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Assessment of the mass attenuation coefficients of granite, basalt, andesite and tuff stones with the Geant4 model of a high-purity germanium detector

A AŞKIN[1],* and M DAL[2]

[1]Mechatronics Engineering Department, Munzur University, Tunceli, Turkey
[2]Civil Engineering Department, Munzur University, Tunceli, Turkey
*Corresponding author. E-mail: aliaskin@munzur.edu.tr

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Abstract. In this work, the radiation shielding properties of various natural stones, such as granite, basalt, andesite and tuff, were determined by using Monte-Carlo simulations performed with the Geant4 model of a high-purity germanium (HPGe) detector. Mass attenuation coefficients were calculated for γ-ray energies of 80.9, 140.5, 356.5, 661.6, 1173.2 and 1332.5 keV and for the sample thicknesses between 1 and 7 cm. The results of this study indicate that the stone samples have lower mass attenuation values varying in the range from −28.8% to −3.7% compared to lead. Among the measured stone samples, the mass attenuation values of tuff stone are closest to lead (above 661.6 keV).

Keywords. Mass attenuation coefficient; Geant4; Monte-Carlo simulation; high-purity germanium; natural stone.

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1. Introduction

The benefits of nuclear technology are widely used in places such as nuclear power plants, radiology departments of hospitals and nuclear research and accelerator centres. One drawback of this useful technology is that the level of exposure of radiation for the personnel and other human beings living in close vicinity of these places must stay below the permissible dose limit. Thus, it is expected that the materials used for the construction of the areas employing nuclear technology must decrease the intensity of γ radiation effectively to protect individuals against the possible hazardous effects of ionising radiation. Mass attenuation coefficient is a substantial parameter defining the penetration and diffusion of γ-rays within the material. This parameter is commonly used to decide whether a material is suitable to block γ-rays. Thanks to its high density, lead is widely used as a shielding material against γ radiation. Because of the large dimensions of the areas where radiation shielding is necessary, the use of lead can be very expensive. Thus, concrete and other materials are used to increase the thickness of the walls. Various experimental studies are conducted to determine the mass attenuation coefficients of different construction materials in order to understand whether these materials can fulfil the needs to block γ-rays. Among these materials, concrete is one of the most widely used construction materials and when used as a γ attenuator, concrete has numerous advantages [1]. Thus, experimental studies were performed to determine the mass attenuation coefficient of ordinary concrete [2] and marble-added concrete [3]. In addition to concrete, mass attenuation coefficients of other construction materials used in Jordan such as ceramic, granite, bricks, concrete and limestone were determined by Awadallah and Imran [4]. Mass attenuation coefficients of various construction materials, such as sand, cement, bricks and tiles, used in Turkey were measured experimentally by Damla *et al* [5]. Gaikwad *et al* [6] and Karaipekli and Sarı [7] experimentally measured the mass attenuation coefficients of some fatty acids which can be used as phase change materials in building material applications. Mass attenuation coefficient of economical high-performance heavy concrete produced with colemanite and galena minerals is investigated by Mortazavi *et al* [8]. Mass attenuation coefficients of 107 different marble samples from Turkey were experimentally investigated by

Cevik *et al* [9]. As an alternative to the experimental techniques, Monte-Carlo simulations can be used to determine the mass attenuation coefficients of the building materials. Monte-Carlo methods are more flexible and provide an easy way to estimate the radiation interaction parameters. MNCP-X and FLUKA models of a NaI(Tl) detector were used to realise Monte-Carlo simulations to estimate the mass attenuation coefficients of ordinary concrete [10,11] and the results were compared with the values from XCOM [12] database. The calculated results from both studies are in good agreement with the XCOM data. Mass attenuation coefficients of concrete, bricks, cement plaster and the effects of barite, which is used as an additive in bricks, on the mass attenuation were determined using Monte-Carlo simulations with the MCNP-X model of NaI(Tl) detector [13]. γ-Ray shielding properties of a polymeric compound with gadolinium were investigated by using Monte-Carlo simulations made with the Geant4 and MCNP-X simulation toolkits [14]. In this study, the mass attenuation coefficients of grey granite from the Bergama district of Izmir city, basalt from the Aliaga district of Izmir city, andesite from the Golbasi district of Ankara city and tuff from the Seydiler district of Afyonkarahisar city were determined by performing Monte Carlo simulations with the Geant4 model of a HPGe detector.

