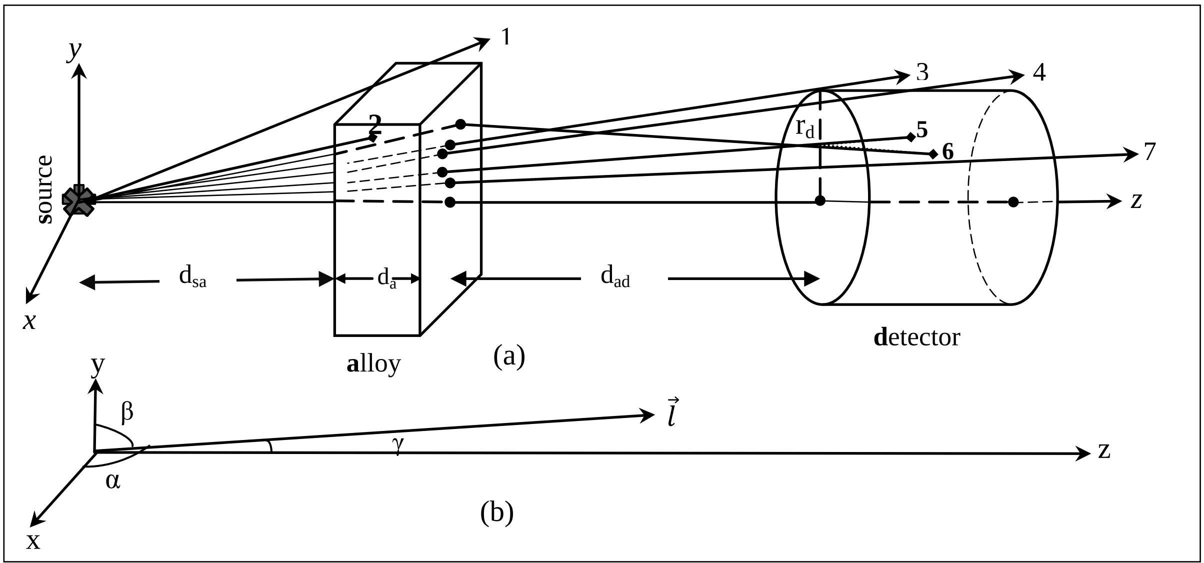

Fig.1: Geometrical configuration simulation of **s**ource-**a**lloy, **a**lloy-**d**etector systems by present Monte Carlo computer program. (a) Fixed dimensions system and (b) reference dimensions system.

The predicted history of each particle (photon) in our simulation is tracked from creation until termination with all interaction based on particular physical and mathematical considerations, and all decisions (location of interaction, incident and scattering angles, etc.) are based on pseudo-random numbers.

For simplicity, assumed that the emitted photons from the radioactive source undergo only one scattering. Also it ignores the small attenuation by the air layers between the source-alloy and the alloy-detector systems. This history is defined during the following main steps:

(1) each photon is emitted from a random chosen point (x_o,y_o,z_o) inside the volume of the source. It has a random direction (α ,β,γ) in the half space containing the alloy determined by direction cosines. The emission point and the direction of the trajectory are referred to the frame described in fig.1.

(2) a set of parametric equations,

$$x = x_o + l\cos\alpha \cdots\cdots\cdots (1)$$
$$y = y_o + l\cos\beta \cdots\cdots\cdots (2)$$
$$z = z_o + l\cos\gamma \cdots\cdots\cdots (3)$$

sequentially, was used. These equations, corresponding to a few of considerations, estimate the location of photons within the source-alloy and alloy-detector systems.

(3) if the incident point dimensions of photon (x_1,y_1,z_1) on the alloy within the dimension of this alloy (width, length, thickness), then these photon collides the forward face of the alloy (i.e: trajectories 2-7) and enter the body of it else (i.e: trajectory 1) another photon has been called.

