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Investigation of shielding properties of nuclear reactor control rod material boron carbide

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ABSTRACT

In this study, potential usage of boron carbide (B_4C) in nuclear technology has been emphasized. B_4C is the base material for control rods used to control the fission rate in nuclear reactors. The high neutron absorption capacity of B_4C material makes it very useful for nuclear applications. In order to examine B_4C to be used in nuclear technology, the values of mass attenuation coefficient (MAC) and linear attenuation coefficient (LAC), half and tenth value layers (HVL, TVL) and mean free path (MFP) values were analyzed with open access Photon Protection and Dosimetry (PSD) software. The clad materials considered for the study are hafnium (Hf), indium (In), silver (Ag), cadmium (Cd) and B_4C. Analyzes were made in the energy range between 1 MeV and 15 MeV. In conclusion, when MeV was reached, the MAC value was found as 0.053 cm^2/g for Hf and 0.015 cm^2/g for B_4C. Moreover, while the HVL value was 1 cm for Hf, it was determined as 17 cm for B_4C at 15 MeV. The obtained results were compared with the literature and it was seen that they were compatible with the literature.

1. Introduction

Boron is a metalloid in group 3A of the periodic table. Its atomic number is 5 and its atomic weight is 10.81 g/mol. The element boron was discovered in 1808 and is present in different minerals in the earth's crust. Main minerals containing boron element are sassolite, tincal, kernite, ulexite and borax [1]. Boron element has been used in different scientific studies. In one of them, a tight binding model for boron was developed based on a binding model used for carbon. As a result of the developed model, they suggested that ^{12}B is one of the main component units of amorphous boron [2].

Ethylene-propylene diene rubber and low density polyethylene composites were investigated in terms of gamma and slow neutron radiation shielding properties in a study prepared with two different boron carbide (B_4C) powder concentrations of 47 wt% and 57 wt%. It was observed that the first 1.5 cm thickness of the composite sample containing 57 wt% B_4C sharply reduced the initial direct slow neutron flux by about 85% [3].

In a study conducted by preparing high density polyethylene composites containing three different amounts of modified B_4C, thermal neutron shielding properties that increase with the increase of boron content in the composite matrix were investigated. In addition, the effects of B_4C on mechanical properties, the effect of thermal oxidative aging on mechanical properties and swelling of composites in different solvents were also investigated in these composites [4].

Researchers examining radiation protection applications have investigated boron nitride and B_4C filled polyethylene matrix composites. As a result of the studies, the radiation protection measurements of the composite material containing 2 wt% boron nitride were superior compared to the pure polyethylene material [5, 6].

In another study, the effects of the addition of three different boric compounds (boric acid, boric frit and borax) on the shielding properties of two radiation shielding concretes were investigated. The results showed that boric acid (H_3BO_3) and frit, 0.5-1 wt% of total concrete weight, had a detrimental effect on the setting of ordinary cement [7].

In a study examining the synthesis of a composite powder containing B_4C compounds by the single-cup sol-gel method and its use as a reinforcement material in the production of a new low density polyethylene (LDPE), the chemical, mechanical, morphological, thermal properties and neutron radiation shielding performance of the composites were investigated. The developed composite exhibited highly effective neutron shielding performance [8].

Nuclear energy is a type of energy that can significantly meet the increasing energy demand in the world.

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Commercial nuclear reactors are used to obtain this energy. Pressurized water reactors are the most widely used nuclear reactors worldwide.

Pressurized water reactors basically consist of three elements which are fuel, coolant and moderator. Apart from these, control rods are very important elements. A control rod is one of a series of rods or tubes containing a neutron absorber, such as boron, that can be inserted or withdrawn from the core of a nuclear reactor to control the rate of reaction. Therefore, a control rod is used to control the fission rate of uranium and plutonium in nuclear reactors. It is made of different chemical elements that can absorb many neutrons without fission, such as boron, silver, indium, and cadmium [9].

There are electronic and mechanical devices to control the chain reaction occurring in the core of the reactor, and the use of these devices is very important to prevent radiation emission. However, it is much more important to control the reactions taking place in the chord before the radiation spreads outside the core. The neutrons that emerge as a result of fission in the reactor core are slowed down until their speed drops by the moderator used in the reactor. Water is usually used as a moderator. Afterwards, the use of absorber rods, that is, control rods, is the most preferred way to control the fission rate [10]. Boron, cadmium, silver, hafnium and indium compounds are mostly preferred as control rod material. Since these elements have a high neutron absorption capacity.