2. Materials and methods

2.1 *Theoretical background*

When a beam of γ-ray photons passes through a material, the intensity of the incident beam shall be attenuated according to the Beer–Lamberts law as given in

$$I = I_0 \cdot e^{-\mu \cdot x}, \tag{1}$$

where I_0 and I are the incident and attenuated photon intensities respectively, x (cm) is the thickness of the material and μ (cm^{-1}) is the linear attenuation coefficient of the sample. In order to measure the incident photon intensity, measurements are run first without the sample between the source and the detector. Attenuated photon intensities were calculated for different material thicknesses placed between the source and the detector. $\ln(I_0/I)$ is plotted vs. the thickness of the sample. The slope of a linear fit to these data gives the linear attenuation coefficient, μ. The mass attenuation coefficient, μ_m ($cm^2\,g^{-1}$), of a material is calculated by using

$$\mu_m = \mu/\rho, \tag{2}$$

where ρ is the density ($g\,cm^{-3}$) of the absorbing material.

2.2 *Monte-Carlo simulations*

In this work, the model of a HPGe detector was coded into Geant4 to carry out Monte-Carlo simulations for the estimation of mass attenuation coefficients of the natural stones. Geant4 is a Monte-Carlo simulation toolkit used for the systems for high-energy, nuclear, accelerator, medical and low-energy physics applications. Geant4 is based on the object-oriented C++ programming. The Geant4 kernel manages runs, events and tracking of passages of particles through matter [15]. It allows users to simulate all aspects of an experimental set-up such as the geometry of a detector, primary particle generation of events, types of particles and physics processes such as electromagnetic, hadronic and decay physics that manage particle interactions. It provides information about the energy, momentum and particle track at each step of the interaction of particles within matter. In this work, the simulated detector geometry is based on the HPGe detector produced by the Canberra semiconductors. The core of the detector consists of a 2.2 kg HPGe crystal installed as an ionisation detector. The crystal is a p-type semiconductor crystal that was grown in a closed-ended coaxial orientation. It is 82 mm in diameter and 81.5 mm in height. The core cavity of the crystal has 10.5 mm diameter and 62.5 mm height. The detector has a 1 mm thick copper endcap window placed 6.3 mm from the top of the germanium crystal. The thickness of the crystal dead layer is 0.8 mm. Figure 1 shows the Geant4 model of the HPGe detector geometry. A few very thin and small parts such as crystal dead layer, infrared radiation (IR) windows made of mylar and kapton and signal contacts are not distinguishable in this picture.

As shown in figure 2, the detector and the γ-ray source were surrounded by a 5 cm thick lead shield. A stone sample was placed between the source and the detector. γ-Rays emitted by the source are collimated by a lead collimator, attenuated by the sample and again collimated and detected by the detector. Thanks to the use of narrow beam geometry and lead collimator, counting of the scattered photons as a part of the transmitted beam is decreased. Therefore, the systematic uncertainties in the measurements are minimised [16].

The mass attenuation coefficients of stone samples were determined for stone thicknesses varying from 1 to 7 cm and for γ-ray energies of 80.9, 140.5, 356.5, 661.6, 1173.2 and 1332.5 keV. The source was defined as a spherical point source. The type, energy, direction and position of particles are user-defined parameters that are input into Geant4. γ-Rays with the aforementioned energies were emitted directly onto the stone samples. The geometry, chemical composition, mass fractions and densities of the stone samples were coded into Geant4 as well. The values used for the stone

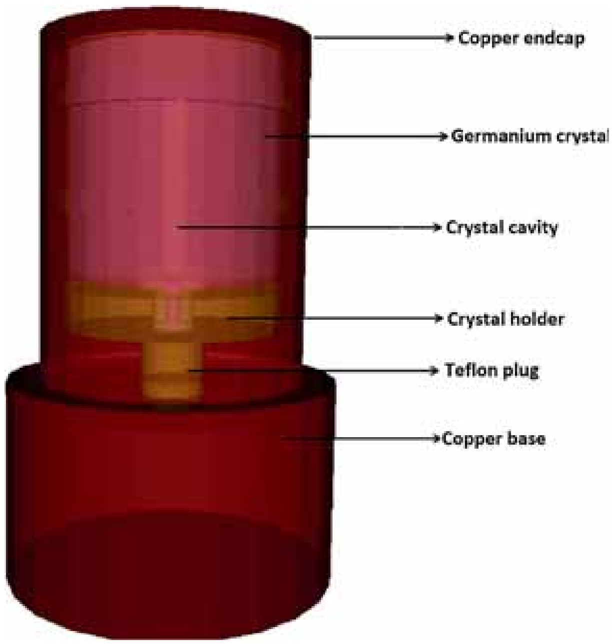

Figure 1. Geant4 model of the HPGe detector used for determining mass attenuation coefficient.

