Neutron shielding behavior of thermoplastic natural rubber/boron carbide composites

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Abstract. Many shielding materials have been designed against the harm of different types of radiation to the human body. Today, polymer-based lightweight composites have been chosen by the radiation protection industry. In the present study, thermoplastic natural rubber (TPNR) composites with different weight percent of boron carbide (B\textsubscript{4}C) fillers (0\% to 30\%) were fabricated as neutron shielding through melt blending method. Neutron attenuation properties of TPNR/B\textsubscript{4}C composites have been investigated. The macroscopic cross section (\Sigma), half value layer (HVL) and mean free path length (\lambda) of the composites have been calculated and the transmission curves have been plotted. The obtained results show that \Sigma, HVL and \lambda greatly depend on the B\textsubscript{4}C content. Addition of B\textsubscript{4}C fillers into TPNR matrix were found to enhance the macroscopic cross section values thus decrease the mean free path length (\lambda) and half value layer (HVL) of the composites. The transmission curves exhibited that the neutron transmission of the composites decreased with increasing shielding thickness. These results showed that TPNR/B\textsubscript{4}C composites have high potential for neutron shielding applications.

1. Introduction
Exposure to high energy or ionizing radiation may result in cell mutation, cancer and death. Therefore, the radiation must be attenuated enough to protect the personnel from the harmful effects caused by it. Radiation shielding is one of the method to control radiation exposure. To design an appropriate radiation shielding, it is necessary to have known the neutron attenuation properties of the shielding materials. Since radiation interacts with matter, its intensity will decrease as it travels through a materials. The attenuation properties of radiation will affect how much shielding is necessary and how much dosage one receives. Attenuation coefficient is the most important factor in determining the effectiveness of shielding material used [1]. This shielding parameter also known as macroscopic cross section (\Sigma) for neutron is related to half value layer (HVL) and mean free path length (\lambda). Many researchers have determined the values of different shielding parameters in various ways to know the shielding effectiveness of the shielding materials developed [2-5].

Neutrons shielding unlike other forms of radiations introduces some complications because of the wide range of energy that must be considered [6]. High speed neutrons are more difficult to shield against because absorption cross sections are much lower at higher energies. Thus, it is first necessary to moderate high energy neutrons through elastic or inelastic scattering interactions. It is widely known that hydrogenous materials are used as neutron shielding for their effectiveness of neutron moderation. Materials such as water, polyethylene, polyester with higher hydrogen content have greater chance of shielding neutrons [7]. Hydrogenous materials can undergo elastic scattering with
fast and intermediate energy neutrons. When boron is added to hydrogenous materials, it promotes the 
absorption of neutrons and reduces secondary gamma radiation. Boron containing polymer composites 
are generally used since boron compounds have excellent thermal neutrons absorption ability and are 
relatively cheap [8-10]. In this work, thermoplastic natural rubber (TPNR) with various amount of 
oboron carbide (B₄C) fillers were fabricated as neutron shielding and the attenuation properties of the 
composites were investigated.

2. Materials and method
Composites with various filler loadings were prepared by melt mixing method. Natural rubber (NR), 
liquid natural rubber (LNR), high density polyethylene (HDPE) and boron carbide (B₄C) (0-30 wt%) 
were mixed in Haake internal mixer for 15 minutes at 135°C. The composite compound was then 
heated press at 135°C to form a slab.

To investigate the attenuation behavior of the composites against neutron, transmission tests were 
performed by measuring the ratio of incident and transmitted neutron fluxes. Samples with various 
thicknesses were exposed to thermal neutron for equal interval of time using the thermal neutron beam 
from Malaysian Nuclear Agency’s 1 MW TRIGA reactor. Samples were installed at the beam port 
located 719 cm from the source. The transmitted beam was collected using a fission chamber detector 
(Model 3053, LND Inc.).

3. Results and discussion

3.1. Macroscopic cross section, half value layer and mean free path
The capability of neutron shielding material lies on its attenuation coefficient value which is known as 
macroscopic cross section, Σ. The macroscopic cross section is applicable to a thick samples that often 
contain a mixture of elements [11]. Macroscopic cross section can be determined by measuring I and 
I₀ of a shielding material of known thickness (x). When a neutron beam traverses a shielding material, 
the intensity of the beam will be attenuated according to the Beer Lambert’s law:

\[ I = I_0 e^{-\Sigma x} \]  

where I₀ is the initial intensity of neutrons, I is the intensity of neutrons after traversing the medium, Σ 
is the macroscopic cross section and x is the thickness of the medium.

