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Performance of Nanoparticle Materials on Radiation Shielding Properties Using Mont Carlo Method

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ABSTRACT

This study aims to design types of shielding materials to protect public and personnel from the effect of ionizing radiation. In this study, the increment in mass attenuation coefficientsμ_m and linear attenuation coefficient $\mu$by using Lead nanoparticles material with chemical composition (93.69% Pb& 0.86% Al & 5.45% O) instead of bulk lead (Pb)and Iron (Fe) material have been investigated. Also the comparison of half value layer (HVL) for lead nanoparticles, bulk lead and Iron material was calculated. Mont Carlo simulation model (MCNP5) was provided to design a gamma radiation detector for comparison the gamma ray dose rate for Lead nanoparticles,bulk Lead and Iron material through different thickness of shield materials.It was found that Lead nanoparticles increased the amount of radiation absorbed in the material inside and as a result of which affected the radiation attenuation properties of material.The obtained result shows that mass attenuation coefficient depends on the photon energy, density of the materials and atomic number. From this study we notice that the valuesof $\mu_m$and $\mu$of Lead nanoparticles material are greater than bulk Lead and Iron material and also the values are decreasing with increasing the photon energy, and its HVL was less than bulk lead and Iron shield. The lead nanoparticles are also good shielding for gamma radiation, and it reduced the dose rate by using a smaller thickness of shield, it's less than bulk lead by (15%) and Iron materials by (30%), so it reduces the cost of the shield. The cost of lead nanoparticles reduces than cost of bulk lead by 33%. This study makes it clear that Lead nanoparticles can be beneficial to address the issues of radiation shielding cost effectiveness. Also showed that MCNP5 is an effective code on Nano size studies and standardized geometry can be useful for further investigations.

Keywords: *Radiation Shielding, Attenuation Coefficient, HVL, Monte CarloMethod (MCNP5), Nanoparticles, Gamma-ray dose rate*

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I.INTRODUCTION

In the recent years, the use of the radiation in the various energy ranges has been increased in different fields, like medical, industrial, agriculture, etc. To forestall radiation staff and population exposure to ionization radiation, public and working areas should be shielded and protected. For this reason, investigations and studies on radiation attenuation properties and designs of new complex materials as an attenuator material have been increasing in the field of radiation protection.

On the other hand, direct and in-direct scattered radiation can be hazardous for the people. The mentioned potential risk are overcome by applying three main fundamental concepts shielding, distance and time. The first of those processes namely shielding commonly depending on gamma-ray energy and price of material. The attenuation features of radiation for a specific target environment are required to determine the amount of shielding necessary [1,2]. The mass attenuation coefficient (μ_m) is one of the most important features for characterizing the penetration and diffusion of gamma-rays in target material [3].

On the other hand, the effectiveness of radiation shielding is described in terms of the half value layer (HVL), it is the thicknesses of attenuator that will reduce the incident radiation amount to half value, [4].

There are some basic principles for radiation shielding. Shielding is generally preferred due to its efficiency in intrinsically safe working conditions, whereas dependence on distance and time of exposure involves continuous administrative control over workers. The type and amount of shielding required depend on the type of radiation, the activity of the radiation source and the dose rate that is acceptable for outside the shielding material. However, there are other factors for choice of shielding material such as their cost and weight. An effective shield will result in a large energy loss in a small penetration distance without emission of more hazardous radiation. Furthermore, the good shielding material should have high absorption cross-section for radiation and at the same time irradiation effects on its mechanical and optical properties should be small[5,6]. A number ofexperimental and theoretical works have been performed on radiation shielding, which has large different application areas with different materials (e.g. concrete, semi- conductor, polymer, etc.) [7-10].

For shielding design, γ-ray is one of the main types of nuclear radiation, which have to be considered, since any shield that attenuates γ-rays will be more effective for attenuating other radiations. In principle, any material can be used for radiation shielding if it has a sufficient thickness to absorb the incident radiations to a safe level. Generally the ALARA principles are ensured by (i)Minimizing the time of an individual spend around radiationources. (ii) Staying far away from the radiation sources. (iii)By shielding the sources away from individuals and (iv) Acombination of all the three approaches or any two of them [11, 12].

