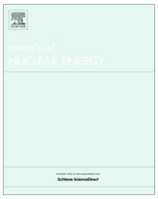
Annals of Nuclear Energy 63 (2014) 619–623

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Determination of shielding parameters for different types of resins

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ARTICLE INFO

Article history:
Received 7 April 2013
Received in revised form 31 August 2013
Accepted 4 September 2013
Available online 27 September 2013

Keywords:
Shielding materials
Neutron
Gamma radiation
Attenuation coefficients
Removal cross-section

ABSTRACT

In this paper, the neutron and gamma shielding properties of four types of resin have been studied. The mass attenuation coefficients (μ_t) have been calculated at the photon energy range of 1 keV–1 GeV by using WinXCom program. The macroscopic fast neutron removal cross-sections (Σ_R) have also been calculated. The dependence of mass attenuation coefficients and the macroscopic fast neutron removal cross-sections on chemical composition of the selected polymers has been discussed. Also, the dependence of mass attenuation coefficients on incident photon energy has been studied. The results show that resins with high density is an effective for shielding gamma rays and resin 250WD is effective for shielding fast neutrons.

1. Introduction

The use of nuclear technology in recent years, is more and more important. This technology is now used by several fields such as experiments in particle physics nuclear power plants, medicine and agriculture. However, this technology produced many types of ionizing radiations, such as gamma rays and neutrons. These radiations are extremely dangerous to human health. Thus, it was necessary to evaluate the risks and quantify the level of exposure to such radiations and to develop technologies for protecting against these radiations. The most important factor for reducing the effect of these, is determining the most adequate material for shielding. Radiation shielding involves at placing a shielding material between the ionizing radiations source and the worker or the environment. The radiations which have to be considered generally are: gamma rays and neutrons, each type of these radiations interacts in different ways with shielding material. While, it is necessary to have the knowledge about the effective shielding materials for neutrons and gamma rays, so it is important to study the attenuation of these radiations in the shielding materials. Hence, the determination of the attenuating parameters of gamma rays or neutrons with shielding materials is extremely important.

Neutron attenuation in shielding materials is characterized by several parameters such as the macroscopic thermal neutron cross-sections and the macroscopic effective removal cross-sections for fast neutrons (Σ_R). The macroscopic effective removal cross-section (Σ_R) presents the probability that a fast or fission-energy neutron undergoes a first collision, which removes it from the group of penetrating uncollided neutrons (Blizard and Abbott, 1962; Duderstadt and Hamilton, 1976). The macroscopic effective removal cross-sections of different materials are determined by some works (El-Khayatt, 2010; El-Khayatt and El-Sayed Abdo, 2009; El-Sayed Abdo, 2002). The total mass attenuation coefficients (μ_t) is the basic parameter which describes the interaction of x and gamma rays with shielding materials. The (μ_t) is a measure of the probability of interactions of photon with matter and it is measured in (cm^2/g) (Hubbell, 1999, 1982; Hubbell and Seltzer, 1995). Several theoretical and experimental studies have determined (μ_t) values (Demir and Han, 2009; Han and Demir, 2009; Un and Sahin, 2011). This coefficient is not constant but depends on the incident photon energy, the material density and the chemical composition of materials.

In this study, the total macroscopic effective removal cross-section (Σ_R) for fast neutrons and the total mass attenuation coefficients (μ_t) for gamma rays were calculated by theoretical approach for four types of resin of different densities and chemical composition. These types of materials are useful in large variety of applications. They are materials which are widely used as a neutron shielding in nuclear power plants (reactor vessels), particle accelerators, research reactors, neutrons source and medical facilities (Positron Emission Tomography cyclotron) (Kang et al., 2008; Morioka et al., 2007; Okuno, 2005; Sukegawa et al., 2011). Also, they can be used as shielding materials in spent fuel storage, transporting and storing radioactive materials. These materials are both moderators and absorbers, in fact, they contain hydrogen which is

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http://dx.doi.org/10.1016/j.anucene.2013.09.007

the most effective 'moderator' because its mass is almost the same as that of the neutron and they also contain boron which is a suitable absorber of thermal neutrons. Fast neutrons are absorbed by these materials via two processes: they are thermalized at first by the moderator (hydrogen and light elements) through elastic collisions, and then absorbed by the absorber (boron). These materials are characterized by a good durability for neutron and gamma ray irradiation, high heat resistance, good dimensional stability, high mechanical strength and chemical proof. These materials were chosen for this study because they are newly developed and used in several applications. The chemical composition of four types of resin is obtained from (Kang et al., 2008; Morioka et al., 2007; Okuno, 2005; Sukegawa et al., 2011).

The macroscopic effective removal cross-sections (Σ_R) have been determined by using the values of the mass removal cross-sections of elemental composition of the resin. For gamma-rays, total mass attenuation coefficients (μ_t) have been calculated in the energy range from 1 keV to 1 GeV by using WinXCom code which is a Windows version of the XCOM database, this s code is used to calculate the cross sections of photons interactions with matter and it can also calculate the attenuation coefficient of gamma and x rays for the chemical elements (Z = 1–100), compound and mixtures at energies from 1 keV to 100 GeV (Gerward et al., 2004, 2001).