(4) when the photon goes into the alloy, the "virtual" path p_l is evaluated. It's the distance which the photon would cover inside the detector in the case of missing interaction. According to an exponential distribution [7], the path length (p_l) of photon traverses to interact is randomly chosen (sampling) using the equation:

$$p_l = -\frac{1}{\mu_l} ln(1 - R_n) \cdots\cdots\cdots (4)$$

where R_n is the random number $(0 \leq R_n \leq 1)$, and μ_l is the linear attenuation coefficient of γ-radiation (with the energy E_γ) in the alloy. XCOM program[8]has been used to calculate the mass attenuation coefficients$(\mu_m = \mu_l/\rho)$ of each element that constructs the alloy, where ρ is the bulk density of the element. The weighting equation [9] can be used, since:

$$(\mu_l)_c = \sum_{i=1}^{n} w_i (\mu_l)_i \cdots\cdots\cdots (5)$$

where: $(\mu_l)_c$ is the linear attenuation coefficient of compound or mixture, w_i and $(\mu_l)_i$ the weighting facotor and linear attenuation coefficient of i^{th} element in compound respectively.

(5)putting the parameter $p_l$of eq. (4) instead of the parameter l in eqs. (1), (2) and (3) with particular new values of random direction (α ,β,γ)determines either the photon completely absorped within alloy material (i.e. trajectory 2) or penterates the alloy forward of the detector (i.e. trajectories 3-7).

(6) carrying out the steps from 2 to 5 to determine either the photon uncollides the front face of the detector (i.e. trajectory 3) or collides (i.e. trajectories 4-7). These photons either escape from side or bottom of the detector (i.e. trajectories 4 and 7) or registered as directly (i.e. trajectory 5) or as indirectly (i.e. trajectory 6).

3. Results and Discussion:

The photon attenuation properties of a material can be evaluated using the linear attenuation coefficients (μ_l), mass attenuation coefficients (μ_m) and related parameters such as mean free path (*mfp*) and half and tenth values thickness or layer (*HVT*) , (*TVT*) respectively etc.

In our simulation, for a good statistical distribution, 10^8 of monoenergetic gamma photons were sent toward the attenuator. These gamma photons emitting from virtual radioactive sources with energies are ^{137}Cs:662 keV, ^{54}Mn: 835 keV and ^{60}Co: (1173, 1332) keV. The used attenuator in this simulation is manufactured of a high-density MCP-96 alloy consisting of bismuth (52.5%), lead (32%), and tin (15.5%) [2].

After verified numbers of conditions, the photons transmitted through the attenuator were detected, as in the experiment. Also, a virtual NaI(Tl) detector was used to detect these photons. By this way, it has been performed that the method was in parallel with the experimental procedure. In order to evaluate the behaviors of varied values of gamma photon energy with respect to the absorber thicknesses, Fig. 2was plotted.

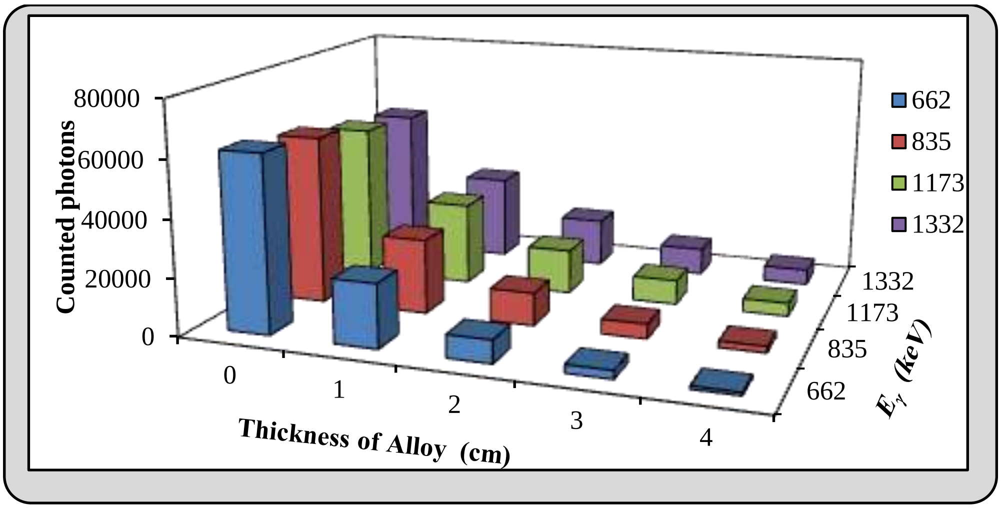

Fig.2: the dependency of counted photons on the thickness of alloy vs. the energy of incident gamma rays.

