INVESTIGATION ON GAMMA INTERACTION WITH WATER, CONCRETE, CO-FREE STEEL, PB AND UO_2

VISHWANATH PRATAP SINGH [1], GUNJAN GANGWAR [2], NAGAPPA MALLIKARJUN BADIGER [1]

[1] Department of Physics, Karnatak University, Dharwad, India
[2] Central Inland Fisheries Research Institutes, Allahabad, India
e-mail: kudphyvps@rediffmail.com

Abstract

Shielding materials used in nuclear reactors have to fulfil the requirements regarding their structure, shielding properties, cooling properties, etc. In present analysis, we have investigated radiation interaction parameters with water, concrete, Co-free steel, Pb and UO_2. Gamma ray interaction parameters viz. mass attenuation coefficients, effective atomic numbers and effective electron density have been calculated for energy range 1 keV to 100 GeV. Using these parameters, gamma ray shielding effectiveness was discussed. The investigation would be very useful in shielding performance assessment of materials in nuclear reactors.

Keywords: *Shielding, Reactor, Uranium, Water, Co-free steel*

Introduction

The gamma ray shielding efficiency is characterized by attenuation of photons in a material. The attenuation of gamma ray is described by linear attenuation coefficient (μ) or mass attenuation coefficient (μ/ρ) of the material for particular photon energy. Higher the values of attenuation coefficients, better is shielding efficiency. In addition to mass attenuation coefficient, effective atomic number (Z_{eff}) and effective electron density (N_{eff}) are other parameters expressing the shielding efficiency. Various studies on interaction of photon with materials are available in the scientific community [1-4].

Gamma radiation is often involved in investigation from nuclear technology, medical applications and industry. High efficient shielding materials are required to maintain low ambient radiation level and improve the level of radiation protection. The shielding materials for gamma ray radiation should be high atomic number elements, compounds or mixture. Various types of radiation shielding materials have been investigated for suitability and are in use in nuclear industries [5-11].

Interaction of photon with a material is dependent mainly on partial photon interaction process such as photoelectric effect, Compton scattering and pair production. These partial interaction processes are dependent on photon energy and atomic number. For a compound or mixture, the partial photon interaction processes depend upon atomic numbers of all the elements. The effect of atomic number will be investigated at different energies.

The objective of present study was to evaluate the shielding efficiencies of water, concrete, Co-free steel, Pb and UO_2 by using mass attenuation coefficients, effective atomic numbers and effective electron densities for photon energy ranging 1 keV to 100 GeV, their variation with energy being also discussed.

Theoretical basis of investigation

Concrete, steel lead and water are commonly used materials for construction of nuclear reactor containment, biological shielding and cooling fluid. These materials are also selected due their properties of providing shielding against radiations. Natural Uranium (UO_2) is used as a fuel material for power production in nuclear reactors. In present study, investigation on gamma ray interaction with water, concrete, Co-free steel [12], Pb and UO_2 is considered, in order to evaluate shielding effectiveness.

The photon intensity through a medium follows the attenuation law $I = I_0 e^{-\mu t}$, where I and I_0 are transmitted and initial photon densities, μ is linear attenuation coefficient and t is the thickness of medium.

Mass attenuation coefficients

The mass attenuation coefficient of a compound or mixture is calculated using the mixture rule [13], $\mu_m = (\mu/\rho) = \sum_i^n w_i (\mu/\rho)_i$, where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of *i-th* element. Proportion by weight is given by the relation $w_i = n_i A_i / \sum_j^n n_j A_j$ with the condition $\sum_i^n w_i = 1$, where A_i is the atomic weight of *i-th* element, n_i is the number of formula units in a compound or composite materials, n_j and A_j are the atomic density and the atomic weight of the *j-th* element. The μ/ρ value of individual element are according to National Institute of Standard Technology and were found using WinXcom program [14].

Effective atomic numbers

Effective atomic number of a compound or mixture is described in literature [15]. Total atomic cross-section (σ_t) for a compound or mixture is obtained using total mass attenuation coefficients by the following relation:

$$\sigma_t = \frac{\mu_m M}{N_A} \tag{1}$$

where $M = \sum_i^n n_i A_i$ is the molecular weight of a compound or mixture and N_A is the Avogadro's number.

Effective atomic cross section (σ_a) of a compound or mixture is calculated by using the equation:

$$\sigma_a = \frac{1}{N_A} \sum f_i A_i \left(\frac{\mu}{\rho}\right)_i \tag{2}$$

where f_i denotes the fractional abundance of the element i with respect to the number of atoms.

