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Vanadium Compounds: As Gamma Rays Shielding Material

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Abstract - **Various parameters of dosimetric interest such as mass attenuation coefficient (μ_m), equivalent atomic number (Zeq), exposure buildup factors (Be_x) have been computed for some vanadium compounds (VF_3, VF_4, VO_2 and V_2O_3) in the photon energy range from 15.0 keV to 15.0 MeV to visualize the feasibility of using these compounds as gamma rays shielding material. The variation of various parameters has been studied as a function of incident photon energy, penetration depth and chemical composition of the selected vanadium compounds. For the better gamma rays shielding material, the equivalent atomic number must be higher and exposure buildup factor must be least. Among the selected vanadium compounds; V_2O_3 possess such qualities, hence it offers better shielding from gamma rays than the other selected vanadium compounds.**

Keywords: **Vanadium compounds, Equivalent atomic number, Exposure buildup factor**

I. Introduction

Different nuclear reactor accidents which occurred in different parts of the world such as the Three Mile Island accident at Dauphin County, Pennsylvania, United States in 1979, The Chernobyl accident at the Chernobyl Nuclear Power Plant in Ukraine, Russia in 1986, and the recent series of reactor explosions at Fukushima, Japan in 2011 realized the importance of precise studies of various dosimetric parameters such as mass attenuation coefficient (μ_m), equivalent atomic number (Z_{eq}) and exposure buildup factors (B_{ex}).

Mass attenuation coefficient (μ_m) is the fundamental parameter which measures the extent of interaction (may be scattering or absorption) of photon with matter. It is the basic tool to compute other photon interaction parameters.

Equivalent atomic number (Z_{eq}) for compound/ mixture is the parameter analogous to the atomic number of elements. However, unlike atomic number, it is an energy dependent parameter.

Exposure buildup factor provides an estimate of radiation leakage from the particular thickness of the interacting material. With the proper utilization of exposure buildup factor data, proper utilization of radiation shielding materials can be used, which results in minimizing the radiation leakage risks.

Recently, different researchers had contributed in providing gamma ray buildup factor data for different materials such as thermo-luminescent dosimetric materials by Manohara *et al.* [1], human tissue by Kurudirek *et al.* [2], teeth by Manjunatha and Rudraswamy [3] and for some essential amino acids, fatty acids and carbohydrates by Kurudirek and Ozdemir [4], samples from the earth, moon and mars by Kurudirek *et al.* [5], different types of concretes by Kaur *et al.* [6], different types of solvents by Singh et al. [7], different types of polymers by Singh *et al.* [8], for some biological samples by Kaur *et al.* [9] and for some building materials by Singh *et al.* [10].

Vanadium is the fifth group element and belongs to the group of transition metals. Hence, it shows multiple oxidation states and due to this property it can easily make compounds with different elements. It is found in more than 50 different minerals as well as phosphate rock, certain iron ores, some crude oils (in the form of complexes) and meteorites. Some of the more important minerals in which vanadium is found include carnotite, roscoelite, vanadinite and patronite.

Vanadium compounds are used in different fields such as an additive for steel, for the production of rust resistant, spring and high speed tool steels to stabilise carbides. It is also used to bond titanium to steel. Due to its low fission neutron cross section, it is also used in nuclear applications. Other applications of vanadium compounds include its use as a catalyst in the ceramics industry, as a mordent in the printing and dyeing of fabrics and in the manufacture of aniline black.

Visualizing the vast applications and availability in abundance, some of the vanadium compounds are selected for present investigations to check the feasibility of using some vanadium compounds (VF_3, VF_4, VO_2 and V_2O_3) as gamma ray shielding materials. Hence various dosimetric parameters such as mass attenuation coefficients, equivalent atomic numbers and exposure buildup factor have been computed for the selected vanadium compounds in the energy region 0.015- 15.0 MeV and upto the penetration depth of 40 mean free path (mfp) i.e. thickness of approximately 400 cm.