The semi-logarithmic calculated distributions of registered counts versus absorber thicknesses (attenuation graphs) for particular gamma energy are shown in Fig.3, Fig.4, Fig.5 and Fig.6.

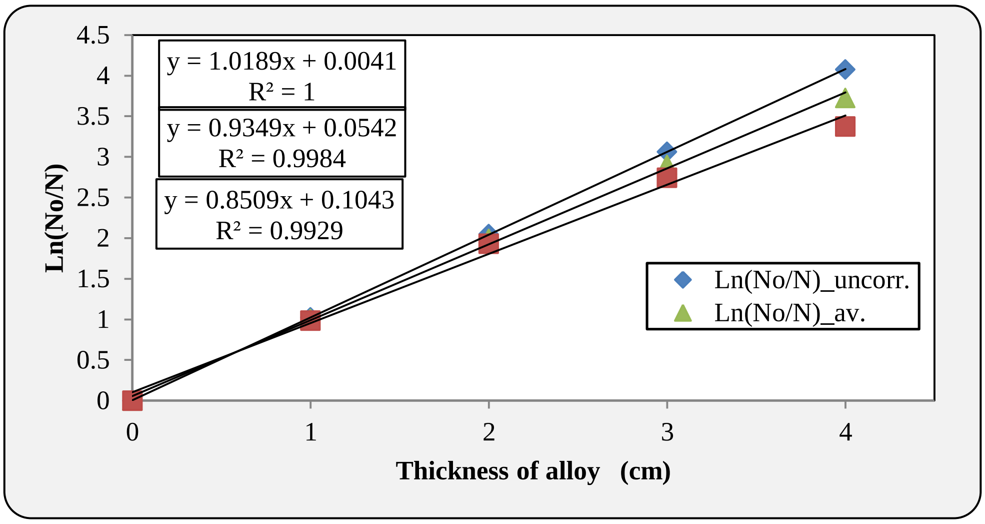

Fig.3: shows linear attenuation data vs. thickness of MCP-96 alloy for 662 keV of gamma rays energy.

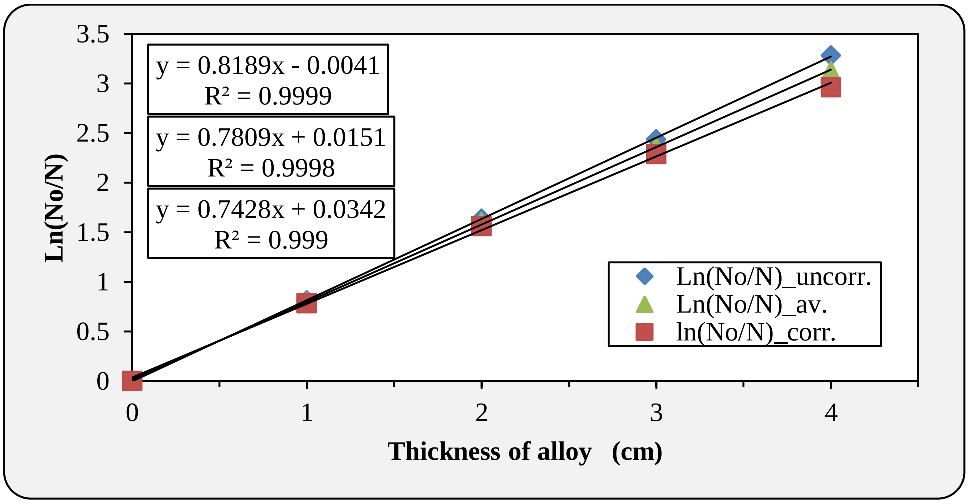

Fig.4: shows linear attenuation data versus thickness of MCP-96 alloy for 835 keV of gamma rays energy.

