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Evaluation of shielding performance for newly developed composite materials

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A B S T R A C T

With the advancement of fabrication technology, composite materials that consist of isotopes with different radiation interaction properties can be manufactured and used as effective radiation shielding materials. This work details an investigation into the contributing factors behind the success of newly developed composite shielding materials. Monte Carlo simulation methods were utilized to assess the shielding capabilities for neutron and the secondary radiation production characteristics in four different composite materials: aluminum boron carbide, tungsten boron carbide, bismuth borosilicate glass, and Metathene. The study is performed under neutron irradiations with various energy spectra.

The resulting data regarding shielding performance and generated secondary radiation suggested that tungsten boron carbide was the most effective composite shield material. An analysis of the macroscopic cross-section contributions from constituent materials and interaction mechanisms was then performed in an attempt to better understand the relative shielding performance of the investigated composite materials. This analysis found that increased thermal absorber content was associated with improved neutron shielding performance within both the thermal and epi-thermal neutron energy regions and that composites containing low Z material demonstrated greater shielding performance within the faster neutron energy regions.

1. Introduction

Traditional neutron shielding methods rely on the use of bulk material placed between neutron sources and areas where lower radiation levels are desired. The more effective shield designs usually feature thermal neutron absorbers, which are materials that can readily remove lower energy neutrons through an atomic absorption interaction. Common elements classified as "thermal absorbers" are cadmium (Cd-113) and boron (B-10) (Sakurai et al., 2004). Considering that neutron radiation typically includes neutrons of varying energy levels, methods relying on thermal absorption also require the use of materials intended to moderate, or slow down, faster neutrons. It is well known that materials with lower atomic masses are considered highly effective at this moderation process and are used as the primary means through which fast neutrons are slowed as neutron energy loss via elastic scattering increases with decreasing atomic mass of the target nuclei (Hayashi et al., 2009). Given the shielding techniques briefly outlined above, it is easy to understand why neutron shields commonly feature multiple material layers, with distinct materials targeting the required moderation and absorption interaction mechanisms (Lamarsh and Baratta, 2001). This also leads to the observation that if a single material could effectively perform both functions, neutron shield design could potentially be simplified significantly.

Consequently, the scientific community has taken a great interest in composite neutron shield materials. The important implication regarding composite material use is that a shield consisting of a single composite could potentially include constituent materials that perform both the moderation and thermal absorption functions required for effective neutron shielding. As a result, there is a great deal of effort being directed into developing and researching composite materials that could potentially outperform current neutron shielding materials that rely on separate material layers.

Given the multitude of both potential and already developed composite materials, the research regarding these materials is primarily focused on experimental assessment and determining the effectiveness of the composites in comparison with current shielding methods (Park et al., 2015; Sakurai et al., 2004; Singh et al., 2014). Fortunately, many of these studies have shown promise; specifically, composite neutron shields containing boron carbide or hydrogen polymers have been found to decrease neutron radiation levels as effectively as non-composite shielding systems (Park

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et al., 2015; Sakurai et al., 2004). The purpose of this work is to build upon these investigations and gain a better understanding regarding the relative performance of various composite materials currently being researched for their potential as neutron shields. This is done through a comparison of composite material shielding performance and cross-section decomposition.

2. Evaluated composite materials

This section will briefly introduce the materials evaluated within this work. Aluminum boron carbide, tungsten boron carbide, bismuth borosilicate glass, and Metathene were chosen from a literature review of radiation shielding evaluation experiments that featured a shield composed of two or more elements. They were chosen for their demonstrated or anticipated success as radiation shielding materials.

Aluminum boron carbide, designated within this text as Al-B4C, is a type of aluminum matrix composite (AMC) well known for its superior mechanical properties. AMCs have always been popular within the field of advanced materials engineering due to their universal strength, ductility, and toughness and are commonly improved through reinforcement with harder ceramic materials (Abenojar et al., 2007; Krishna et al., 2013).

Further, the Al-B4C composite is impressive with regards to neutron shielding when one considers the high probability of thermal neutron interaction that boron possesses. As a result of its mechanical properties and inherent thermal neutron absorption characteristics, Al-B4C has been studied extensively for the purposes of radiation shielding (Buyuk et al., 2015; Akkas et al., 2015) and was chosen to be a part of this investigation.