II. Computational Work

Using the software package WinXcom by Gerward et al. [11], the mass attenuation coefficient (μ) values for partial photon interaction processes (Rayleigh scattering, Compton scattering, photoelectric effect, pair production and total of all these) of selected vanadium compounds as well as its constituent elements have been generated in the desired energy range of (15.0 KeV to 15.0 MeV) dominant range of Compton scattering process. Then, these mass attenuation coefficient values are further used to compute the equivalent atomic numbers, G.P. fitting parameters and exposure buildup factors. The computational work of buildup factors has been divided into following three steps:

A. Calculations of Equivalent Atomic Number

The ratio of mass attenuation coefficient values for the Compton scattering and total of all photon interaction process ($R=\mu_{Comp}/\mu_{total}$) has been computed for the selected vanadium compounds as well as different elements up to the atomic number 26 in the required energy range. Then, the equivalent atomic numbers of the selected vanadium compounds have been computed by matching the ratio (R) of a particular vanadium compound at a given energy with the corresponding ratio of elements at the same energy. In case, the ratio of compound lies between the ratio of two successive elements and the value of equivalent atomic numbers are computed using the logarithmic interpolation expression as given by Singh *et al.* [7-8] and Kaur *et al.* [6, 9]:

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{(\log R_2 - \log R_1)}$$

Where $Z_1$and Z_2 are the atomic number of successive elements corresponding to the ratios R_1 and R_2 respectively and R is the ratio for selected vanadium compound, which lies between ratios R_1 and R_2.

B. Calculations of G.P. Fitting Parameters

ANSI/ANS-6.4.3 [12] provides the various GP fitting parameters (b, c, a, Xk and d) used for the calculation of the exposure buildup factors for various elements starting from beryllium to iron in the energy range of 0.015 to 15.0M.eV for the penetration depths up to 40 mfp. The exposure G-P fitting parameters (b, c, a, X_k, d) for the selected vanadium

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1}$$

Where parameter P stands for all five GP fitting parameters (b, c, a, X_k and d); Z_1 and Z_2 are the atomic number of successive elements in which Z_{eq} of the vanadium compound lies.

C. Calculations of Exposure Buildup Factor

The computed GP fitting parameters (b, c, a, X_k, d) were then used to compute the exposure buildup factors for the selected vanadium compounds at some standard incident energies in the range of 0.015-15.0 MeV and up to penetration depth of 40 mfp, using equations given by ANS/ANSI 6.4.3 [12]; Harima *et al.* [13] and Sakamoto *et al.* [14]:

$$B(E, x) = 1 + (b-1)(K^x-1)/(K-1) \qquad \text{for } K \neq 1$$

$$B(E, x) = 1 + (b-1)\,x \qquad \text{for } K=1$$

$$K(E,x)=\{cx^a+d[\tanh(x/X_k - 2)-\tanh(-2)]\}/[1-\tanh(-2)]$$

where x= source- detector distance of the medium in mean free path and above formulas are applicable upto the penetration depth of 40 mfp,

B = buildup factor,

K (E, x) = Dose multiplication factor which represents the change in the shape of the dose weighted spectrum with increasing depth and is represented as hyperbolic tangent function of penetration depth in mfp,

(b, c, a, X_k, d) = G.P. fitting parameters that depends on attenuating medium and source energy.

III. Results And Discussions

Different shielding parameters such as equivalent atomic numbers and exposure buildup factors have been computed for vanadium compounds using Microsoft Excel software package and the variation of these parameters with different physical parameters viz. incident photon energy, chemical composition, thickness (penetration depth) etc. have been discussed in the following sub-sections:

A. Variation of Equivalent Atomic Number with Incident Photon Energy

The variation of equivalent atomic number with incident photon energy can be clearly seen in Fig. 1. From the figure, it has been confirmed that unlike atomic number, the equivalent atomic number varies with incident photon energy.

The equivalent atomic numbers of the selected vanadium compounds initially increases very slightly with the increase in incident photon energy, and almost remains constant upto 1.0 MeV (approximately) and in the limited incident photon energy region from 1.0 MeV to 5.0 MeV, the equivalent atomic numbers decreases. Beyond 5.0 MeV, the equivalent atomic numbers of the selected vanadium compounds again becomes almost constant. This variation in equivalent atomic number for the selected vanadium compounds can be explained on the basis of dominance of Compton scattering process with energy for the selected vanadium compounds.

Among the selected Vanadium compounds, V_2O_3 possesses maximum equivalent atomic numbers, whereas minimum equivalent atomic numbers are observed for VF_4 compound and the equivalent atomic numbers for other vanadium compounds VO_2 and VF_3 lies in between these limits. This can be explained on the basis of weight fraction of different constituent elements, higher is the weight fraction of higher atomic number element; higher will be its equivalent atomic number. The fraction of vanadium (maximum atomic number element among the selected vanadium compounds) is maximum in V_2O_3 compound (68 % approx) and is minimum in VF_4 compound (40 % approx).