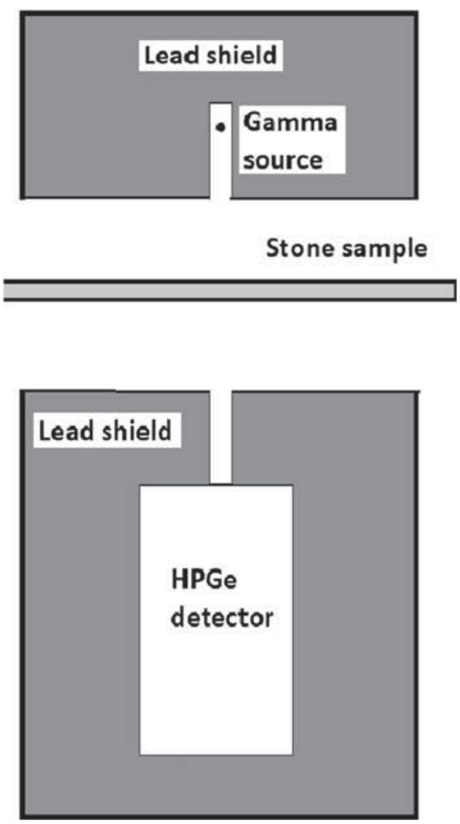

Figure 2. Schematic diagram of the Geant4 set-up.

samples are shown in table 1. Prior to performing the measurements of the stone samples, mass attenuation coefficients of lead were determined with the Geant4 model of HPGe detector and compared with the existing experimentally calculated values to validate the geometry and for the benchmarking of the calculated results.

3. Results and discussion

In order to validate the Geant4 model of HPGe detector, the mass attenuation coefficients of the lead sample were calculated for the γ-ray energies of 661.6, 1173.2 and 1332.5 keV in the present study. In table 2 the calculated mass attenuation values of lead are compared with the previously determined experimental values [19]. The deviations in the obtained results with respect to the experimental data were calculated according to

$$D = \frac{R_E - R_p}{R_E} \times 100, \tag{3}$$

where R_E is the experimentally determined mass attenuation coefficient of lead and R_P is the results from the present study.

The calculated mass attenuation values for the lead sample from this study are in agreement with the experimental results. This proves the reliability of the Geant4 model of HPGe detector and the reliability of the results from the Monte-Carlo simulations. The estimated mass attenuation values for the grey granite, basalt, andesite and tuff samples are presented in table 3. Mass attenuation values decrease with the increasing γ energy. This is because the high-energy γ's have more penetration and diffusion ability within the material. The plot shown in figure 3 compares the calculated results for all four types of stone samples. As can be seen from table 3 and figure 3, the basalt has the highest mass attenuation value at 80.9 keV. This is due to the higher ratio of Fe_2O_3 compound in the basalt. High atomic number of Fe is an important factor for blocking the low-energy γ-rays. At low energies, photoelectric absorption is the dominant interaction mechanism and the cross-section of the interaction is proportional to Z^4/E^3, whereas for the γ-ray energies starting from 661.6 keV, the tuff sample has the highest mass attenuation values. This can be explained by the higher ratio of SiO_2 in the tuff sample compared to the other samples. If the mass attenuation values of the stone samples are compared with the experimentally determined mass attenuation values of lead, stone samples have lower mass attenuation between −28.8% and −18.1% at 661.6 keV, between −18% and −8.9% at 1173.2 keV and between −28.3% and −3.7% at 1332.5 keV. The lowest differences are observed in the values calculated for the tuff sample.

Table 1. Chemical compound and mass fractions (%) of grey granite (density $= 2.74\ g\ cm^{-3}$), basalt (density $= 2.72\ g\ cm^{-3}$), andesite (density $= 2.63\ g\ cm^{-3}$) [17] and tuff (density $= 2.4\ g\ cm^{-3}$) [18] samples.