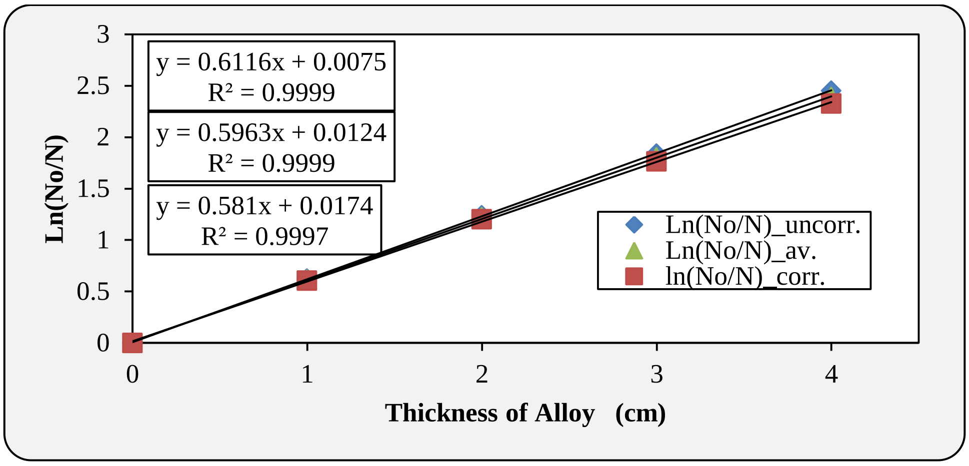

Fig.5: shows linear attenuation data versus thickness of MCP-96 alloy for 1173 keV of gamma rays energy.

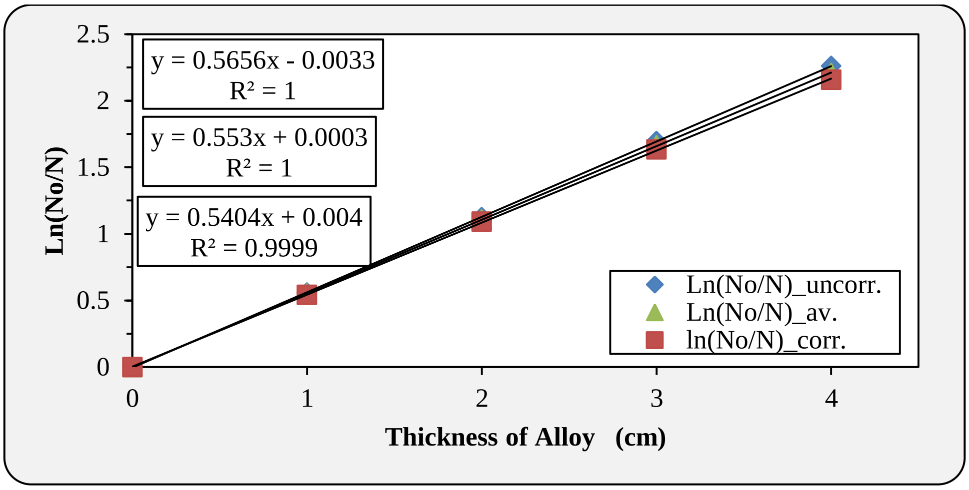

Fig.6: shows linear attenuation data versus thickness of MCP-96 alloy for 1332 keV of gamma rays energy.

In these figures, for geometrical considerations of simulated set up, counted photons was treated by means of correction factor. It is a function of the noise (uncollided count rate). This factor loses its importance, obviously, at a few values of thickness and whenever the values of energy increase. The average values of corrected and uncorrected counts give the simulated results good agreement with the experimental results of Hopkins [2] as shown in fig.7.