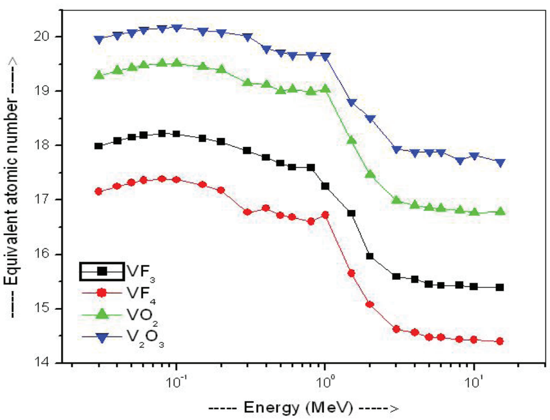

Fig. 1 Variation of equivalent atomic number of selected vanadium compounds with energy

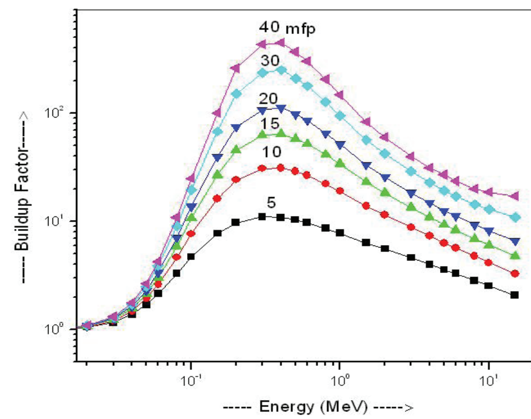

Fig. 2 Variation of exposure buildup factor with energy for VF3 at different mean free paths

B. Variation of Exposure Buildup Factor with Incident Photon Energy

The variation of energy exposure buildup factor with incident photon energy at fixed penetration depths of 5, 10, 15, 20, 30, and 40 mean free path (mfp) has been shown in Fig. 2 for VF3 compound. From this figure, it has been observed that with the increases incident photon energy from 15.0 keV to 200.0 keV, the value of exposure buildup factor increases and becomes maximum.

Beyond 200.0 keV, with the further increase in energy, the value of exposure buildup factor decreases. This increasing and decreasing variation of exposure buildup factors with incident photon energy can be explained on the basis of dominance of different partial photon interaction processes in different energy regions.

In the lower energy region, photoelectric effect is the dominant photon interaction process, whose cross-section varies inversely with energy as $E^{3.5}$. Due to dominance of this process, maximum number of photons will be absorbed by the vanadium compounds. Hence, it results in reducing the exposure buildup factor value in the lower energy region.

Similarly in higher energy region, another photon absorption process that is pair production is dominant one, whose cross-section varies inversely with energy as E^2. This process again reduces the value of exposure buildup factor. In the intermediate energy region, Compton scattering is dominant photon interaction process, which only help in degradation of photon energy due to scattering and fails to completely remove the photon. So in this energy range, the life time of the photon is more and hence the probability of photon to escape from the vanadium compound is also more. This process results in increasing the value of exposure buildup factor.

Further, it is also observed that the exposure buildup factors increases with increases in the penetration depth for the selected vanadium compounds. This can be explained on the basis that with increase in penetration depth, the probability of multiple scattering increases which results in the increase of multiple scattered photons. This results in increasing the value of exposure buildup factors. Similar trends have been observed for othe selected materials VF_4, VO_2, and V_2O_3.

C. Variation of Exposure Buildup Factor with Penetration Depth

The variation of the exposure buildup factor has been studied with penetration depth at some constant energies of 0.015, 0.5, 0.6, 0.2, 0.8, 5.0, and 10.0 MeV and shown in Fig. 3 for VF_3 compound. It has been observed that the exposure buildup factor increases with increase in penetration depth for different constant energies. However, the rate of increase in exposure buildup factor varies for different incident photon energies. The variation in the exposure buildup factor with penetration depth is low at lower incident photon energies and it increases with increase in the energy of incident photons, becomes maximum in the intermediate photon energy and thereafter starts decreasing at higher energies. The dependence of buildup factor on energy can be explained on the basis of dominance of different interaction processes in different energy regions. In lower energy region, the dominant interaction process is photoelectric absorption, so the value of buildup factor is lower. The value of buildup factor is maximum in medium energy region as Compton scattering is dominant in this region. Again in region of dominance of pair production region, the value decreases due to its absorption behavior.

