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Photon and neutron shielding features of quarry tuff

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ABSTRACT

The shielding characteristics of quarry tuff (cantera) against photons and ^{241}AmBe neutrons, were determined. The effective atomic number of cantera, the Exposure and the Energy absorption buildup factors for photons in cantera were also calculated. The XCOM code was used to calculate the photon interaction coefficients. Also, Monte Carlo method was used to model a photon transmission experiment in cantera. Collided and uncollided photon fluence, Kerma in air, and Ambient dose equivalent were estimated. With the uncollided photon fluence the linear attenuation coefficients were determined and compared with those calculated with the XCOM code. The linear attenuation coefficient for 0.662 MeV photons was compared with the coefficient measured with a NaI(Tl)-based γ-ray spectrometer and a ^{137}Cs source. The Monte Carlo model was also used to estimate the neutron spectra of ^{241}AmBe neutrons in function of cantera thickness, the Effective and the Ambient dose equivalent for the collided and uncollided neutrons. Cantera has good shielding properties for low energy photons and poor shielding features against ^{241}AmBe neutrons.

1. Introduction

Nuclear radiation is widely used in several fields; its applications increase constantly because in the interaction with matter radiations produce a desired effect or useful and unique information. The common factors in these applications are the radiation source and the need to use radiation protection protocols where shielding is a compulsory item (Narici et al., 2017; Sayyed, 2016).

Among the applications of gamma radiations are to sterilize, food processing, medical diagnostics and therapy, elemental analysis, to evaluate the weld integrity in pipes or vessels working with high pressures, etc. Here, is important to avoid the radiation exposure using the adequate shielding (Kaur et al., 2016).

The prompt gamma neutron activation analysis (PGNAA) requires a neutron source and its shield, the sample to be analysed and a gamma-ray spectrometer. In this application neutrons produced by ^{252}Cf, ^{241}AmBe or 14 MeV neutron generator are used. In this application the shielding must deal with neutrons and gamma-rays. In the aim of maximize the neutron moderation and minimize the gamma-rays from the ^{252}Cf source, and those produced in the sample through (n, γ) reactions Hadad et al. (2016) designed the shielding using Monte Carlo methods.

Nuclear well logging tools are used in the oil logging industry to measure the porosity formation and the element concentration. In this application a neutron source is used requiring a compact shielding. A compact shielding tank, for a 0.67 TBq ^{241}AmBe source, was designed using Monte Carlo method. Anywhere outside the tank the total dose rate was less than 0.025 mSv/h (Zhang et al., 2017).

Efforts to determine the shielding features of different materials are constantly reported (El-Khayatt et al., 2014; El-Khayatt, 2017). The shielding characteristics of building materials (Singh et al., 2014; Mann et al., 2013), ores (Oto et al., 2015), glass (Kaewjang et al., 2014), plastics and polymers (Mann et al., 2015), and concrete with different aggregates (Waly and Bourham, 2015; Oto et al., 2016) have been carried out. In these works the shielding features were concerned about the effective atomic number, the effective electron density, the half value layer (HVL), the energy absorption and exposure buildup factors, the linear attenuation

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coefficient (μ), and the mass attenuation coefficient (μ_m) for photons. The characterization has been carried out through measurements, calculations or combining both procedures. Singh et al., (2014) also include the shielding features against neutrons of building materials.

Concrete is a material widely used in the construction industry, also it is used as biological shielding because is effective to attenuate X-rays, γ-rays, and neutrons. Hormirad™ is a high-density concrete whose shielding features against ^{241}AmBe neutrons were studied through measurements and Monte Carlo calculations (Gallego et al., 2009). Neutron shielding features on NGS-concrete, polymer and standard cements mortars have been also reported (Piotrowski et al., 2015a, 2015b). Here, the half and the tenth-value layer were evaluated. Another features related with the shielding characteristics of materials are the Exposure Buildup Factor (EBF) and the Energy Absorption Buildup Factor (EABF). Wally et al. (2016) have studied the γ-ray shielding characteristics of different compositions of glasses having higher content of PbO and Bi_2O_3 which have better shielding properties in comparison to concrete. However, the EBF for these glasses is very large in comparison to concrete. Glasses made with higher concentration of silicon have EBF and EABF similar to the building factor than concrete (Mann, 2017). In the case of polymers and tissue substitute materials, the EBF and the EABF for low energy photons remain constant, whereas both building factors tend to increase with increasing penetration depths (Kurudirek and Ozdemir, 2011).

Soils and locally-abundant materials (dolomite, gypsum, igneous rock and lime stone), have been studied to be used as shielding. All samples have the same shielding effectiveness for 0.30–3.0 MeV photons, and it is related with the effective atomic number. Studied soils can be used for low-cost shielding as they are abundant (Mann et al., 2012).

