NUCL SCI TECH (2017) 28:95
DOI 10.1007/s41365-017-0253-4

Simulations of mass attenuation coefficients for shielding materials using the MCNP-X code

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Received: 24 June 2016 / Revised: 29 September 2016 / Accepted: 9 October 2016 / Published online: 30 May 2017

Abstract In this paper, mass attenuation coefficients of concrete, bricks and cement plaster, as shielding materials, are calculated at 59.5, 356, 662, 1173, 1274 and 1333 keV by using the MCNP-X (version 2.4.0) code. The numerical simulation results are compared with previous Monte Carlo studies, experimental results and XCOM data. The effects of barite on mass attenuation coefficients are investigated. The mass attenuation coefficients increase with the barite content. Thus, our results agree well with experimental studies on gamma ray shielding of barite. It is flexible for the MN method to change the barite rates in material by small increments, which is experimentally difficult. Also, modeled geometry can be used for future approaches such as new designs and new structures especially in investigating new barite-containing materials to build nuclear reactors or high-energy radiation therapy facilities.

Keywords Monte Carlo simulation · Gamma ray attenuation · Barite ($BaSO_4$)

1 Introduction

Nowadays, radiations of different energies are widely used in medicine, nuclear technology and industry. On the other hand, direct and scattered radiations can be hazardous to human health. Therefore, it is an important issue to study radiation protection properties and new materials. This potential risk can be overcome by three main procedures: time, distance and shielding. The third has been allowing new materials usage and various investigations for better radiation protection.

The shielding method is related to gamma ray energy and charge of related material [1]. By comparison with some other structure materials used in radiation areas, concrete has numerous benefits as an attenuator material [2]. Also, there are some other building materials such as bricks and cement plaster [3]. Alternatively, manufacture of concrete with different types of aggregates such as barite ($BaSO_4$) is important for radiation protection and new shielding material approaches [4].

The study of barite concrete as an attenuator material for nuclear reactor constructions was started in the USA [5]. Photon attenuation coefficients of barite-containing concrete were studied by Akkurt et al. [6]. Gamma ray attenuation coefficient of barite concrete was studied by Bouzarjomehri et al. [7]. Ling et al. [8] studied X-ray shielding properties of cement mortars prepared with different types of aggregates. Barite effect on radiation shielding of cotton–polyester fabric was studied by Akkurt et al. [9]. Gamma and neutron attenuation properties of barite–cement mixture were studied by Picha et al. [10].

The MCNP (-4B or -4C) code has been popular in simulating radiation attenuation of various materials and aggregates. Using the MCNP code, Sharifi et al. [11] simulated shielding properties of some materials and compared the results with experimental results; Shirmardi et al. [12] studied attenuation properties of barite concretes and lead by comparing the simulation results with XCOM and experimental data; and Singh et al. investigated mass

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attenuation coefficient for some polymers by using Monte Carlo method [13]. Unlike the oldest versions, MCNP-X uses nuclear data charts to transport protons and physics models to transport 30 extra particle types (alphas, pions, muons, etc.), and it can mix and match data charts and models of physics due to problem definition [14].

The usage of new library in MCNP-X made us to compare our results with previous data obtained with MCNP-4C. In this paper, barite shielding effect is simulated with the MCNP-X code for γ-rays from ^{241}Am (59.5 keV), ^{133}Ba (356 keV), ^{137}Cs (662 keV), ^{22}Na (1274 keV) and ^{60}Co (1173 and 1333 keV). The six isotopes and their gamma rays have a wide range of applications. The results are compared to experimental data [15] reported in the literature and XCOM [16] data. Availability of modeled geometry for radiation attenuation studies of barite-containing building materials is discussed.

2 Materials and methods

2.1 MCNP-X simulation code

MCNP-X is a general code used for modeling interactions of radiations with materials and tracking all particles at all energies. Being fully three dimensional, it utilizes extended nuclear cross-sectional libraries and uses physics models for particle types [17]. Availability of MCNP-X on detection efficiency for different experimental and Monte Carlo studies was reported by Akkurt et al. [18]. Tekin et al. [19] used MCNP-X for dose distribution studies. Initially, we modeled the same geometric data as the experiment in Ref. [20]. As a variance reduction technique, the mother volume cell was optimized by considering total simulation area to reduce statistical error and unnecessary particle tracking in simulation. Figure 1 shows schematically the modeled geometry for the simulation using MCNP-X. The gamma rays are collimated by the lead shielding, attenuated by the sample, collimated again and detected by the detector.