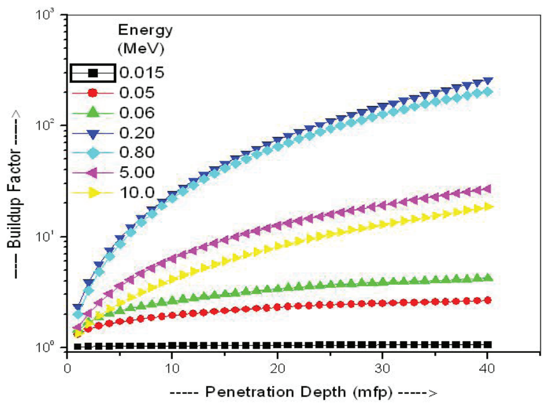

Fig. 3 Variation of exposure buildup factor with penetration depth for VF_3 at different energies

It has been observed that the maximum increasing rate of exposure buildup factor with penetration depth for VF_3 and VF_4 compounds has been observed at the constant photon energy of 0.2 MeV, whereas for VO_2 and V_2O_3 compounds, the maximum increasing rate of exposure buildup factor with penetration depth has been observed at the constant photon energy of 0.8 MeV. This can be explained on the basis that different vanadium compounds have different chemical composition and hence different equivalent atomic numbers (Fig. 1) and the cross-section of different photon interaction process depends upon atomic number (element) / equivalent atomic number (compound/mixture) as well as incident photon energy. Hence the probability of maximum number of multiple Compton scatterings is at different energies for different vanadium compounds.

D. Variation of Exposure Buildup Factor with Chemical Composition

To visualize the dependence of chemical composition/ equivalent atomic numbers of the selected vanadium compounds on the exposure buildup factor, the variation of exposure buildup factors with penetration depth of all the selected vanadium compounds have been plotted and shown in Figs. 4 - 6 at the fixed incident photon energies of 0.20, 5.0 and 10.0 MeV.

From Fig. 4, for the fixed photon energy of 0.2 MeV, it has been observed that VF_4 (lowest equivalent atomic number compound among the selected compounds) possesses maximum values for exposure buildup factor whereas minimum exposure buildup factor values are observed for V_2O_3 (highest equivalent atomic number compound among the selected compounds). It can be concluded from this figure that exposure buildup factor varies inversely with equivalent atomic number. Higher is the equivalent atomic number, lower will be the value for exposure buildup factor.

For the fixed photon energy of 5.0 MeV, the variation of exposure buildup factor increases with the penetration depth for all the selected compounds has been shown in Fig. 5. It has been observed that at this particular photon energy, the exposure buildup factor becomes almost independent of chemical composition. As compared to previous Fig. 4, the magnitude of exposure buildup factor has been reduced, but the number of multiplicity of Compton scatterings has been increased so much that it cannot even recognize the interacting material.

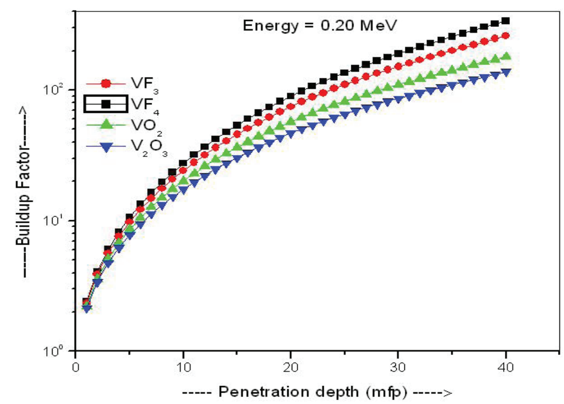

Fig. 4 Variation of exposure buildup factor with penetration depth for all compounds at 0.20 MeV

Further, keeping the photon energy constant at 10.0 MeV, the variation of exposure buildup factor with penetration depth has been shown in Fig. 6 for all the selected vanadium compounds. Again an increase in exposure buildup factor values with increase in penetration depth has been observed for all the selected vanadium compounds. However, a reversal in the trend has been observed.