2. Theoretical method

2.1. Effective removal cross-sections of fast neutrons

Neutrons are electrically neutral particles, during their passage through a material medium, they interact with the nuclei of atoms in two ways, either by diffusion or absorption. The interaction of neutrons with the atoms described by the total microscopic cross-section (σ_t), expresses the probability that a neutron of a given energy interacts with the atoms of the traversed material and it is defined as the sum of the microscopic cross section scattering (σ_s) and the microscopic cross-section absorption (σ_a).

$$\sigma_t = \sigma_s + \sigma_a \tag{1}$$

The neutrons attenuation during their passage through material medium depends not only on the microscopic cross-section but also on the number of nuclei within this environment. The physical quantity bounding these two parameters, is called total macroscopic cross-section denoted (Σ_t) and defined by (Martin, 2000; Shultis and Faw, 2008, 1996):

$$\Sigma_t = \frac{\rho N_a \sigma_t}{A} \tag{2}$$

where (ρ) is the density (g cm^{-3}), N_a is Avogadro's Number and A is the atomic mass. (Σ_t) has the dimensions of the length inverse, its unit is (cm^{-1}). In the same way as a photons beam, when the parallel beam of monoenergetic neutrons passes through a material medium, it will be attenuated due to absorption and scattering. The attenuation of neutrons in matter follows the following law (Martin, 2000; Shultis and Faw, 2008; Shultis and Faw, 1996):

$$I = I_0 e^{-\Sigma_t x} \tag{3}$$

where I_0 and I are the incident and transmitted intensities, x (cm) is the thickness of the material medium and Σ_t represents the total macroscopic cross-section.

So the case of fast neutron attenuation is described by another parameter called the removal cross-section, denoted by (Σ_R) (cm^{-1}) and is different from the total macroscopic cross-section but it has a fraction of it. The removal cross-section presents the probability that a fast or fission-energy neutron undergoes a first collision, which removes it from the group of penetrating uncollided neutrons (Blizard and Abbott, 1962; Duderstadt and Hamilton, 1976). Indeed, in the MeV-energy region, the neutrons absorption cross-section is very low compared to the scattering cross-section. In fact, the fast neutrons are not directly absorbed during their passage through the shielding hydrogenated, but they slow primarily by successive elastic collisions with the nuclei of light elements. When their energy is in the order of the thermal energy (0.025 eV), they are absorbed by the nuclei of heavy elements via interaction radiative capture (Chilton, 1984).

For energies between 2 and 12 MeV, the effective removal cross-section will be almost constant when the traversed medium contains a large amount of hydrogen $\Sigma_R = \Sigma_t$ and when materials contain a small fraction of hydrogen $\Sigma_R = 2/3\Sigma_t$ for energy between 6 and 8 MeV (Kaplan, 1989; Glasstone and Sesonske, 1986; Profio, 1979; Wood, 1982).

A material sample having as components: simple elements and compounds, its removal cross-section is given by the following formula (Kaplan, 1989; Glasstone and Sesonske, 1986; Profio, 1979; Wood, 1982):

$$\Sigma_R = \sum_i W_i (\Sigma_R/\rho)_i \tag{4}$$

where W_i, (ρ) and $(\Sigma_R/\rho)_i$ are respectively the partial density (g cm^{-3}), density and mass removal cross section of the ith constituent. The partial density of the ith constituent is given by:

$$W_i = (t_i)(\rho)_s \tag{5}$$

where (t_i) is the weight fraction of the ith constituent and $(\rho)_s$ is the sample density.

In this study, the effective removal cross-section (Σ_R) of fast neutrons has been calculated for different shielding materials by using Eq. 4. The values of the mass removal cross-sections of the elements that constitute of these materials is taken from (Chilton, 1984; El-Khayatt, 2010; El-Khayatt and El-Sayed Abdo, 2009; El-Sayed Abdo, 2002; Kaplan, 1989; Profio, 1979). The elemental composition of materials used in this work, its fractions by weight, partial densities, (Σ_R/ρ) and calculated (Σ_R) values are listed in Table 1–4.

2.2. The total mass attenuation coefficient

During its passage through material medium, a photon undergoes several interactions such as photoelectric absorption, Coherent scattering, scattering Incoherent and Pair Production (Hubbell, 1999, 1982; Hubbell and Seltzer, 1995). If a photon beam having an initial intensity I_0 penetrates the matter, it will be attenuated and its intensity decreases exponentially according to the exponential law:

$$I = I_0 e^{-(\frac{\mu_{linear}}{\rho})\rho x} = I_0 e^{-\mu_t d} \tag{6}$$

This is called the Beer–Lambert law, where I is the transmitted intensity, (μ_{linear}) is the linear attenuation coefficient in cm^{-1}, ρ is the material density in g cm^{-3}, x is the thickness of the absorbing

Table 1
The calculation results of the fast neutrons effective removal cross-sections for K-resin (ρ = 1.45 g cm^{-3}).

Element	$\sum_R/\rho$ (cm^2 g^{-1})	Fraction by weight	Partial density ρ (g cm^{-3})	$\sum_R$ (cm^{-1})
H	0.598	0.1486	0.2155	0.1289
C	0.0502	0.33	0.4785	0.0240
N	0.0448	0.02	0.0290	0.0013
O	0.0405	0.54	0.7830	0.0317
Al	0.0293	0.026	0.0377	0.0011
Total $\sum_R$ (cm^{-1})				0.1870