Metal nanoparticles are small cluster of metal atoms with size less than 100 mm [13]. Nanomaterial have properties that are different from those of bulk materials. Most nanostructure materials are crystalline nature and have unique properties. The properties of nanomaterial are very much different from those at a larger scale. Two principle factors cause the properties of Nanomaterial to differ significantly from other material; (1) Increased relative surface area and (2) Quantum confinement effect.Although metal nanoparticles have been used in various scientific and other fields for some time, their physical and electronic properties are still not fully understood. The potential applications for metal nanoparticles include use in Nano electronics, electronics with components of nanometer scale. Recently, researchers are trying to reach a detailed understanding of the electrical properties of nanomaterial [14,15].

Studies of the prospects of application of lead nanostructures and shaped solids demonstrate that lead nanoparticles are capable to improve essentially either the ecological safety or the effectiveness of Nuclear power plants (NPP). Such improvements are based on development of units and devices for, operative differential monitoring of radiation flows inside active reactors zones for instantaneous detection of damages of fuel rod cladding inside nuclear reactors [16,17].

The objective of this study is to design the proper thickness and more efficient gamma rays shielding material in radiation research. For this purpose, Total mass attenuation coefficients were also calculated using MCNP5. The calculated values were used to estimate another parameter such as half-value thicknesses. For the comparison, linear and mass attenuation coefficients of Nanoparticles lead, bulk lead and Iron material have been calculated. The gamma-ray dose rate for three types of materials at different thickness were calculated.

II.RADIATION SHIELDING

A shield is a physical entity interposed between a source of ionizing radiation and an object to be protected which leads to reduce the radiation level at the position of that object. Lead is the most widely and effective material used as radiation shield because of its high density, large atomic number, high resistance to chemical corrosion and easy to fabricate. However lead is not common and is very expensive hence there is a limitation to its availability as radiation shield.

Gamma radiation shielding is the absorption and attenuation of gamma energy in shielding material. Most materials absorb the energy of gamma rays to some extent. The extent of attenuation depends on the density and thickness of the shielding material. A useful measure of shielding property is the mass per unit area of material. Hence a thick layer of a lighter material will have the same effect as a thin layer of a denser material. Radiation Shielding is used to reduce the radiation exposure to personnel and equipment in the vicinity of radiation sources. It is called biological and thermal shielding, respectively.

2.1 Radiation protection

The three basic methods used to reduce the external radiation hazard are time, distance, and shielding. Good radiation protection practices require optimization of these fundamental Techniques (ALARA).

2.1.1TimeThe amount of radiation an individual accumulates will depend on how long the individual stays in the radiation field.

2.1.2DistanceThe amount of radiation an individual receives will also depend on how close the Person is to the source.***2.1.3 Shielding***

When reducing the time or increasing the distance may not be possible, one can choose shielding material to reduce the external radiation hazard. The proper material to Use depends on the type of radiation and its energy.

2.2 General Safety Requirements

The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation. This objective must be achieved without unduly limiting the operation of facilities or the conduct of activities that give rise to radiation risks. Therefore, the system of protection and safety aims to assess, manage and control exposure to radiation so that radiation risks, including risks of health effects and risks to the environment, are reduced to the extent reasonably achievable. These Standards are based on the varioussafety principles stated in the Fundamental Safety Principles [IAEA], [18]:

The guiding principle throughout this manual is the ALARA Principle which demands that the doses received by workers and members of the public be kept As Low As Reasonably Achievable, social and economic factors taken into account.The dose limit for non-Nuclear Energy Workers and members of the public is 1mSv in one calendar year. The ALARA principle applies and every effort must be made to reduce the actual doses received by non-Nuclear Energy Workers to as low a level as possible [19].

2.3 Common Shielding materials

Making an appropriate and effective shielding against gamma- rays requires proper selection of materials and thickness. Choosing the right material for making protective shield interconnected optimality analysis are the weight, volume and cost considerations such as these. Most important characteristic of a material protection is its ability in attenuation of gamma radiation. In general, and heavy materials have higher ability in attenuation of gamma-rays. The design of a radiation protective shield will depend in addition on such factors as the type and characteristics of the radiation source, type of installation and the properties of the shield material.Lead: As one of the conventional gamma-ray shielding materials, it is the most widely used material. Principally, lead is effective at attenuating gamma-rays because of its high density and high atomic number. Lead shields are frequently used where space is limited or where only a small area of absorber is required.[13] There is a great variety in the types of shielding available both to protect people and to shield equipment and experiments.