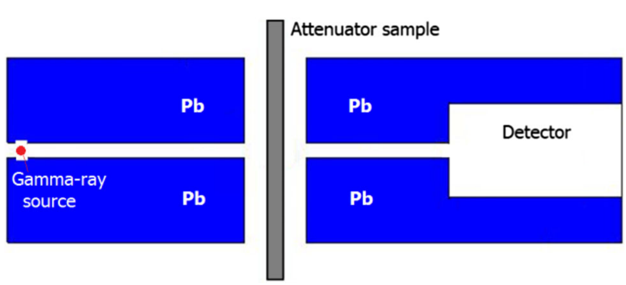

Fig. 1 (Color online) Schematic view of the MCNP-X simulation geometry

The gamma ray sources and their features were defined in data card section of MCNP-X input by considering different variables, each variable having different abilities in the simulation. In the present study, our variables commanded source cell, energy, direction, source position and particle type. The sample material was specified by the atomic number, mass number, elemental mass fraction (for compounds or mixtures) and density. So, material definitions of samples of brick, concrete and cement plaster were defined in input file. The elemental compositions [21] by mass fraction of the building material samples are given in Table 1. Densities (ρ) of sample materials ranged from 1.52 to 2.26 g/cm^3. Samples of the three kinds, in certain thicknesses from 1 to 7 cm, were simulated with gamma rays of the six energies. The average cell flux tally F4 was used during the mass attenuation coefficient calculation.

2.2 Gamma ray attenuation properties sentence

The interaction of radiation with matter is of importance in medical, radiobiology and some other applied sciences. The probability of photon interaction by one physical process or another per unit distance traveled is called the linear attenuation coefficient, μ_l. The mass attenuation coefficient $\mu_m = \mu_l/\rho$ is used [22] in the Lambert–Beer's law: $\mu_m\, x = \ln\,(I_0/I)$, where I_0 and I are the incident and attenuated photon intensity, respectively, and x is thickness of the sample slab.

2.3 Validation of MCNP-X

As a validation of modeled MCNP-X simulation geometry, the mass attenuation coefficients for building materials of bricks, cement and concrete were calculated at 59.5, 356, 662, 1173, 1274 and 1333 keV. The results were compared with previous MCNP-4C results by Ali [15], and with XCOM and available experimental data [21]. Figure 2 shows mass attenuation coefficients of the bricks, cement and concrete samples.

Table 1 Elemental mass fractions of concrete (ρ = 2.26 g/cm^3), bricks (ρ = 1.92 g/cm^3) and cement plaster (ρ = 1.52 g/cm^3)

Elements	Concrete	Bricks	Cement plaster
O	0.492	0.504	0.468
Na	0.005	0.001	0
Mg	0.003	0.001	0.006
Al	0.037	0.041	0.062
Si	0.370	0.387	0.301
Ca	0.082	0.065	0.114
Fe	0.011	0.001	0.049

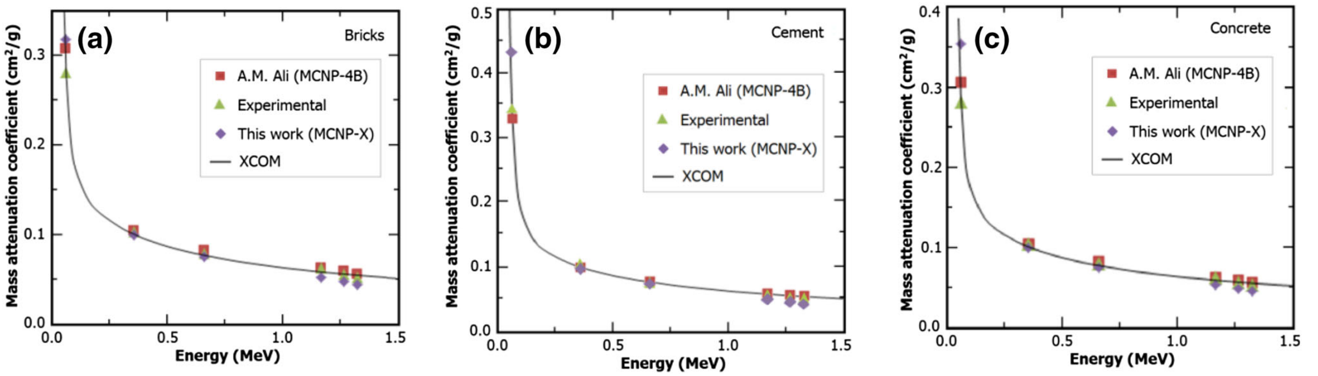

Fig. 2 (Color online) Mass attenuation coefficients of brick (**a**), cement (**b**) and concrete (**c**) samples

The mass attenuation coefficients decrease with increasing gamma energies, and the MCNP-X simulation results agree well with the MCNP-4C and experimental data, and the XCOM calculation results. The MCNP-X simulation results have relative error of less than 0.1%.

