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Evaluation of Gamma-Rays Attenuation Properties of Vanadium-Doped Alloys

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Abstract

In this work, the gamma ray shielding properties of vanadium doped alloys have been evaluated. The values of mass attenuation coefficients (μ_m), effective atomic numbers (Z_{eff}), effective electron densities (N_{el}), mean free path (*MFP*) and half value layers (*HVL*) were computed by WinXCom software program at photon energy range 1 keV – 100 GeV. The values of μ_m, Z_{eff} and N_{el} were decreased with an increasing in V content whereas *MFP* and *HVL* were increased with an increasing in V content. It was extrapolated that the increasing in the composition of vanadium in alloys system which vanadium to decrease in the gamma ray shielding properties of alloys system.

Keywords: Alloy;Vanadium; Mass attenuation coefficient

Introduction

The applications of alloys have been used wildly in nuclear reactors, aerospace industry, biodegradable metallic materials, marine applications, medicines, production of sports equipment and petro–chemical industries require strong mediums [1 – 4]. Vanadium were developed for the structural material in the structures fusion reactor owing to the excellent of their potential for intrinsic low activation and attractive high-temperature properties. Erewhile, there were many studies of pure vanadium and vanadium–based alloys properties such as retention, diffusion, and permeation either experimentally and theoretically [5 – 8].

In the field of radiation physics, there are many values like mass attenuation coefficient (μ_m), effective atomic numbers (Z_{eff}), effective electron density (N_{el}), mean free path (*MFP*) and half value layer (*HVL*) were discussed the penetration of photon in medium [9]. Generally, the γ-ray and neutron attenuation coefficients were explained characterize of photon interaction with medium. As well known, the compound or mixture had the elements with high *Z* were preferred in attenuating γ-ray, while elements with low *Z* were used to attenuate neutron particles [10, 11].

In this context, the studies of the theoretical of mass attenuation coefficient (μ_m), effective atomic numbers (Z_{eff}), effective electron density (N_{el}), mean free path (*MFP*) and half value layer (*HVL*) of Fe–Mo–C–Cr–V alloys were computed by WinXCom software program at photon energy range 1 keV – 100 GeV.

Theoretical Basis and Computation Method

The density is fundamental parameter using to calculate the other parameters. The density, $\rho_{mix,}$ of alloy were calculated by the rule of mixtures (ROM) as Eq. (1) [12];

$$\rho_{mix} = \frac{\sum_{i=1}^{n} c_i A_i}{\sum_{i=1}^{n} \frac{c_i A_i}{\rho_i}} \tag{1}$$

where ρ_i, c_i, and A_i are density, atomic fraction and atomic weight of element *i* th, respectively.

The mass attenuation coefficient (μ_m) is the value assigned for photon interaction. It was explained theoretical values of material compound and calculated by mixture rule as Eq. (2) [13];

$$\mu_{m_{alloy}} = \sum_{i}^{n} w_i \left(\frac{\mu}{\rho} \right)_i \tag{2}$$

where w_i and $(\mu/\rho)_i$ are proportion by weight and mass attenuation coefficient of element *i* th, respectively, and determined by using WinXCom software program.

Effective atomic number, Z_{eff}, is quantity to explaining photon interaction and were determined by Eq. (3) [14];

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \tag{3}$$

where $\sigma_{t,a}$ and $\sigma_{t,el}$ are respectively total atomic cross-section and total electronic cross–section, which calculated by using Eq. (4) and (5) [14, 15];

$$\sigma_{t,a} = \frac{(\mu_m)_{alloy}}{N_A \sum_{i}^{n} (\mathrm{W}_i / A_i)} \tag{4}$$

$$\sigma_{t,el} = \frac{1}{N_A} \sum_{i}^{n} \frac{f_i A_i}{Z_i} (\mu_m)_i \tag{5}$$

where A_i, Z_i and f_i are respectively atomic weight, atomic number and fractional abundance of element *i*, N_A is the Avogadro constant.

The effective electron density (N_{el}) is value to represent electrons number per unit mass, and it was computed as follows Eq. (6) [14, 16];

$$N_{el} = \frac{\mu_m}{\sigma_{t,el}} \tag{6}$$

That is well known an interaction of photon with material will reduced the intensity of photon by various processes such as complete absorption, partial absorption, energy reduction and multiple scattering inside medium. Mean free path, *MFP*, is the average distance pass through by photon in matter before the interaction occurs. The *MFP* is given as Eq. (7) [17];

$$MFP = \frac{1}{\mu_{alloy}} \tag{7}$$

where μ_{alloy} is linear attenuation coefficient of alloy.