III.MATERIAL AND METHOD

3.1. MCNP5 code

MCNP5 is a general purpose radiation transport code for modeling the interaction of radiation with materials and also tracks all particles at all energies. MCNP is fully three-dimensional and it utilizes extended nuclear cross section libraries and uses physics models for particle types [20]. Data libraries provided in MCNP contain information relating to the probability of unique particle interactions per elements used during simulation. In MCNP, a particle (neutron or photon) is randomly generated in the source volume and the path of the particle is tracked from its point of origin in the source to the point of its complete absorption in the detector or up to its point of escape from the detector. A large number of particles are generated and ultimate result is given as the average of all the successes. Depending on the number of particles generated, the error can be as small as desired by the user, given sufficient time to complete the calculation. MCNP5 has a wide range of applications in the fields of medical physics, reactor physics calculations, detector design and analysis, radiation shielding, reactor safety calculations and radiation dose estimates.Implementation of Mont Carlo computational code requires the preparation of an input file which depends upon the problem data. In this section, methods to calculation and conditions required to perform a calculation are described [21].

3.2 Method to analysis

MCNP5 is one of the most useful codes performing shielding calculations using Mote Carlo Method. Mont Carlo Modelling is a statistical method used here to simulate radioactive transfer by simulating photon interaction with a medium. Input file that is subsequently read by MCNP. This file contains information about the problem in areas such as geometry specification, the description of materials and selection of cross section evaluations, the location and characteristics of neutron, photon or electron source, the type of answers or tallies desired, and any variance reduction techniques used to improve efficiency. Before performing MCNP5 calculation, followings are required to get appropriate results: [22]

- ***Geometry of a simulation model***: to describe the geometry of model, it must be specify thecell and the surfaces that makeup the model.
- ***Material properties of structures***: the material composition of the cell is also specified in the geometry model.
- ***Radiation source***: we specify types of source to be simulated (neutron source or gammasource) and also the energy or activity of the source and direction at which the source emits particles.
- ***Tally***: it provides summery information to user related to particle interactions, collision,energy particles, radiation dose, particle flux and other useful information needed for problem analysis.
- ***Run the model***: this step determines the type of simulation being performed.

The MCNP diagram is seen in fig.1.a.

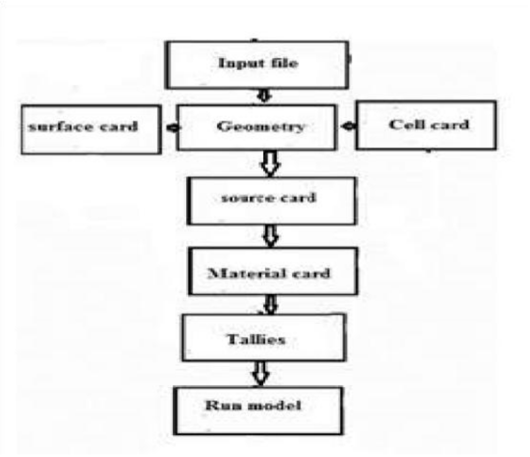

Fig. 1.a MCNP Geometry Model

3.3Simulation modelling of gamma detector

In this study, MCNP5 simulation model was written to simulate the transport of gamma-rays through the shield material. The gamma detector is modeled as spherical. A point isotropic source emitted photons surrounded by an Iron annular spherical shell 30 cm in thickness. The point detector was placed at a considering point 160cm away from the source to calculate the photon intensity (I). In our study, variables commanded source cell, energy, direction, source position respectively. On the other hand, one of important definition is material specification by considering atomic number, mass number and density (d) for pure elemental materials and atomic number, elemental mass concentrations and density for compounds or mixtures. By considering these variables, we defined firstly the Iron attenuator material, secondly the pure lead attenuator material and thirdly lead nanoparticles attenuator material with chemical composite that contains (93.69% Pb& 0.86% Al & 5.45% O) in input file respectively, the nanoparticles chemical composition is display in table 1. The Comparison between three materials Iron, bulk lead and lead nanoparticles at different thickness (5cm to 30cm) and energy range (0.8 MeV to 7 MeV) were also studied. The mass attenuation coefficients of Iron (Fe), bulk lead (pb), andlead nanoparticle have been calculated. Also the gamma- ray dose rate for Iron, lead as a bulk material and lead nanoparticle have been calculated. The total simulation geometry is seen in fig.1.b.