Compound	Grey granite	Basalt	Andesite	Tuff
SiO_2	66.25	57.25	62.10	73.50
Fe_2O_3	4.15	9.30	6.0	0.52
CaO	3.80	6.50	3.40	0.85
MgO	2.10	3.50	0.40	0.11
Na_2O	3.30	2.80	4.40	3.78
Al_2O_3	15.0	15.20	16.50	14.70
K_2O	3.90	2.50	2.70	5.70
TiO_2	–	–	–	0.06

Table 2. Calculated mass attenuation coefficients (μ_m) of lead (density $= 11.3\ g\ cm^{-3}$) and comparison with the previously determined experimental values.

	μ_m ($cm^2\ g^{-1}$)		Deviation (D) (%)
Energy (keV)	Present work	Experimental values	
661.6	0.096 ± 0.0065	0.091 ± 0.0070	−5.2
1173.2	0.063 ± 0.0028	0.064 ± 0.0050	1.6
1332.5	0.053 ± 0.0027	0.061 ± 0.0084	15.0

Table 3. Calculated mass attenuation coefficients (μ_m) of natural stones from Turkey.

	μ_m ($cm^2\ g^{-1}$)			
Energy (keV)	Grey granite	Basalt	Andesite	Tuff
80.9	0.191 ± 0.007	0.216 ± 0.006	0.195 ± 0.005	0.192 ± 0.005
140.5	0.138 ± 0.003	0.138 ± 0.003	0.123 ± 0.003	0.138 ± 0.003
356.5	0.0965 ± 0.0033	0.0957 ± 0.0034	0.0927 ± 0.0034	0.0900 ± 0.0036
661.6	0.0682 ± 0.0036	0.0648 ± 0.0036	0.0669 ± 0.0038	0.0745 ± 0.0041
1173.2	0.0556 ± 0.0043	0.0540 ± 0.0044	0.0525 ± 0.0045	0.0583 ± 0.0046
1332.5	0.0534 ± 0.0048	0.0437 ± 0.0047	0.0532 ± 0.0049	0.0587 ± 0.0050

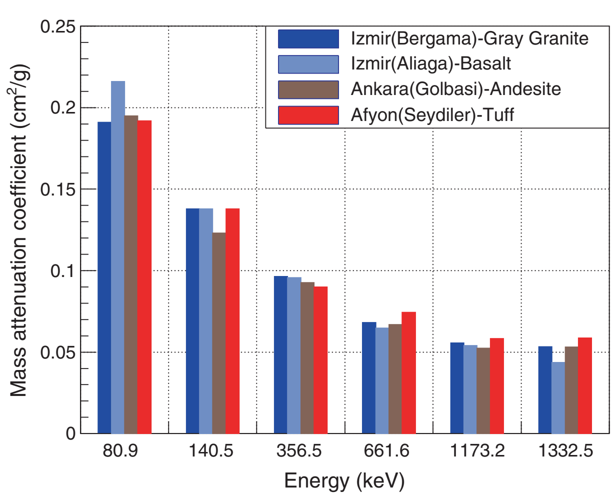

Figure 3. Comparison of the mass attenuation coefficients calculated for the stone samples.

4. Conclusion

A Geant4 model of an HPGe detector is used for the first time to perform Monte-Carlo simulations in order to numerically obtain the mass attenuation coefficients of the naturally occurring materials. This study proves that the Geant4 model of an HPGe detector is reliable to estimate the mass attenuation coefficients of grey granite, basalt, andesite and tuff stones originating from different cities in Turkey. Since the mass attenuation coefficients of these special stones have not been determined previously, the results of this study are important to show the shielding potential of these stones against γ-rays. The results of this study indicated that the tuff stone has the highest mass attenuation value (above 661.6 keV) and these values are close to the experimentally determined values for lead. Thus, tuff stone can be used as a shield against γ-rays and can be an economical alternative to lead. Slightly thicker grey granite, basalt and andesite can also be used to block γ-rays. As Monte-Carlo simulations are flexible methods, the Geant4 model of an HPGe detector can be employed to determine the mass attenuation coefficients of not only the naturally occurring materials but also the composites or synthetically developed and produced materials.

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