Effective electronic cross-section (σ_e) of a compound or mixture is calculated by the following equation:

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_a}{Z_{eff}} \tag{3}$$

with $\sum_i^n f_i = 1$, Z_i the atomic number of *i-th* element, and Z_{eff} the effective atomic number of the compound or mixture, given by the relation:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{4}$$

Effective electron density

The effective electron density of a compound or mixture is given by the following relation:

$$N_{eff} = \frac{N_A}{M} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \tag{5}$$

The effective atomic numbers and effective electron densities of a compound or mixture can be estimated by using Eqs. (4) and (5), respectively. An user-friendly program has been developed, called as "direct-Z_{eff}", for calculation of mass attenuation coefficients, effective atomic numbers and effective electron densities for a compound or mixture for photon energy ranging 1 keV to 100 GeV [16]. Therefore, we have utilized direct-Z_{eff} program for calculation of mass attenuation coefficients, effective atomic numbers and effective electron densities of selected elements, mixture and compounds. This program was used further in the present investigation.

Results and discussion

The graph presenting the evolution of mass attenuation coefficients, effective atomic numbers and effective electron densities versus photon energy (1keV to 100 GeV) are shown in Figures 1, 2 and 3, respectively. The variations of these interaction parameters are explained using partial photon interaction processes i.e. photoelectric effect, Compton effect, and pair production.

Mass attenuation coefficients

Figure 1 present the mass attenuation coefficients (μ/ρ) for the selected materials in photon energy range 1 keV-100 GeV. From this figure, it can be easily observed that the μ/ρ values decrease very sharply at low photon-energies, the reduction rate becomes rather small at intermediate energies and, finally, show a slowly increase at high photon energies.

The variation of μ/ρ can be easily explained based on this division of the graph into three energy regions via low-, intermediate- and high-energy. The μ/ρ values reduce sharply in low-energy region due to dominance of the photoelectric effect [17] (interaction cross section α $Z^{4-5}/E^{7/2}$). Therefore, μ/ρ values are found to be higher for those elements/materials which contain elements having high atomic numbers.

As photon energy increases and reaches to intermediate region (100 keV < E < 1.022 MeV), the reduction rate of μ/ρ values decreases due to dominance of the Compton scattering, where interaction cross section is dependent on Z. It is to be noted that rate of reduction of μ/ρ values are greater for Pb and UO_2 than the ones for water, concrete and Co-free steel. Finally, as the photon energy goes to high-energy region (1.022 MeV < E < 100 GeV), μ/ρ values start to increase and become stable due to dominance of pair production process (interaction cross section α Z^2). There are various sharp peaks in elements, mixture and compounds except water at particular energies in μ/ρ values due to K-, L- and M- absorption edges. It is observed that the μ/ρ values for UO_2 compound are the largest among the selected materials up to Compton scattering region. Therefore, UO_2 compound provide efficient shielding effects compared with other selected materials against gamma radiation in the photoelectric and Compton effects regions.

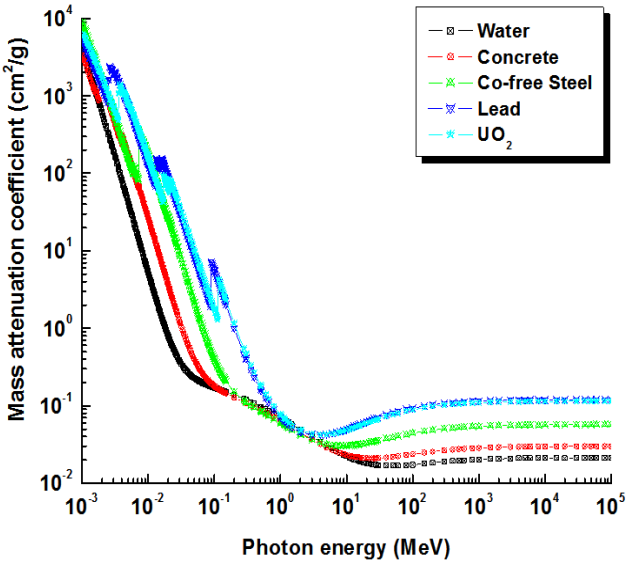


Fig. 1. Mass attenuation coefficients variation with photon energy for water, concrete, Co-free steel, Pb and UO_2

Effective atomic numbers

The variation of effective atomic numbers (Z_{eff}) of selected materials in the photon energy range 1 keV to 100 GeV is shown in Figure 2.

