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MCNPX and GEANT4 simulation of γ-ray polymeric shields

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Abstract. In this work, the shielding ability of a polymeric compound with gadolinium for gamma radiation has been investigated. The conceptual calculation of radiation attenuation and energy absorption as a function of different Gd percentages and the calculation of total compound density are performed using MCNP and GEANT4. It is found that, 2 mm of the compound can reduce up to 5% and 50% of 1 MeV and 50 keV γ-rays respectively. Both Monte Carlo tools are in a good agreement.

Keywords. Polymeric shield; MCNPX; GEANT4.

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1. Introduction

The growing trend of nuclear technology requires more research and development in radiation protection technology to protect the workers from ionizing radiation. Also, there are instruments with sensitive components that need to be protected, for example the electronic components under exposure of radiation sources and cosmic rays. For astronomic applications [1,2] and many other applications, using common materials may lead to some limitations, while polymeric compounds can be promising candidates in nuclear shielding [1–6].

In this work, we study photon attenuation and energy deposition in a polymeric compound with different gadolinium percentages and different total densities. The calculations are conducted for energies of 50 keV, 500 keV and 1 MeV as three typical photon sources using MCNPX [3,7–10] and GEANT4 [6,10–13] Monte Carlo tools.

Monte Carlo simulation tools play important roles in radiation shielding calculations, However, both methods need benchmarking with experimental or standard data. Monte Carlo method using statistical techniques may give precise results (less statistic error) but with discrepancies in the experiment [14,15]. Therefore, in the standpoint of nuclear

Table 1. The atomic fraction of the elements.

Element	Atomic fraction in the compound (%)
H	32–37
C	15–17
O	25–27
Si	13–16
Gd	8–16

safety to evaluate the reliability of MCNPX and GEANT4 results for the new materials, the same calculations were conducted for lead and tungsten which are two commonly used shielding materials, and the results are compared with ANSI/ANS [16] standard data.

2. Materials and method

The high-Z elements like lead and tungsten are widely used as pure materials or mixed with other compounds to attenuate γ-rays. But, in this work, to attenuate thermal neutrons as well, we have considered gadolinium as additive to the polymer because of its large cross-section for thermal neutron [10]. The following calculations were performed for different atomic percentages of gadolinium. Table 1 presents the atomic fraction of the elements as it was defined for MCNPX and GEANT4 input materials. The density of the compound varies from 2 to 9 g/cm^3.

The geometry consists of a slab as shield with a surface area of 10 cm$\times$10 cm and various thicknesses in front of a monodirectional point source.

MCNPX (2.4.0) outputs are tallied by f1 and f6 for surface current and energy deposition respectively. Photonuclear production has been included using KAERI and LA150 photonuclear data libraries and ENDF60 and NJOY for neutron interaction.

In GEANT4, photon and neutron libraries were implemented using EMLOW6.19 and G4ENDL3.14 respectively. The neutron interactions are considered by means of G4NeutronHP-dataset in the PhysicsList.

As mentioned before, Monte Carlo results need benchmarking against experimental or standard data. Table 2 shows the comparison between the mass attenuation coefficient values (μ/ρ) of lead and tungsten for five typical photon energies obtained from MCNPX/GEANT4 and ANSI/ANS standard data. It is emphasized that in MCNPX and GEANT4 calculations, MCPLIB02 [17] and NIST [18] data libraries were used respectively. However, both Monte Carlo tools use standard data with regard to their libraries but the method of calculation is based on the probability of occurrence of an event that causes discrepancies presented in table 2.

3. Results and discussion

Polymers as hydric compounds are used to slow down neutrons but they are not useful for γ-rays attenuation. To make these compounds applicable for γ-ray, a high-Z element like the previously discussed gadolinium has to be added to the compound. In the following, the attenuation of γ-rays is calculated for different atomic percentages of gadolinium and

Table 2. The mass attenuation coefficient (μ/ρ) of lead and tungsten for five photon energies obtained from MCNPX, GEANT4 and ANSI/ANS [16].

	Lead (ρ =11.3 g/cm^3)			Tungsten (ρ = 19.3 g/cm^3)		
Energy (MeV)	MCNPX	GEANT4	ANSI/ANS (cm^2/g)	MCNPX	GEANT4	ANSI/ANS
0.05	7.8	7.25	8.04	5.77	5.3	5.9
0.5	0.101	0.113	0.1614	0.09	0.108	0.1378
1	0.086	0.0612	0.071	0.049	0.047	0.066
2	0.052	0.056	0.046	0.029	0.034	0.044
10	0.056	0.0478	0.0497	0.032	0.037	0.047

total compound densities. The importance of increasing the density was also investigated. The calculations were conducted for 50 keV, 500 keV and 1 MeV incident γ-rays.