At a very high constant energy of 10.0 MeV, It has been observed that VF_4 (lowest equivalent atomic number compound among the selected compounds) possesses minimum values for exposure buildup factor whereas maximum exposure buildup factor values are observed for V_2O_3 (highest equivalent atomic number compound among the selected compounds). Here, it can be concluded that exposure buildup factor varies directly with the equivalent atomic number. Higher is the equivalent atomic number, higher will be the value for the exposure buildup factor.

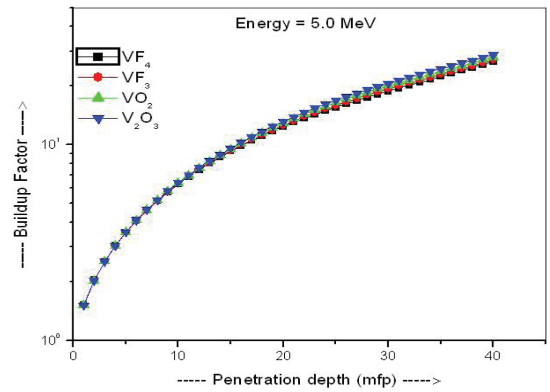

Fig. 5 Variation of exposure buildup factor with penetration depth for all compounds at 5.0 MeV

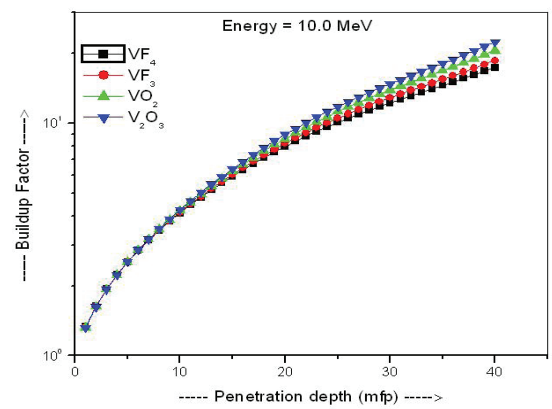

Fig. 6 Variation of exposure buildup factor with penetration depth for all compounds at 10.0 MeV

This reversal trend in dependence of exposure buildup factor on equivalent atomic number can be explained on the basis that at the fixed photon energy of 10.0 MeV, pair production is the dominant photon interaction process; which results in the production of electron-positron pair. The electron-positron pair, so created has very small penetrating power. After multiple collisions within the interacting material, these particles will come to rest, where another process known as annihilation can occur. This annihilation process is reverse of the pair production process. According to this annihilation process, two particle - anti particle (at rest mass) combine together and results in the emission of two gamma ray photons in opposite directions of energy equivalent to the rest mass of the individual particles.

Hence for very high incident photon energy (equal to or above 10 MeV), the pair production process cannot be simply visualized as absorption process if the penetration depth of the interacting material is thick enough to provide the conditions for the occurrence of annihilation process. As a result of annihilation process of electron - positron, two gamma ray photons are emitted and contribute in multiple Compton scatterings and thereby increases the exposure buildup factor values.

IV. Conclusion

From the present studies, following conclusions can be made:

- Different shielding parameters viz. equivalent atomic number, exposure buildup factor depends on incident photon energy as well as chemical composition/nature of the materials.
- Compounds with the higher weight fraction of the higher atomic number element have higher values of equivalent atomic number. Among the selected vanadium compounds, V_2O_3 possesses maximum equivalent atomic number.
- Exposure buildup factor possesses maximum values in the intermediate energy region, where Compton scattering is the dominant photon interaction process and have minimum values in lower and higher energy regions, where photon absorption processes (photoelectric and pair production) are dominant ones.
- Chemical composition dependence of exposure buildup factor shows multiple trends depending upon the incident photon energy
- For lower photon energy, exposure buildup factor is inversely proportional to equivalent atomic number
- For higher photon energy, exposure buildup factor becomes independent of equivalent atomic number
- For very high photon energy, exposure buildup factor is directly proportional to equivalent atomic number.
- Among the selected vanadium compounds, V_2O_3 compound possess maximum equivalent atomic number and least exposure buildup factor below 10.0 MeV. Hence, it will provide better shielding from gamma rays of energy below 10.0 MeV.

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