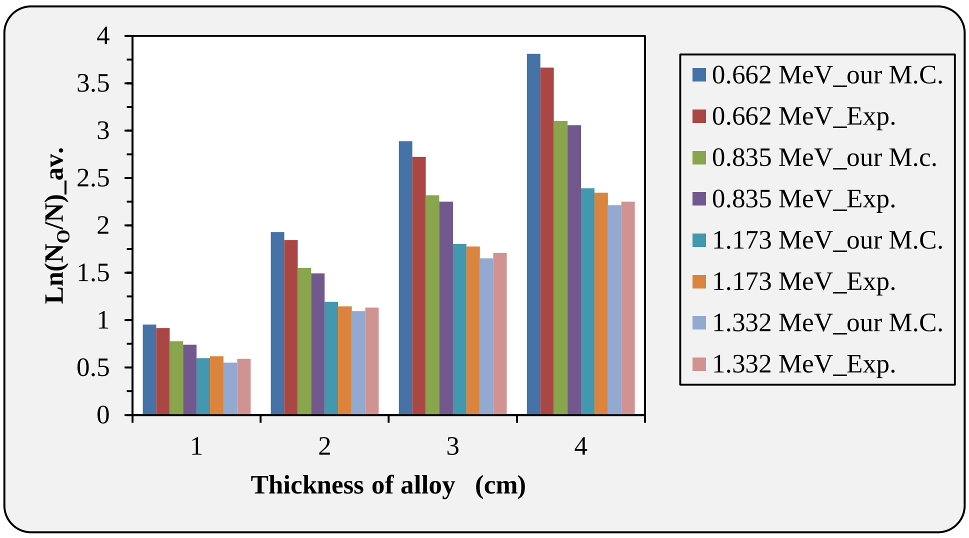

Fig.7: our Monte Carlo results of attenuation data compared to published experimental results for varies energies of gamma rays.

The linear attenuation coefficient for each virtual source is represented by the slope of the linear curve on $Ln(N_o/N)$ versus thickness graph as shown in fitting equations of figures from fig.3 to fig.6. Table-1- shows the experimental linear attenuation coefficients for energies (0.662, 0.835, 1.173, and 1.332) MeV [2] and simulated of their. Where the correction factor and, subsequently, $Ln(N_o/N)_{av.}$ positively reflected on the results.

Table-1-: Linear attenuation coefficients for each source and energy level for MCP-96 alloy attenuator.

source	E_γ (MeV)	μ_l (cm^{-1})		Error%
		Exp.	Present work	
^{137}Cs	0.662	0.9129±0.0064	0.9349	2.35
^{54}Mn	0.835	0.7622±0.0077	0.7809	2.39
^{60}Co	1.173	0.5961±0.0089	0.5963	0.033
^{60}Co	1.332	0.5613±0.0081	0.553	-1.50

The linear attenuation coefficient decreases with increasing gamma beam energy. As the beam energy increases, the MCP-96 attenuates fewer photons than the lower energy photons.

The effectiveness of gamma ray shielding is often described as the half-value thickness (*HVT*) [2, 9]. The half-value thickness, or half-value layer, is the thickness of the material that reduces the intensity of the beam to half its original value [10], viz, $N/N_o$is equal to 1/2.Moreover, N/N_o equal to 1/10 is called tenth-value thickness (*TVT*).Thus, from Lambert-Beer's law can be easily shown that:

$$HVT = \frac{ln2}{\mu_l} \cdots\cdots\cdots (7)$$

$$TVT = \frac{ln10}{\mu_l} \cdots\cdots\cdots (8)$$

The half or/tenth -value thickness increases linearly with gamma beam energy as seen in Fig.8. the good agreement The lower energy photons are more easily stopped in the attenuating material, so there are fewer photons reaching the detector. As the energy of the photons increase, they are able to penetrate the attenuator materials more deeply (see Fig.2), resulting in a higher *HVT*.