Figure 1 shows the calculated attenuation of 50 keV photons vs. the compound thickness based on MCNPX results. The percentages of gadolinium are 4.3% with a total density of 2 g/cm^3, 8.3% with two densities of 3 and 9 g/cm^3 and 15.4% with a density of 9 g/cm^3. As one can see, a thickness of 2 mm attenuates 45%, 70% and 90% of 50 keV photons corresponding to 4.3%, 8.3% and 15.4% gadolinium respectively. The importance of density was illustrated in this figure too. The filled triangle represents lower gadolinium (8.3%) with higher density (9 g/cm^3) and 100% attenuation while the empty triangle represents higher percentage of gadolinium (15.4%) but lower density (4.5 g/cm^3) and 90% attenuation.

In this figure, the attenuation of gadolinium-free compound was given for comparison. The line with star symbol represents the gadolinium-free compound with density the same as the compound represented by the filled triangle (9 g/cm^3) and shows 30% attenuation for 2 mm thickness.

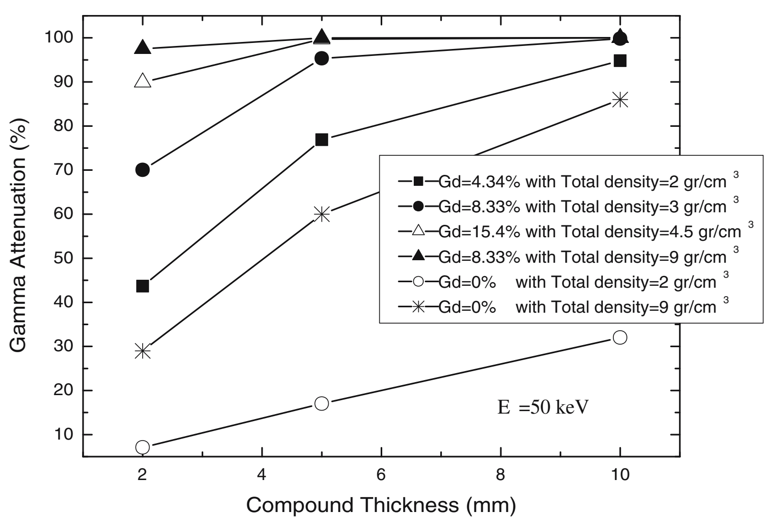

Figure 1. Attenuation of 50 keV γ-rays vs. thickness for different gadolinium atomic fractions and total compound densities.

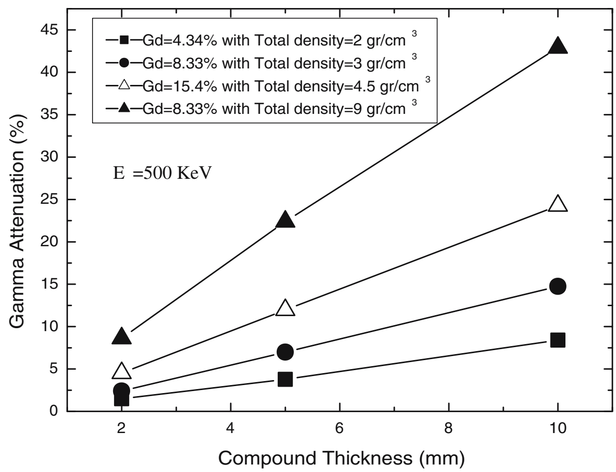

Figure 2. Attenuation of 500 keV γ-rays vs. thickness for different gadolinium atomic fractions and total compound densities.

Figure 2 shows attenuation of 500 keV γ-rays in terms of thickness based on MCNPX results. Accordingly, 2%, 2.5% and 5% attenuation can be achieved by 2 mm thickness corresponding to 4.3%, 8.3% and 15.4% gadolinium. In this figure, the importance of the density also is illustrated. 8.3% gadolinium with higher density attenuates two times more than the compound with 15.4% gadolinium with lower density corresponding to the lines with filled triangle and empty triangle respectively.

Figure 3 depicts the attenuation of 1 MeV γ-rays in terms of the thickness based on MCNPX results. As one can see, the maximum attenuation of 2 mm thickness is 4% corresponding to the density of 9 g/cm^3 shown by filled triangle. One can conclude that the desirable attenuation for 1 MeV γ-rays is achievable by a few centimetres.