B_4C compounds, which are frequently preferred as control rod material in nuclear reactors, are very important in nuclear technology. B_4C is a very hard material used in different industrial applications. In addition to its physical properties, it is frequently used in nuclear technology with its neutron absorber feature.

In a study emphasizing the importance of B_4C, a high-entropy alloy (HEA) composite was synthesized by adding B_4C to Ni-containing HEA. The microstructure and mechanical properties of the formed composite were investigated. In addition, as a result of the investigation of the nuclear radiation shielding properties of the Ni-containing material using experimental and theoretical methods, it was observed that the hardness increased more than twice with the addition of 2.5 wt% B_4C to the alloy. The addition of B_4C to the HEA matrix resulted in an approximately two-fold increase in compressive strength [11].

In another study using B_4C with a neutron absorber effect, examining accelerated corrosion tests of Al-B_4C neutron absorber in a spent nuclear fuel pool, microstructure characterization, electrochemical analysis and neutron attenuation tests were evaluated. Two types of galvanic corrosion were discovered, namely Al matrix/stainless steel and Al matrix/B4C particles [12].

In a study, B_4C reinforced Al matrix composites were produced by hot pressing. It was aimed to evaluate the effect of B_4C reinforcements on thermal and mechanical properties of composite materials. For this reason, materials were produced with B_4C particles in different volume fractions. Afterwards, thermal properties such as thermal conductivity and coefficient of thermal expansion were modelled. As a result of the study, it was seen that up to 12 vol.% inclusion of B_4C particles in the Al matrix increased the hardness of the composite material and decreased the ductility [13].

B_4C particle reinforced Al matrix composites were used for radiation shielding due to their neutron absorbing properties. In a study based on this, linear and mass attenuation coefficients were investigated for B_4C using various gamma energies. As a result of the study, as the incident photon energy increased, the mass and linear attenuation coefficients for composite materials decreased, and the mass and linear attenuation coefficient calculated with the decrease of the weight fraction increased significantly [14].

In a study examining materials made of compounds of B_4C, zirconium boride (ZrB_2), titanium boride (TiB_2) or hafnium boride (HfB_2) [15] that can absorb neutrons as control rod material, some shielding properties, especially linear attenuation coefficient (LAC) and mass attenuation coefficient (MAC) were calculated for the energy range of between 1 keV and 20 MeV.

There are studies [16, 17] examining the nuclear shielding properties of B_4C material. In this study, the importance of B_4C in nuclear technology was emphasized, MAC, LAC, half value layer (HVL), tenth value layer (TVL) and mean free path (MFP) values were analyzed with Phy-X software. In this context, first of all, shielding properties of the studied materials were calculated. Then the obtained results were evaluated comparatively with each other. Effect of the B_4C which is used as a clad material in nuclear reactors, on the radiation shielding ability was investigated. Thus, an experimental study that could be used in nuclear technology was prepared.

2. Materials and Methods

The material used in this study is nuclear reactor control rod material of B_4C. B_4C is frequently used in aerospace and armor construction due to its hard structure, low density and high chemical stability. It is also preferred in nuclear technology due to its neutron capture and semiconductor properties [18].

In this study, the shielding properties of B_4C were investigated with Phy-X software. Phy-X software [19] was developed as a software that can compute all shielding and dosimetry parameters for different materials at the same time, in desired energy ranges, quickly and accurately. With this program, LAC, MAC, HVL, TVL MFP, effective atomic number (Z_{eff}) and effective electron density (N_{eff}), effective conductivity (C_{eff}) energy absorption factor (EABF) and exposure accumulation factor (EBF) can be calculated. This software is freely available after registration on the Phy-X page.

Within the scope of this study, LAC and MAC values were analyzed for the selected energy values (between 1 MeV and 15 MeV) of the B_4C within the scope of the program. MAC and LAC are radiation interaction parameters [20] and their importance is also very high in nuclear technology.

After examining the MAC and LAC values, HVL, TVL and MFP values, which are other important parameters in the radiation shielding analysis, were also examined.