The second material chosen to be investigated is another composite featuring boron carbide. However, in the case of this composite, the aluminum has been chosen to be replaced with tungsten, a much heavier, denser element. The resulting composite, deemed tungsten boron carbide, and referred to as W-B4C within this work, has not been studied extensively with regards to radiation shielding experimentally, however, considering that the analysis within this work is accomplished using simulations, it was decided that a somewhat theoretical composite would be appropriate to investigate. The choice for aluminum to be replaced by tungsten in this theoretical composite stems from the fact that tungsten is a commonly used material in gamma radiation shielding, due its high atomic number (Salimi et al., 2013). Therefore, replacement of aluminum with tungsten could potentially yield a material composite that is effective at shielding both neutrons, due to the boron content, and secondary gamma radiation, due to the tungsten component. Tungsten was chosen over other commonly used high Z shielding materials due to the fact that is not toxic and can be easily mixed with other materials to form composites (Salimi et al., 2013).

Bismuth borosilicate glass, referred to as Bi-BSi within this work, is a specific type of glass that has recently been studied for use as a radiation shielding material. Glasses for use as a shielding material have long been thought to be potentially preferable over other materials due to their inherent transparency (Singh et al., 2014). Further, the shielding properties of glasses can be easily modified by simply varying the chemical composition of the glass. While, this material has been primarily investigated for use as a gamma radiation shield, it does contain boron and a significant amount of high Z material; and therefore has been chosen as a material to be investigated for the purposes of this work.

Metathene is a metathesis-polymer of dicyclopentadiene (DCPD, C10H12) developed by the Hitachi Chemical Co. that has been investigated for use in thermal neutron shielding (Sakurai et al., 2004). The promise of Metathene with regards to neutron shielding lies in its ability to be mixed with common thermal neutron absorbing materials such as LiF, enriched LiF, and B4C in excess of 200% of its own weight during manufacturing (Sakurai et al., 2004). Within this work, the composition chosen to be modeled utilizes B4C as the neutron absorber.

3. Simulation methods

This section will provide a comprehensive description of the simulations, and their associated parameters, that were performed as a part of this investigation. All simulations detailed hereafter were accomplished through use of the MCNP6 software (Goorley et al., 2012).

The selected composite materials were tested across four distinct energy regimes in order to comprehensively characterize their shielding performance capabilities. The energy regimes investigated within this work are referred to as the thermal, epithermal, fast, and high energy energy spectra. These are well-known neutron energy classifications that have been developed as a result of prevalent neutron energies found within nuclear reactors and accelerators. The specific cutoff values for the different energy regimes investigated within this work are based on those utilized as a part of the shielding analysis of the metathesis polymer Metathene discussed within the paper by Sakurai et al. (2004). These values are shown in Table 1.

For simplicity's sake, all simulations within this work then featured monoenergetic neutrons, with a source energy equal to that of the upper boundary for the energy spectrum being investigated. The source energy is also shown in Table 1.

The general geometry utilized for simulated shielding performance within this work can be seen in Fig. 1.

The model features a rectangular plane source, found on the left side of the figure, emitting neutrons normally and monodirectionally towards a voided rectangular prism with a target face having the same dimensions as the source plane. The face of the prism closest to the source plane was the surface used to define the neutron and photon tallies discussed later. During the simulations, the specific composite material being tested for shielding effectiveness was placed between the source plane and target prism, with one face directly against the source plane. The shield geometry was also that of a rectangular prism with face dimensions matching that of both the source plane and target prism. Fig. 2 demonstrates the location of a 1 cm thick shield being placed at the described location.

The weight percentage, or mass fraction, of an element within a compound can be determined through use of Eq. (1).

$$w_i = \frac{M_i * n_i}{\sum_{i=1}^{n} M_i * n_i} \quad (1)$$

where M_i is the atomic mass of the element and n_i is the number of atoms of that element per molecule, for a compound containing n elements.

The theoretical density of that compound can then be estimated through the summation of the weighted elemental densities, ρ_i, via Eq. (2).

Table 1
Energy regime boundaries and source definition.

Energy regime	Lower boundary (eV)	Upper boundary (eV)	Source energy (eV)
Thermal	0.00E+00	5.00E−01	5.00E−01
Epi-thermal	5.00E−01	1.00E+04	1.00E+04
Fast	1.00E+04	1.00E+06	1.00E+06
High energy	1.00E+06	1.50E+07	1.50E+07