Figure 1 presents the macroscopic cross section of TPNR composites as a function of B₄C filler 
loading. It is clear that macroscopic cross section of the composites with B₄C addition is greater than 
TPNR matrix. The graph reveals a significant increase in macroscopic cross section as the B₄C filler 
loading increase which means that the probability of interaction increases as B₄C content became 
higher. The macroscopic cross section is the probability that a neutron will undergo a reaction per unit 
path length travelled in the material. Therefore, the greater the macroscopic cross section values, the 
higher the number of neutron that can be absorbed by shielding material. The macroscopic cross 
section reaches up to 343% upon raising the B₄C loading to 30 wt%. Increasing of macroscopic cross 
section value of TPNR composites with B₄C loading is due to the high thermal neutron absorption of 
¹⁰B isotope in B₄C. Natural boron consists primarily of two stable isotopes, ¹¹B (80%) and ¹⁰B (20%) 
and its (n, α) reaction cross section for thermal neutrons is about 3840 barns (for 0.025 eV neutron) 
[12].
Figure 1. Macroscopic cross section of TPNR composites as a function of $B_4C$ loading

The calculated macroscopic cross section, half value layer and mean free path length values of TPNR/$B_4C$ composites have been shown in table 1. An increase in $B_4C$ loading decreases the half value layer and mean free path length of the neutron. Half value layer (HVL) is an important parameter in designing any radiation shielding since half value layer indicates the required thickness of an absorber to reduce the radiation level to half of its initial value [13]. HVL is calculated by the following equation:

$$HVL = \frac{\ln 2}{\Sigma} = \frac{0.693}{\Sigma}$$  \hspace{1cm} (2)

where $\Sigma$ is the macroscopic cross section of the absorber. From the table, it is seen that the half value layer decreases from 0.207 cm to 0.047 cm with a weight percent of $B_4C$ increase from 0% to 30% indicating an improvement of the attenuation properties of the composites. This results attributed to the increase of the macroscopic cross section values with the increase of the filler content. The results also indicate that composite with 30 wt% of $B_4C$ loading requires only 0.047 cm of the thickness to attenuate 50% of the neutron intensity thus making it a better shielding material than others.

Similarly, decreasing trend of mean free path length ($\lambda$) values can be seen in table 1. The mean free path length is the average distance between two successive interactions. Neutrons travel on certain mean free path before undergoing a collision. The mean free path appears in the exponential and for this reason it is sometimes called the “relaxation length”. This parameter is equivalent to the reciprocal of macroscopic cross section which is:

$$\lambda = \frac{1}{\Sigma}$$  \hspace{1cm} (3)

where $\Sigma$ is the macroscopic cross section of the absorber. The mean free path length depends on both the type of material and the energy of the neutron. After each collision, the energy is decreased and the mean free path length is affected accordingly [11]. By studying this parameter, the shielding properties of the materials can be easily compared. As shown in table 1, raising the loading of $B_4C$ filler to 30 wt% result in reduction of mean free path length to 77% from the starting value. It also can be
concluded that high B\textsubscript{4}C content can attenuate neutron in a short distance while low amount of B\textsubscript{4}C need a longer distance to attenuate the neutron.

### Table 1. Macroscopic cross section ($\Sigma$), half value layer (HVL) and mean free path length ($\lambda$) values of TPNR composites with various B\textsubscript{4}C loadings.

| B\textsubscript{4}C loading (wt\%) | $\Sigma$ (cm\textsuperscript{-1}) | HVL (cm) | $\lambda$ (cm) |
|-----------------------------------|----------------------------------|----------|----------------|
| 0                                 | 3.343                            | 0.207    | 0.299          |
| 10                                | 7.014                            | 0.098    | 0.143          |
| 20                                | 10.604                           | 0.065    | 0.094          |
| 30                                 | 14.803                           | 0.047    | 0.068          |

#### 3.2. Neutron transmission

Neutron transmission test was conducted for different thicknesses of the composites and the variation of neutron transmission factor ($I/I_o$) with shielding thickness for TPNR composites with 0-30 wt% of B\textsubscript{4}C are depicted in Figure 2. The shape of the graph are approximately the same for all types of composites. Neutron transmission factor ($I/I_o$) decreases with increasing shielding thickness which follows the exponential law (equation 1) for all composites. From this figure, it can be observed that composite with 30 wt% of B\textsubscript{4}C has the lowest neutron transmission factor due to its high macroscopic cross section value. So at this composition, it could be say that the shielding performance against neutron is much better than others. From this figure, it is also shows that higher thickness of shielding material gives a better protection against radiation. Transmission factor at 0.3 cm thickness of 10 wt%, 20 wt% and 30 wt% composites were found to be 0.106, 0.05 and 0.025 respectively. Whereas composite without B\textsubscript{4}C addition has the highest transmission value of 0.369.

![Figure 2. Comparison of neutron transmission factor of composites at different filler loadings](image)

#### 4. Conclusion

Neutron attenuation properties of TPNR filled with various filler loadings of B\textsubscript{4}C were investigated in this study. It has been found that the addition of B\textsubscript{4}C into TPNR matrix greatly influenced the shielding effectiveness of the composites. The macroscopic cross section increases whereas half value...
layer and mean free path length decrease by the increase of B$_4$C filler in the composites. Meanwhile, increasing shielding thickness gives a better transmission against neutron radiation.

5. References

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