Tuffs are volcanic rocks made of an ash matrix with grain sizes ranging from fine clay minerals up to silt-sized material. Quarry tuffs are mostly soft and porous rocks used as building stones and for artwork because can be easily cut and reworked. Volcanic tuff stones are in different colours, they are used as covering materials for insulating and ornamental purposes on the exterior and interior of buildings (López-Doncel et al., 2016; Wedekind et al., 2013; Degerlier, 2013; Turhan et al., 2015). In the construction industry the quarry tuff (hereinafter referred to as cantera) is used to coat the interior and exterior wall surfaces of buildings and houses avoiding the use of paint. Its use is part of the Mexico's stone heritage being present in pre-Hispanic, Colonial and modern architecture (Pérez et al., 2014). A radiometric analysis of this material from Turkey has been reported (Degerlier, 2013; Turhan et al., 2015), being in mostly of cases safe. In Mexico there are several cities where the cantera is widely used; however, its features to shield neutrons, X-or-γ photons are unknown, therefore in facilities with cantera hosting X-ray units or γ-ray sources cantera is not accounted for shielding design or evaluation.

The aim of this work was to determine the shielding characteristics of cantera. For 0.03, 0.07, 0.1, 0.3, 0.662, 1, 2, and 3 MeV mono-energetic photons, the linear attenuation coefficient (μ), and the mass attenuation coefficient (μ_m) were calculated using Monte Carlo methods and the XCOM code (Berger et al., 2015). The effective atomic number (Z_{eff}), the EBF, and the EABF were also calculated for various photon energies and depth penetrations. The relative transmission of Kerma in air, K_a, and the ambient dose equivalent, $H^*(10)$, was also determined. For 0.662 MeV photons, the calculated μ was compared with the μ measured with a NaI (Tl)-based γ-ray spectrometer and a ^{137}Cs source, using a narrow beam geometry. The neutron spectrum, the $H^*(10)$, and the effective dose for rotational geometry (E_{rot}) of ^{241}AmBe neutrons were also calculated.

Obtained information could be useful in the shielding evaluation in constructions using cantera as the main building material or as decorative complement in walls of facilities having X-ray equipment, γ-ray sources or ^{241}AmBe neutron sources.

2. Materials and methods

From the local market a large piece of cantera was purchased and it was cut in 10x10 cm pieces with different thickness, ranging from 1 up to 40 cm. Each piece was weighted to determine the density, being 1.8 ± 2% g cm^{-3}. Other pieces were selected to measure the chemical composition using Energy Dispersive X-ray Fluorescence technique with a spectrometer PANalytical, model Epsilon3-XL. Measurements were replicated five times using different pieces.

Cantera, is mainly composed by SiO_2, Al_2O_3, K_2O, Na_2O, Fe_2O_3, and CaO, being in agreement with the chemical composition reported by Celik and Ergul (2015). Due to the total alkali (Na_2O + K_2O) versus silica (SiO_2) composition, this quarry tuff is Rhyolite (Celik and Ergul, 2015; Le Bas et al., 1992).

2.1. Calculations

The elemental concentration, in weight fraction, of cantera was calculated being O (0.4604%), Si (0.2476%), Al (0.1022%), C (0.0651%), Fe (0.0509%), K (0.0459%), Na (0.0156%), Mg (0.0074%), and Ca (0.0049%). These data were used to calculate the shielding features against photons. Calculations were carried out with the XCOM and the MCNP5 (X-5 Monte Carlo Team, 2003) codes.

2.1.1. XCOM

With the XCOM code the partial mass interaction coefficients and the total mass attenuation coefficients, for 10^{-3}–10^{5} MeV photons, were calculated for cantera.

2.1.2. Effective atomic number

The effective atomic number (**Z_{eff}**) of cantera, for 1.5E(-2) to 20 MeV photons, was calculated using Eq. (1).

$$Z_{eff} = \frac{\sum_i f_i A_i \mu_{mi}}{\sum_i f_i \frac{A_i}{Z_i} \mu_{mi}} \tag{1}$$

here, f_i is the atom fraction, Z_i is the atomic number, A_i is the atomic mass, and μ_{mi} is the total mass attenuation coefficient (μ/ρ) of the *i*th element in cantera.

2.1.3. Buildup factors

The Exposure and Energy absorption buildup factors, EBF and EABF respectively, for cantera were calculated for 0.015–15 MeV photons, and for penetration depths ranging from 0.015 to 40 mean free paths (mfp). Calculations were carried out using the Geometric-progression fitting parameters (G-P) for the elements in the cantera taken from the ANS (1991). Buildup factors for cantera were calculated using the five-parameter fitting formula for mixtures and compound reported by Harima et al. (1991) shown in Eqs. (2) and (3).

$$B(E,x) = \begin{cases} 1 + \frac{b-1}{K-1}(K^x - 1) & \text{for } K \neq 1 \\ 1 + (b-1)x & \text{for } K = 1 \end{cases} \tag{2}$$

$$K(E,x) = cx^a + d\frac{\tanh\left(\frac{x}{X_k} - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \qquad \text{for } x \leq 40 \text{ mfp} \tag{3}$$

here, **E** is the photon energy, **x** is the penetration depth in mfp units, and **a**, **b**, **c**, **d** and **X_k** are the G-P fitting parameters. The value of