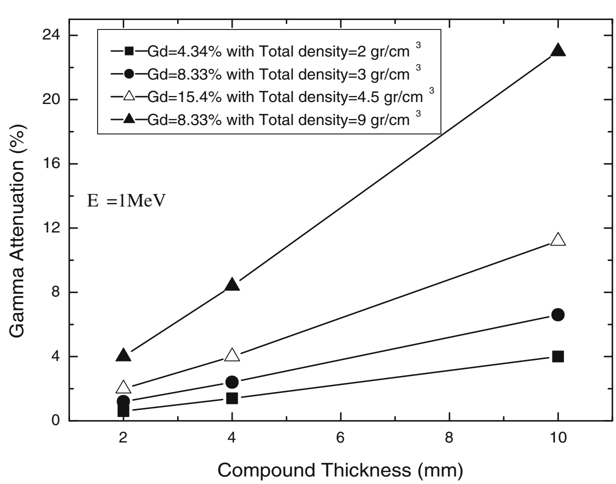

Figure 3. Attenuation of 1 MeV γ-rays vs. thickness for different gadolinium atomic fractions and total compound densities.

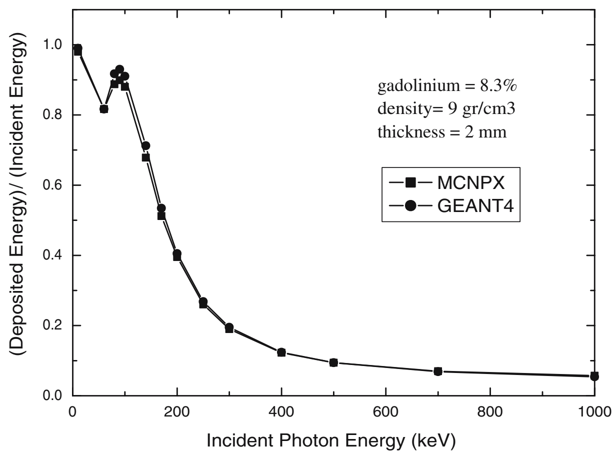

Figure 4. Total absorbed energy vs. incident gamma energy.

As an important parameter in shielding calculation, the total deposited energy in the materials was investigated. The deposited energy in the compound with 2 mm thickness is shown in figures 4 and 5 for gamma and thermal neutron respectively. The results were obtained from MCNPX and GEANT4 based on 8.33% gadolinium with 9 g/cm^3 density corresponding to the line with filled triangle in the previous figures.

Figure 4 shows the ratio of the total photon energy deposited to the photon source energy as a function of source energy from 10 keV to 1 MeV. As shown in this figure, by increasing the incident photon energy, the deposited energy in the compound will decrease with respect to an interrupt around 90 keV as the absorption edge. The simulation clearly shows an enhancement in photoelectric interaction at this energy. This figure also shows less than 5% discrepancy between MCNPX and GEANT4 at absorption edge.

Figure 5 shows the ratio of the total energy deposited by the neutrons to the incident neutron energy as a function of incident neutron energy from 100 eV to 1 MeV. This figure

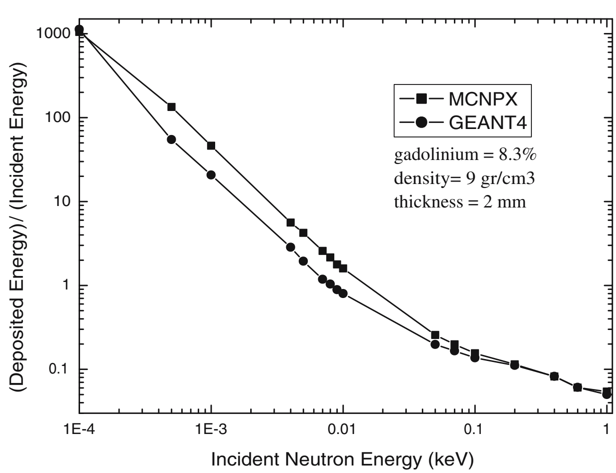

Figure 5. Total absorbed energy vs. incident neutron energy.

illustrates the large values of total energy deposition for low neutron energies contributed by γ-rays produced in neutron inelastic scattering. As one can see, 100 eV neutrons deposit energy up to 0.1 MeV which is equal to 10^3 times of their primary energies, while 1 MeV neutrons deposit 0.05 MeV energy. There is discrepancy between MCNPX and GEANT4 results.

4. Conclusion

The agreement between MCNPX and GEANT4 results for γ-ray attenuation in a typical polymeric compound was investigated. In the nuclear safety point of view, this agreement may give the reliability required in designing polymeric shields for γ-rays. But, it is emphasized that there are complementary studies in this field. For example, the secondary particle produced, the thermal properties, the damage and change in properties in the mentioned compounds due to continuous irradiation have to be studied in detail.

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