Similar to the μ/ρ values, the Z_{eff} values also present various peaks for UO_2 in the photoelectric effect region. Similarly, Z_{eff} values show analogous variation in intermediate- and high-energy photon regions.

The variation of Z_{eff} with photon energy can be explained using partial photon interaction processes similar to above variation of mass attenuation coefficients with photon energies. It is noted that the Z_{eff} values of water are lowest among those of the other selected materials with insignificant variations in concrete and cobalt-free steel.

Minor variation of Z_{eff} is observed to be in the Compton effect and pair production regions for UO_2 compound. The shape of Z_{eff} variation is due to presence of O atom with U atom.

It is evident from the variation of the Z_{eff} values with photon energies that UO_2 compound and Pb element are showing almost equal level of shielding against gamma rays. Also, the UO_2 and Pb provide superior gamma shielding properties as compared with Co-free steel, concrete and water. The water provides the lowest shielding against gamma in the selected materials.

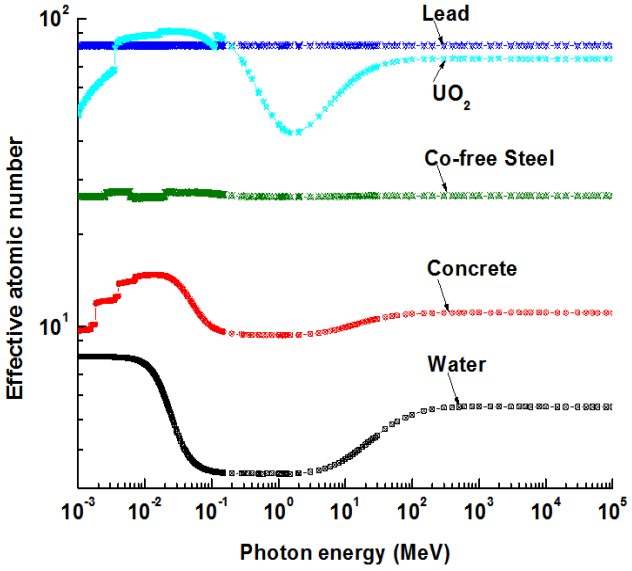


Fig. 2. Effective atomic numbers of variation of photon energy for concrete, Co-free steel, Pb and UO_2

Effective electron density

The variation of effective electron densities (N_{eff}) of the selected materials in photons energy range 1 keV to 100 GeV is presented in Figure 3.

The variation of N_{eff} with photon energy can be explained similar to the above interaction parameters (Z_{eff} and μ/ρ) using partial interaction processes.

It is to be noted the N_{eff} values of Co-free steel are constant with maximum N_{eff} for water in photoelectric effect and pair production regions. Sharp reducing and increasing behaviour of N_{eff} is observed for UO_2 in intermediate energy region due to presence of O element.

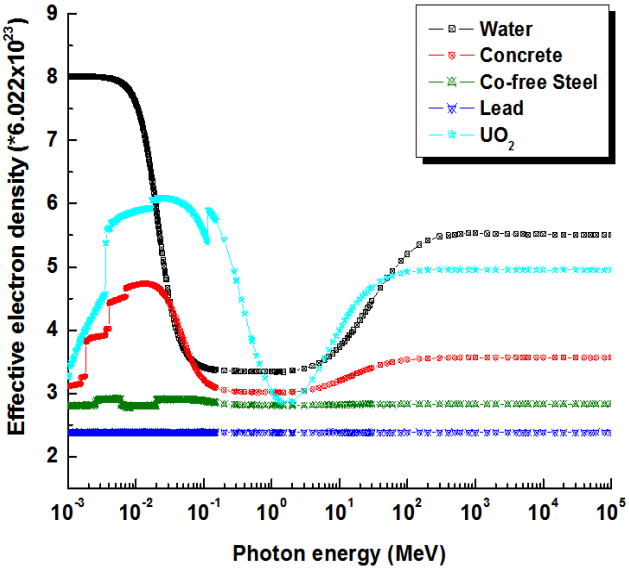


Fig. 3. Effective electron densities variation with photons energy for water concrete, Co-free steel, Pb and UO_2

Conclusions

In the present investigation, mass attenuation coefficients, effective atomic numbers and effective electron densities for water, concrete, Co-free steel, Pb and UO_2 have been studied for photon energy in the range 1 keV to 100 GeV.

The variations of these parameters with photons energy were explained using partial photon interaction processes.

It was found that UO_2 and Pb provide almost equal level of shielding against gamma rays, whereas water provides the lowest shielding against gamma rays.

The UO_2 and Pb were found to have high shielding efficiency against gamma rays.

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