Table 1. Chemical composition of Nanoparticles, bulk lead and Iron material shield

Material shield	Weight %	Density g/cm^3
Lead nanoparticle:		ρ = 13.2
O	5.45 **%**	
Al	0.86 %	
Lead	93.69 **%**	
Bulk lead (Pb)	100%	ρ = 11.34ρ
Iron (Fe)	100%	= 7.87

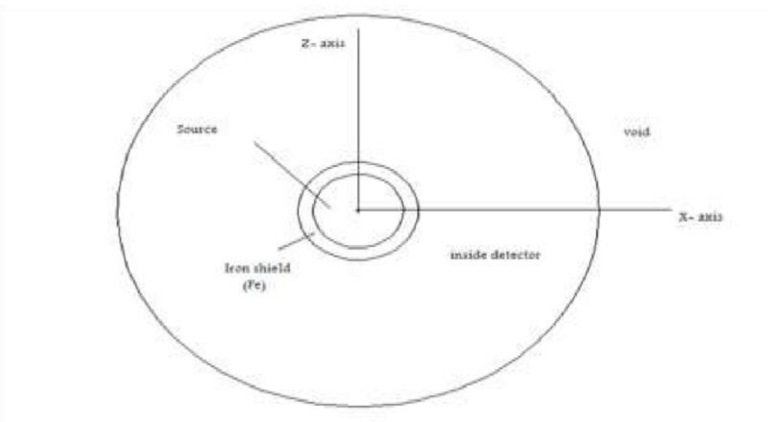

Fig. 1.b Geometry model of gamma detector

IV.RESULTS AND DISCUSSION

The mass attenuation coefficients and linear attenuation coefficient of Iron, bulk lead and Lead nanoparticles materials have been calculated at photon energies of 0.8 Mev to 7MeV. Comparison results were presented in table 2.Fromthis table, it is seen that using nanoparticles affected the increasing rate of the mass attenuation coefficients and linear attenuation coefficient in different rates on different energies. It is observed that mass absorption is inversely proportional with gamma energy and as the energy increases, effect of the nanoparticles has been observed increasingly.

Table2. Linear attenuation coefficient (cm^{-1}) and mass attenuation coefficient (cm^2/g) of Iron, bulk lead and leadnanoparticlesmaterials

Photon energy (MeV)	Iron material [23] $\rho = 7.87\ g/cm^3$		Bulk lead material [23] $\rho = 11.34\ g/cm^3$		Lead nanoparticles material $\rho = 13.2\ g/cm^3$	
	μ (cm^{-1})	μ_m (cm^2/g)	μ (cm^{-1})	μ_m (cm^2/g)	μ (cm^{-1})	μ_m (cm^2/g)
0.8	0.517	0.065	1.016	0.089	1.139	0.089
1	0.459	0.058	0.811	0.071	0.928	0.075
3	0.252	0.032	0.407	0.035	0.496	0.038
5	0.199	0.025	0.407	0.035	0.465	0.038
7	0.173	0.021	0.409	0.035	0.456	0.036

Theeffectiveness of gamma ray shielding is described in terms of (HVL) of Lead nanoparticles, bulk lead and Iron material as showed in table 3. The HVL is the thickness at which an absorber will reduce the attenuation to half. The lower value of HVL is the better of the radiation material in terms of thickness requirements. From this table we noticed that the HVL for lead nanoparticles is less than in bulk Lead and Iron material, also it increases with energy increase.