Half value layer, *HVL* is value to discuss photon interactions of medium. The *HVL* is thickness of medium need to decrease photon intensity to 50% of its initial value. The *HVL* was given as Eq. (8) [18];

$$HVL = \frac{0.693}{\mu} \tag{8}$$

Results and Discussion

Density

Density of alloys system as shown in Table 1 [19], it decreases with increase in content of vanadium (V) due to V has lower molar mass as compared to iron (Fe).

Table 1 The chemical compositions of vanadium doped alloys.

Code	Elemental % by weight					Density (g cm^{-3})
	Fe	Mo	C	Cr	V	
V0	86	5	5	4	–	7.49
V2	84	5	5	4	2	7.46
V4	82	5	5	4	4	7.43

Mass attenuation coefficient

To evaluate the shielding properties of alloys system, the mass attenuation coefficients (μ_m) in energy range 1 keV – 100 GeV were computed using WinXCOM software program and results were plotted in Fig. 1. From Fig. 1, the plotting discontinuous due to absorption edge of elements

as shown in Table 2. The μ_m value of alloys decreased rapidly with increasing photon energy until to 0.10 MeV due to photoelectric absorption effect process was main and became decreased slowly in energy range 0.10 MeV – 4 MeV where the Compton scattering is main. After that, μ_m value increased slowly where pair production process is major. From the plotting in Fig. 1, it found that the μ_m values were decreased with increasing V concentration. It was seen that the replacement of Fe by V causes decreased in μ_m values and alloy V0 shown highest μ_m value.

Table 2 Absorption edges of photon energy (keV).

Element	Z	L3	L2	L1	K
Mo	42	2.52	2.63	2.87	2.00
Fe	26	–	–	–	7.11
Cr	24	–	–	–	5.99
V	23	–	–	–	5.47

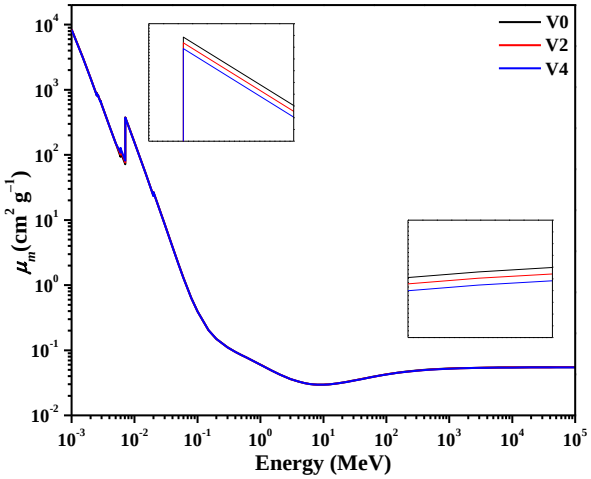

Fig. 1 μ_m for alloys system in energy range 1 keV – 100 GeV.

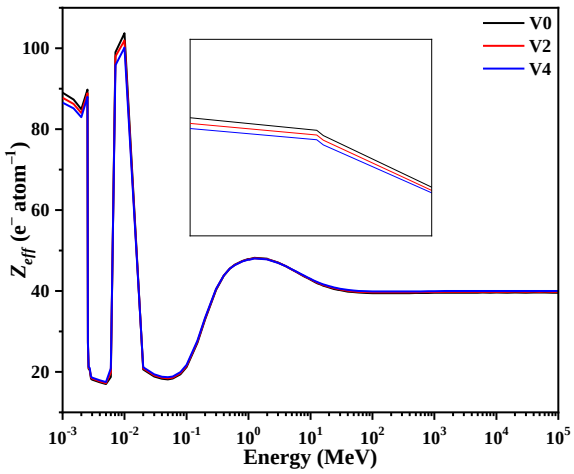

Fig. 2 Z_{eff} for alloys system in energy range 1 keV – 100 GeV.

Effective atomic number (Z_{eff}) and effective electron density (N_{el})

The Z_{eff} and N_{el} with energy for alloys system were shown in Figs. 2 and 3, respectively. Clearly, Z_{eff} value for alloy samples were decreased in low energy range and sudden jumps occurred at 2.52, 7.11 and 10.00 keV. These events were discussed on fundamental of absorption edges of elements. The values of Z_{eff} at energy range 1 – 2 keV, 3 – 6 keV and 20 – 60 keV are decrease with increasing photon energy, for alloy samples, this were discussed based on dependence of photoelectric absorption effect cross-section process which varies inversely with photon energy as 3.50 eV.