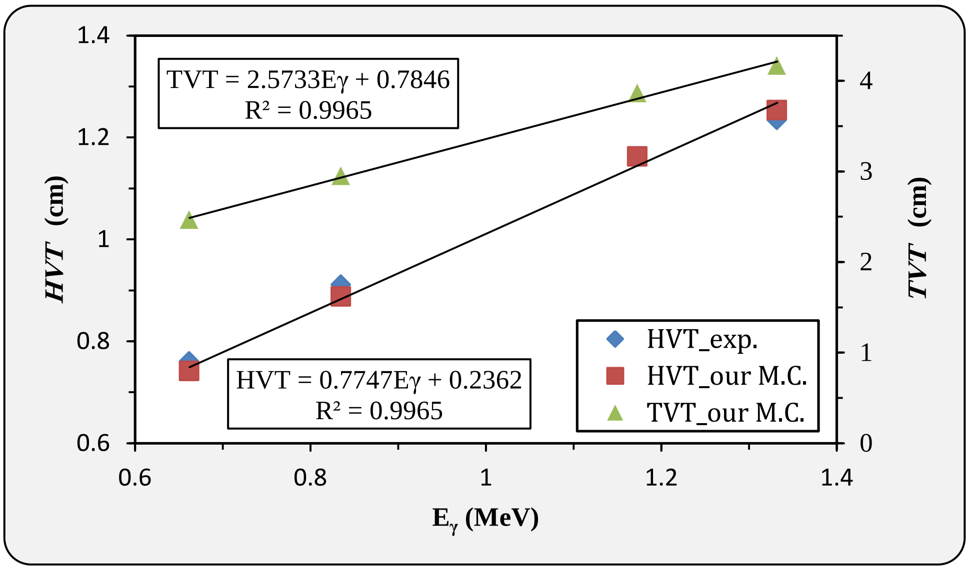

Fig.8: half and tenth -value thickness (*HVT)* and (*TVT*) for MCP-96 alloy vs. gamma ray energy.

The bulk density of the alloy reflects indirectly the structural condition and compactness of the alloy. Knowing the value of this parameter, gives information about porosity. As well-known, bulk density can be determined by taking the particle mass and volume of samples. The gamma-ray attenuation method represents one of the most used non-destructive tools to evaluate bulk density. By inverting the lambert-Beer's equation, the density of the sample can be determined:

$$\rho = \frac{1}{\mu_l x} ln\left(\frac{N_o}{N}\right) \cdots\cdots\cdots (9)$$

Based on eq. , the density curves of MCP-96 alloy as a function of thickness, from (1-4) cm, of alloy for each energy (662, 835, 1173 and 1332) keV were plotted in fig.9.

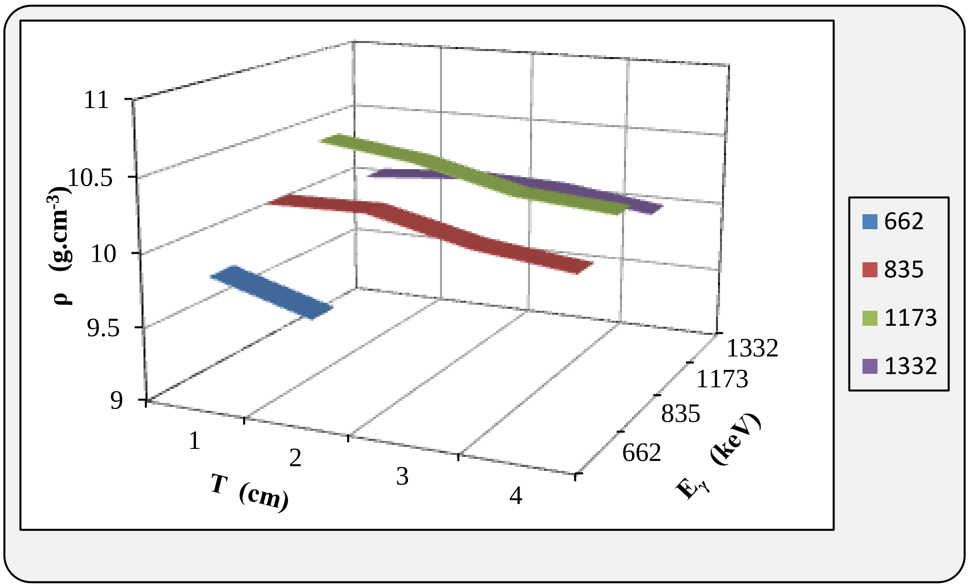

Fig.9: density distribution vs. thickness of alloy at particular energy.

The average value of density ($\rho_{av.}$) for each energy compared to experimental [2] and standard of 5N Plus Inc. [11] values were listed in the table-2-.