MAC value is an important parameter related to the photon attenuation of the material [21]. MAC value is calculated as in Eq. 1 [20].

$$\mathrm{MAC} = \mu/\rho = [1/(\rho x)] * \ln(I0/I) \qquad (1)$$

In this equation, μ is the linear attenuation coefficient for a given gamma energy, χ is the material thickness, ρ is the physical density of the material, and I0 is the initial count value. The formulation of the LAC value is also shown in Eq. 2 where ρ is the material density, (μ/ρ) is the mass attenuation coefficient, and ρl is the mass thickness [21].

$$LAC = I_o . e^{-(\mu/\rho).\rho I} \qquad (2)$$

The thickness specific to the shielding material, which reduces the radiation beam intensity to one-tenth, is called the TVL value. The specific thickness of the shielding material, which reduces the radiation beam intensity to half its value, is also called HVL. TVL, HVL and MFP formulas are shown in Eq. 3, 4. In these equations, N_A is the avogadro constant and fi, Ai and Zi are the mole fraction, atomic weight and atomic number of the ith constituent element in the material [22]. Mean free path (MFP) value of a photon is the average distance of the photon can travel across the barrier before interacting.

$$\mu = \frac{ln2}{HVL} = \frac{ln10}{TVL} \qquad (3)$$

$$MFP = {}^{1}/_{\mu} \qquad (4)$$

3. Results and Discussion

Change in MAC values with respect to energy for B_4C obtained as a result of the shielding analysis using Phy-X software is shown in Figure 1.

According to Figure 1, MAC values otained for energy values up to 15 MeV are shown. When the energy value reaches to 15 MeV, MAC value decreases to 0.01539 for B_4C. Due to the relationship between energy and mass, the MAC value decreased with increasing energy.

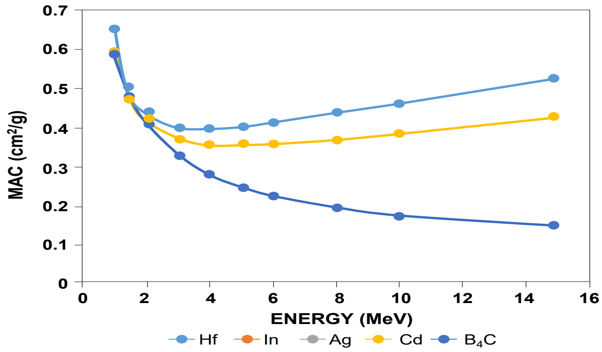

Figure 1. Change in MAC values according to energy.

The linear attenuation coefficient is a measure of the rate of attenuation per unit depth of the incident photon [23]. Its unit is cm^{-1}. Change in LAC values according to selected energy values for B_4C is shown in Figure 2. The fact that the LAC value is high at low energy values and decreases as the energy increases in correlation with the literature [24]. As the photon energy value increased, a sharp decrease in the mass attenuation coefficient value was observed. At low energies, the photoelectric effect is the main interaction mechanism [25].

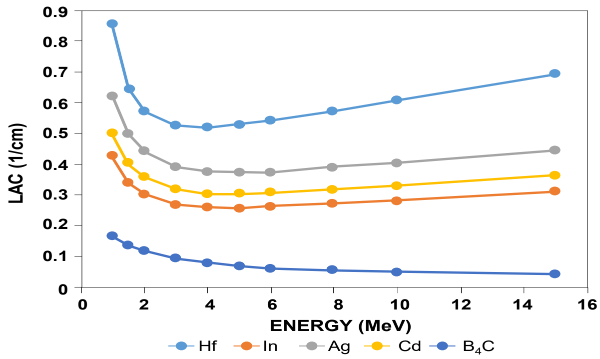

Figure 2. Change in LAC values according to energy.

According to Figure 2, the LAC value reaches to 0.0387 at 15 MeV energy. In a table showing the linear and mass attenuation coefficients for some elements [26], it shows that the mass and linear attenuation coefficients change similarly for increasing energy. In some absorber materials, cross-sections of Compton scattering gain importance between 100 keV and 10 MeV energies. Incoming gamma photons are completely absorbed only in photoelectric absorption. This is not the case with pair production and Compton scattering [27, 28].

The MAC value characterizes the ability of light, sound or particles to penetrate a material. The coefficient is proportional to the material density ρ. The density of boron material is lower than other control rod materials [25]. At the end of the analysis, the MAC value of the boron material was lower than the other control rod materials such as hafnium, indium, silver and cadmium [29].

The choice of fuel cladding material is one of the most important safety barriers in nuclear reactors, as it prevents most of the radioactive fission products from escaping [30]. As a result of the analysis, it was seen that the MAC and LAC values showed an increasing trend in the attenuation of photons in clad materials with high density values. As the density of the clad material increases, there is a tendency to decrease in the passage of photons through the sample [31]. It was found that LAC and MAC values decreased with increasing energy. Maximum MAC and LAC values were observed at the lowest energy tested, and the clad material Hf had the highest MAC and LAC values of all other clad materials studied.