Next, increasing of photon energy range at 0.10 – 1.00 MeV for all samples, Z_{eff} value was become nearly free of photon energy. This may be because of main for Compton scattering method. At photon energy over above 1 MeV, Z_{eff} value was slowly decreases and becomes nearly constant above 80 MeV. This was discussed on fundamental of main for pair production at high energy range as shown in Fig. 3, N_{el} with photon energy range at 1 keV – 100 GeV, had demonstrated same behavior of Z_{eff}.

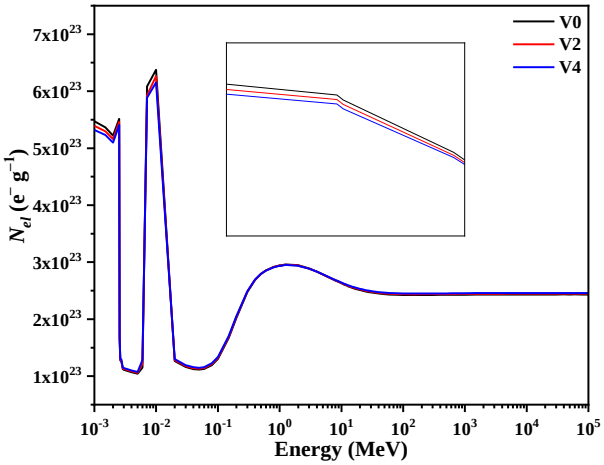

Fig. 3 Z_{eff} for alloys system in energy range 1 keV – 100 GeV.

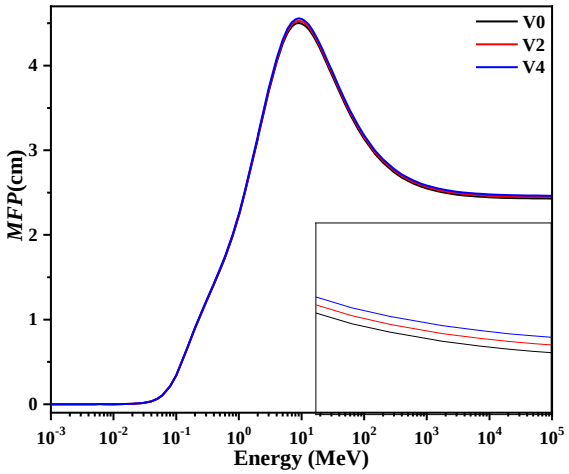

Fig. 4 *MFP* for alloys system in energy range 1 keV – 100 GeV.

Mean free path and half value layer

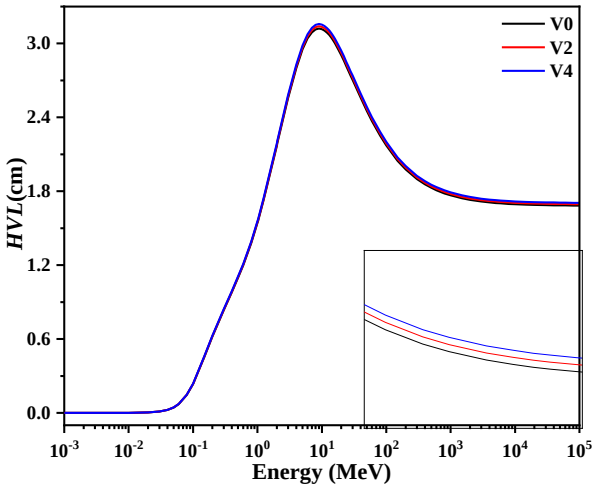

Fig. 5 *HVL* for alloys system in energy range 1 keV – 100 GeV.

The mean free path, *MFP*, values with photon energy of alloys were shown in Fig. 4. It found that *MFP* values were low in photoelectric absorption effect process range and gradually becomes free of photon energy in Compton range and varies inversely with the photon energy in pair–production range. It can be noted that the V4 alloy requires largest thickness compared with other alloys in interest energy range. The V0 alloy was shown minimum *MFP* values, therefore it can be concluded the V0 is the best shielding among the various alloys. The *MFP* of alloys is dependent upon densities. Fig. 5, show that the behavior in *HVL* for alloys system with photon energy. It same as the variation observed by *MFP* with photon energy and difference is only in the magnitude.

Conclusion

The present evaluate gives values for gamma-rays mass attenuation coefficients, effective atomic numbers, effective electron densities, mean free path and half value layer of vanadium doped alloys system at photon energy range from 1 keV – 100 GeV. The results shown that μ_m, Z_{eff} and N_{el} are dependent on photon energy, ascended by different interactions showing peaks (absorption edges) at low photon energy because of main photoelectric effect near the M-, L- and K absorption edge of alloy compositions. The vanadium doped alloys (V0) was found to have the lowest mean free path and half value layers which indicated that the V0 alloy sample is good medium for gamma–rays shielding applications.

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