3 Results and discussion

Using MCNP-X, we simulated radiation attenuation properties of barite-containing bricks sample. Mass attenuation coefficients of the bricks sample simulated with MCNP-X code were compared with available data in the literature. Although the mass attenuation coefficients agreed well with other results, it can be seen in Fig. 2 that accordance of the results decreased with increasing energy. Henceforth, investigation of barite effect was simulated by changing just the material contents, i.e., barite rates in bricks sample. The validated MCNP-X simulation geometry was used for calculating the mass attenuation coefficients of bricks added with different rates of barite (0, 25, 50, 75 and 100%), at photon energies of 59.5, 356, 662, 1173, 1274 and 1333 keV.

The simulated mass attenuation coefficients of the barite-added brick samples, as a function of gamma ray energy, are shown in Fig. 3a. The mass attenuation coefficients increase with the concentration of barite in the samples and decrease with increasing photon energy. Each curve has two slopes, due to the dominance of fractional interaction processes in energy regions under consideration.

Figure 3b shows the mass attenuation coefficients versus weight fraction of barite in the brick samples at photon energies of 356, 662, 1173, 1274 and 1333 keV. While they decrease with increasing photon energy and increase with the barite weight fraction, the mass attenuation coefficients can be expressed by linear regression equations, with excellent correlation coefficient R^2. In this study, low-energy photons could not be transmitted through the barite-added sample; therefore, no data were obtained in simulation, and the photon energy of 59.5 keV was not considered in barite-added bricks calculation.

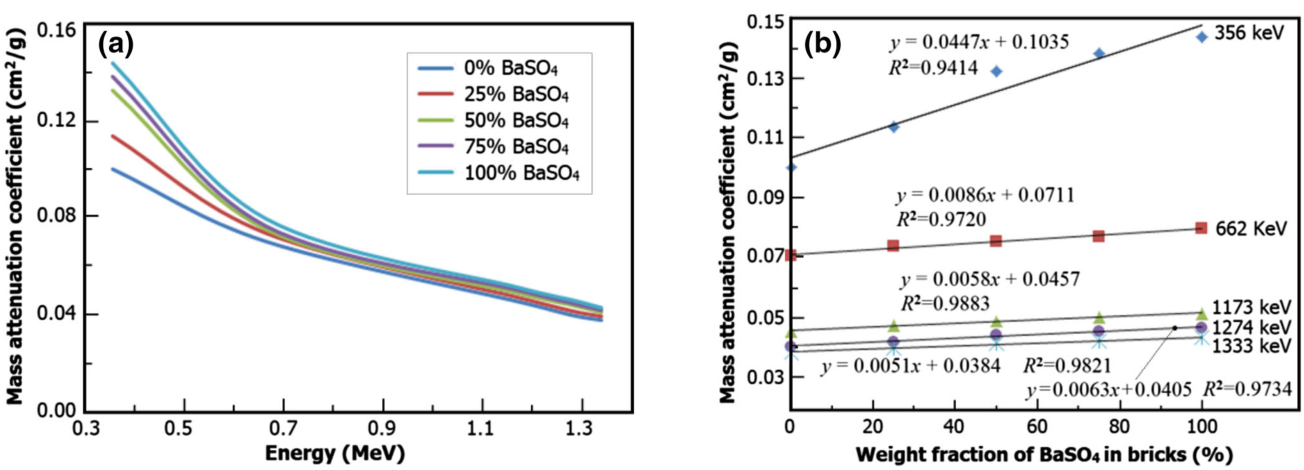

Fig. 3 (Color online) Mass attenuation coefficients of different composites as a function of **a** energy and **b** barite weight fraction

The use of barite in different materials has some advantages. The effects of barite have been investigated by different groups. Akkurt et al. [23] reported that radiation shielding properties of concrete were affected by chemical media and barite was advantageous in this regard. Bouzarjomehri et al. [7] reported that barite concrete was the most suitable mixture for high-energy radiotherapy rooms. On the other hand, brick is one of the most used construction material in different types of structures. Considering the barite's advantages on radiation protection, this study investigated the effect of barite on radiation attenuation properties of bricks, confirming that barite-added bricks, with enhanced radiation attenuation properties, are suitable building material for the medical radiation environments.

4 Conclusion

The MCNP-X code, and other Monte Carlo codes, can be applied to predict the mass attenuation coefficients for different attenuator and energies and can be an alternative method for experimental method, due to their flexibility and convenience in defining geometry. It can be also concluded that modeled geometry can be used for future approaches such as new designs and new structures, especially where no analogous experimental data exist for investigating building materials used in nuclear reactors and high-energy radiation therapy facilities. This standard geometry can be utilized for studying shielding effects of barite in different shielding materials.

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