Table-2-: present work, experimental and standard vales of density for MCP-96 alloy per gamma ray energy.

E (keV)	ρ (g.cm^{-3})		
	Exp.	our M.C.	standard
662	9.72	9.545116	9.85
835		10.07515	
1173		10.30074	
1332		10.06592	
	$\rho_{av.}$= 9.99673		

In present simulation, MCP-96 alloy consists, exactly, of bismuth (52.5%), lead (32%), and tin (15.5%). That is to say, ideally, no pores. While, the difference of experimental density value about them of standard, as shown in table-2-, confirms that numbers of pores were formed during the experimental preparation process of the alloy. The porosity percentage can be calculated by [12]:

$$p\% = \left[1 - \left(\frac{\rho_a}{\rho_{th}}\right)\right] \times 100\% \cdots\cdots\cdots (10)$$

where: $\rho_a$and ρ_{th} are the actual (experimental) and theoretical density respectively.
Therefore, 1.32% and 2.76% of the porosity percentage of the experimental and simulated (ideal) alloys contributes in the error percentage of calculated density values.

Multiply the values of linear attenuation coefficient by density yields mass attenuation coefficient. In order to check the reliability of present work, obtained values of mass attenuation coefficient of MCP-96 alloy from present simulation were compared with mass attenuation coefficient calculated using XCOM program for energies ranging from 100 keV-10 MeV. From fig.10 it can be analyzed that our calculated mass attenuation coefficients of MCP-96 are in excellent agreement with XCOM program data. This gives confidence in our results for MCP alloy types.

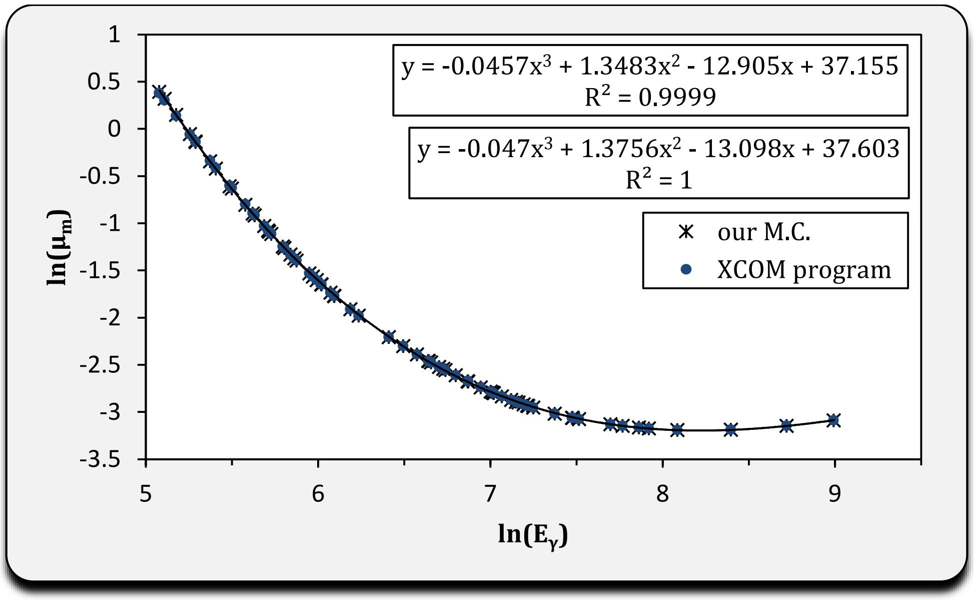

Fig.10: log-log axises of gamma energy vs. simulated (*) and calculated (●) values of mass attenuation coefficient for MCP-96 alloy.

4. Conclusions:

i. Gamma attenuation technique can be effective viable tool for studying some properties of alloys against gamma ray shield.
ii. The present simulation computer program was based on Monte Carlo method and gamma attenuation technique can be used as virtual computer experiment instead of the real experimental set up.
iii. The present simulation program can be characterized and quantified of various types of alloy.
iv. This technique can be utilizing as a densitometer system.
v. The present simulation program can be performs to design different experimental geometries.

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