Table 3. Half value layer (HVL) of Iron, bulk Lead and lead nanoparticles materials At energy range 0.8 MeV to 7 MeV

Poton energy (MeV)	Iron material (23) $\rho = 7.87\ g/cm^3$	Bulk lead material (23) $\rho = 11.34\ g/cm^3$	Lead nanoparticles material $\rho = 13.2\ g/cm^3$
	HVL (cm)	HVL (cm)	HVL (cm)
0.8	1.46	1.17	0.91
1	1.64	1.31	1.10
5	3.39	1.67	1.47
7	3.66	1.61	1.58

Fig. 2 and fig. 3represent the comparison of linear attenuationcoefficient(μ)and mass attenuation coefficient (μ_m) values at energy range from 0.8 MeV to 7 MeV for Lead nanoparticles with another shielding materials common in reference bulk Lead and Iron material. In fig. 2 the results showed an inverse relationship betweenthe linear attenuation coefficient and the energy range. At low energy, the linear attenuation coefficient decreases rapidly, whereas it decreases slowly at high energy and the attenuation of leadnanoparticles is higher than the attenuation of bulk lead and Iron material. While in fig. 3 the comparison of mass attenuation coefficient for lead nanoparticles, bulk led and Iron materials at different energy were presented. From this curve we notice that the mass attenuation coefficient is dependent on the energy of gamma ray, and also the type of material effect on the mass attenuation coefficient. Where it is observed that the mass attenuation of nanoparticles is higher than in bulk lead and Iron materialand it is decreasing with the energy increase.Therefore, for an improved shielding effectiveness, a small thickness of lead nanoparticles would be required.

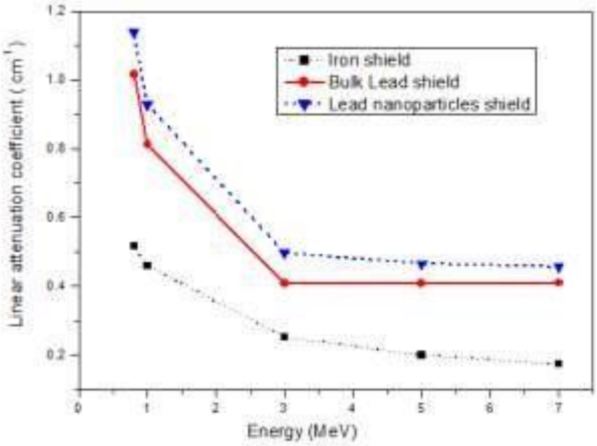

Fig. 2 Comparison of linear attenuation coefficient of gamma ray according energy range for Iron, Lead and lead nanoparticle

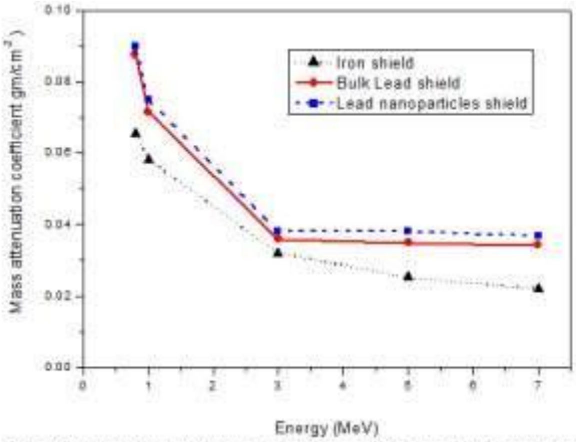

Fig. 3 Comparison of Mass attenuation coefficient of gamma ray according energy range for Iron, Lead and Nanoparticle

The plotting of variation of Ln (I_o/I) with material thickness for Lead nanoparticles, Iron and bulk Lead at shield thickness from 5 cm to 30 cm at energy 7 MeV were shown in fig. 4. From this figure, it is clear that the relation gives the straight line. Also we have seen that the value of Ln (I_o/I) is increasing with the shield thickness is increasing. And the relation value of lead nanoparticles is higher than in bulk lead and iron material.

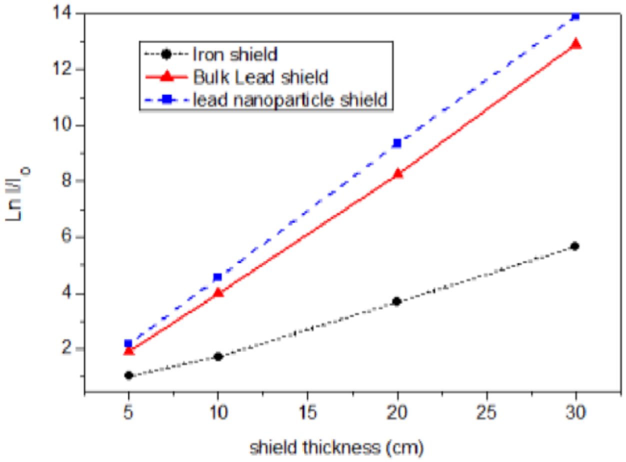

Fig. 4. A plot of ln I_o / I against thickness for Iron, Lead and lead nanoparticles at energy 7 MeV

Table 4.Displayed the comparison of gamma dose rate for lead nanoparticles, bulk lead and Iron material at different shield thickness [5 cm to 30 cm]. From this table we notice that the gamma dose rate is decreasing with

increasing the shield thickness, also the gamma dose rate for lead nanoparticles is higher than in bulk lead and Iron shield.