In Figures 3, the HVL, TVL and MFP values change for the clad materials discussed are shown. According to the graphs, the HVL, TVL and MFP values increase as a function of increasing energy. In the low energy region, these values are close to zero. However, since most photons in the Compton scattering region tend to scatter, the average free paths of the photons are longer. This causes a sudden increase in HVL, TVL and MFP values in the middle energy region. While the HVL value was 1 cm for Hf, it was determined as 17 cm for B_4C at 15 MeV. Similarly, while the TVL value was approximately 5 cm for Hf, it was determined to be 54 cm for B_4C. The increase in HVL and TVL values for B_4C with increasing energy is in accordance with the literature [32].

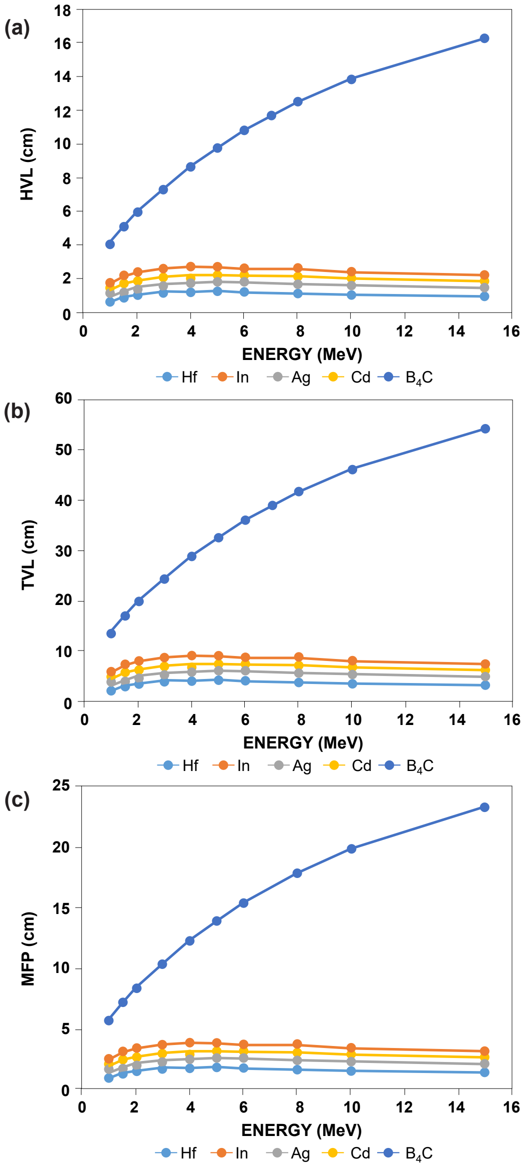

Figure 3. a). Change in HVL values according to energy. b). Change in TVL values according to energy. c). Change in MFP values according to energy.

While MFP, HVL and TVL values increase with energy, the probability of photon shielding decreases with increasing energy. Increasing the density of the clad material results in decreased MFP, HVL, and TVL. The Hf clad material has higher LAC and MAC values and lower MFP, HVL and TVL values than other selected samples.

It is expected that clad materials with high density, high LAC values and low MFP, HVL and TVL values will be preferred as gamma shields [31].

In Figure 3c, the variation of the MFP value is shown. According to the figure, while the MFP value was approximately 1.44 cm for Hf, it was determined to be 23.5 cm for B_4C at 15 MeV. In Figure 3b, MFP variation is the average distance travelled by a gamma ray within a medium until it interacts with the same medium. It is clear that the MFP increases with the increase in incoming gamma energy. The variation of MFP value for B_4C is in agreement with the literature [33]. Similar to MAC and LAC, attenuation performance increases as the density of the clad material increases. Therefore, the Hf material with the highest density has the best shielding efficiency among the clad materials considered.

4. Conclusions

In this research, Phy-X software, an open access software, was used to examine the B_4C material for important radiation interaction parameters, MAC, LAC, HVL, TVL and MFP. The clad materials considered for the study were Hf, In, Ag, Cd and B_4C. Analyzes were made in the energy range between 1 MeV and 15 MeV. As a result of the examination, it was seen that the MAC and LAC values of B_4C was lower than other control rod materials. However, HVL, TVL and MFP values reached higher values than other control rod materials. When the clad materials discussed were compared among themselves, the best radiation shielding property was when Hf was used. However, in clad material selection, some parameters such as the creep resistance, the mechanical strength, the toughness, the neutron radiation resistance, the thermal expansion, the thermal conductivity and the chemical compatibility with fissile products and coolant, moderator and fuel materials are very important. By evaluating all these parameters together, the most suitable clad material can be selected.

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