Table 4. Comparison of gamma- ray dose rate for Iron, bulk lead and lead nanoparticles shield at different thickness

Shield thickness (cm)	Dose rate(µSv/hr)		
	Iron material ρ = 7.87 g/cm^3	Bulk lead material ρ = 11.34 g/cm^3	Lead nanoparticles material ρ = 13.2 g/cm^3
5	2.1231E-17	8.8105E-18	6.7230E-18
10	1.0652E-17	1.1097E-18	6.2786E-19
15	3.0233E-18	1.3132E-19	5.6814E-20
20	1.5052E-18	1.5711E-20	5.2685E-21
25	3.7523E-19	1.8845E-21	3.976E-22
30	2.0711E-19	1.5006E-22	3.7038E-23

Fig.5 represents the comparison of gamma ray dose rate for bulk lead, Iron material and investigated material lead nanoparticles at different thickness of shield material (5cm to 30 cm). In this fig. we noticed that, the gamma ray dose rate is decreasing with the shield thickness increasing. It is observed that the value of gamma ray dose rate for nanoparticles is lower than in bulk lead and Iron shield. We notice that the values is decreasing slowly in Iron material but it is decreasing rapidly in both bulk lead and nanoparticles shield.

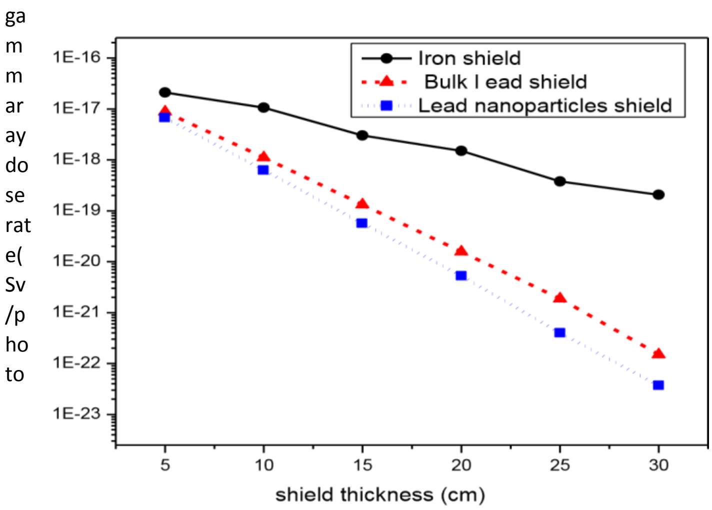

Fig. 5. Comparison of gamm ray dose rate for Lead nanoparticles, bulk lead and Iron material through shield thickness

The comparison of gamma ray dose rate for three different materials at various energy were presented in fig. 6. From this fig. we notice that the dose rate is increasing with the increasing of energy and the values are close in low energies then it far at high energies. Also the values of gamma dose rate for lead nanoparticles is lower than in bulk lead and Iron shield.

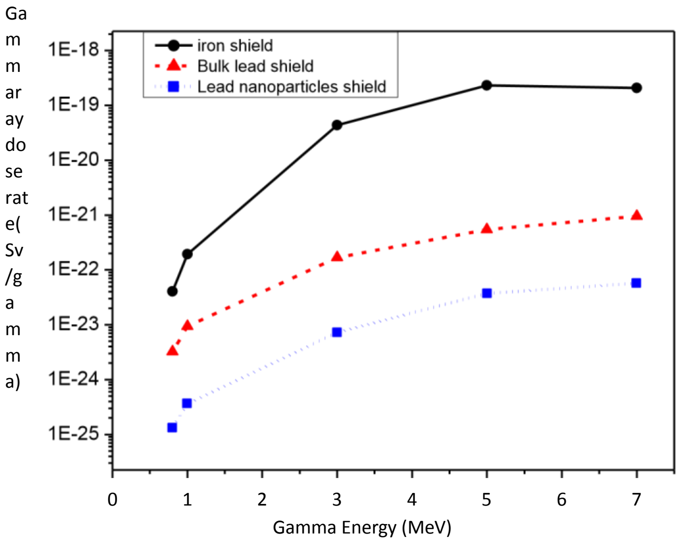

Fig. 6. Comparison of gamm ray dose rate versus gamma energy for lead nanoparticles, bulk lead and Iron shield material

The comparison of gamma dose rate for lead nanoparticles, bulk lead and Iron shield material at shield thickness was displayed in table 5. From this table we notice that the value of dose rate at thickness 10 cm of lead nanoparticles is approximately the same value at 15 cm of bulk lead and 30 cm of Iron shield. This means that we can use a small thickness of shield material to attenuate the same value of dose rate, so the nanoparticles is important for the cost of the shield material.

Table 5. Comparison oflead nanoparticle, bulk lead and Iron shield thickness at the same value of gamma ray dose rate

Dose rate (μSv/hr)	Shield thickness (cm)		
	Lead nanoparticles material at 10 cm	Bulk lead material at 15 cm	Iron material at 30 cm
	6.2786E-19	1.3132E-19	2.0711E-19

It is observed that the shielding thickness with leads nanoparticles is less than the shielding with bulk lead by relation:

Thickness of bulk lead = Thickness of lead nanoparticles * 1.5

Also the cost of shielding with bulk lead 0.265 (1/4") thick is 39.89 $ and the cost of (1/2") thick is 79.60$ [24].Wecan calculate the shielding with lead nanoparticles from previous relation. So the thickness from lead nanoparticles which will use to reduce the samevalue of dose rate with bulk lead will be0.17"that less than thick 0.265" and 0.33" less than 0.50", then the costwill decreases to 26.59$ and 53.06$ by using lead nanoparticles. Table 6. Shows the comparison between the cost of lead nanoparticles and bulk lead. From this table it is observed that the percentage of cost reduction for lead nanoparticles is reducing than bulk lead by33%.

Table 6. Comparison between the cost of lead nanoparticles and bulk lead

Bulk lead		Lead nanoparticles		% of Cost reduction byNanoparticles
Shield thickness	The cost	Shield thickness	The cost	
0.26" 0.50"	39.89 $ 79.60 $	0.17" 0.33"	26.48 $ 53.06 $	33% 33 %

V. CONCLUSIONS

Radiation protection and choice of appropriate materials has become one of the major research topics.The selection of attenuator materials for radiation shielding mostly depends on the amount of radiation, type of radiation and energy of radiation. In this study, we studied thePerformance of nanoparticles materials on radiation shielding propertied using Mont Carlo method. During the first step of our study, MCNP-5 geometry model was design. This work presents a methodology to determine mass attenuation coefficients for Iron, bulk Lead and lead nanoparticles materials to be used as gamma ray shield and the gamma ray dose rate at different shield thickness.The results is concluded that:

- The shielding properties of lead nanoparticles are more effective than bulk lead and Iron materials, where the thickness is less than bulk lead and Iron. This means that less weight and also save the cost and good shielding.
- Also, the Iron and bulk lead used in the gamma detector can be replaced with lead nanoparticles where 10 cm for lead nanoparticles is equivalent to 30 cm of Iron and 15 cm of bulk lead with the same function.
- The gamma ray dose rate decreases with increasing the shield thickness, and the lead nanoparticles absorbed the amount of gamma ray dose rate more than the bulk lead and Iron.
- The cost of the thickness from lead nanoparticles which will use to reduce the same value of dose rate with bulk lead will be decreases to 26.59$ and 53.06$ by using lead nanoparticles and the percentage of cost for lead nanoparticles is reducing than bulk lead by 33%.

So we can conclude that Nanoparticles are considered cost effective and less space consuming shielding material against gamma radiation.Also effect of Nano-sized in shield material can be used for better shielding in different application fields such as industrial and medical radiation areas. On the other hand, this study showed that the standardized geometry for Monte Carlo simulation can be applied for possible future studies on Nano-sized particles.

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