A wide energy range neutron shielding material based on natural rubber and boron

Chayanit Jumpee¹, Tithinun Rattanaplome² and Natthaporn Kumwang³

¹Department of Radiologic Technology, Faculty of Associated Medical Sciences, Chiang Mai University, Chiang mai 50200, Thailand
²Faculty of Engineering and Agro-Industry, Maejo University, Chiang Mai, 50290 Thailand
³Nuclear Technology Service Center, Thailand Institute of Nuclear Technology (Public Organization), Ongkharak, Nakorn Nayok, 26120 Thailand

•Corresponding author: chayanitj@cmu.ac.th

Abstract. Neutron have been used in many applications. Neutrons have no electric charge and have high penetrating power. Therefore, the use of neutron shielding material is one of the methods to effectively prevent neutron radiation hazard. In this work, neutron shielding materials were designed using the Monte Carlo N-Particle (MCNP) transport code in order to select proper materials for a wide energy range neutron shielding. Thicknesses of 1 cm and 4 cm were chosen for shielding neutron in the wide energy spectrum \((10^{-8} - 100 \text{ MeV})\). MCNP simulation results indicated that the best shielding material was 2 layers of 2 cm natural rubber (NR) and 2 cm NR with 20 part per hundred rubber (phr) boron powder. This shielding material can reduce the neutron dose by \(17.91 \pm 0.09\%\) with the total macroscopic cross section of \(0.042 \text{ cm}^{-1}\). The optimal neutron shielding materials were fabricated. The mechanical properties and aging properties of shielding materials was found to meet the requirement of Thai Industrial Standard (TIS 2377-2551 Rubber flooring). Therefore, the designed shielding material can be utilized to shield against wide energy range neutrons.

1. Introduction

Neutron is widely used in many applications. As neutrons are high penetrative, they can directly interact with atomic nucleus of living cells. Therefore, exposure to free neutrons could be increased the risk of health problems. Neutron shielding requires materials with an atomic mass close to that of the neutron, for example, hydrogen atom since hydrogen both slows down and scatters neutron. Therefore, hydrogenous materials including water, paraffin and hydrocarbon polymer are usually used for neutron shielding. Natural rubber (NR) is a hydrocarbon polymer which contains a lot of hydrogen atoms. Besides, NR can be easily mixed with high neutron cross-section materials. The combination of NR and high neutron cross-section materials could improve neutron shielding's performance.

There were several studies to investigate the shielding performance of hydrocarbon polymer compounds. Materials composed of epoxy resin and borates mineral, for example, colemamite and ilmenite are used to shield against neutrons. Polyethylene/ boron compound composites are also wildly used for neutron shielding.
flexibility materials for radiation shielding, for example wrapping a neutron shielding layer around irregular shape surface of the neutron source container, NR based material which combined with boron compound materials could be applied (5; 6), however, they were competent to shield only thermal or low energy neutron and, the neutrons emitted from the sources are fast neutrons or high energy neutron which may gradually slow down by collision with the hydrogen atom. Hence, the effective neutron shielding requires a wide energy range neutron shielding materials.

2. Experimental

2.1. Material selection and Design by MCNP simulation

The Monte Carlo method was performed with Monte Carlo N Particle Version 5 (MCNP5) transport code to optimize the designs and compositions of neutron shielding materials. The shielding materials 4 cm thickness were simulated in a spherical shape because preliminary simulation exhibited that fast neutron dose rate initially decreasing. A simulated source of isotropic wide energy range neutron (1E-8 - 100 MeV) was placed at the center of the spherical shielding model. Surface flux tally (F2) with flux to dose rate conversion factors based on the International Commission on Radiological Protection (ICRP-21) was used to determine the neutron dose equivalent rate (rem/h/neutron) on the outer surface of the spherical model. The main compositions of each neutron shielding material were listed in Table 1. The amount of 50 phr Fe$_2$O$_3$ and/or boron were assigned for each neutron shielding sample beneficial to compare their shielding performance. Then determined the optimum amount of Fe$_2$O$_3$ and/or boron additions by simulation shielding material with varying amounts of them.

| Sample No. | Material composition | Density (g/cm$^3$) | Mass ratio of element content |
|------------|---------------------|-------------------|-------------------------------|
|            |                     |                   | H    | C    | $^{10}$B | $^{11}$B | O   | Fe   |
| 0          | No material (Air)   | 0.00120           |       |      |          |          |      |      | Air  |
| 1          | NR                  | 0.9200            | 10.378 | 89.622 | -       | -       | -    | -    |
| 2          | NR+Boron            | 1.1557            | 10.378 | 89.622 | 2.460   | 9.963   | 27.577 | -    |
| 3          | NR+Fe$_2$O$_3$      | 1.2678            | 0.789  | 0.5878 | -       | -       | 0.1002 | 0.2331|
| 4          | NR+Boron+Fe$_2$O$_3$| 1.4346            | 0.0592 | 0.4408 | 0.0498  | 0.2002  | 0.0751 | 0.1748|

| Layer1*    | Layer2              |
|------------|---------------------|
| 5          | Sample 2 (NR+Boron) | Sample 3 (NR+Fe$_2$O$_3$) |
| 5.1        | Sample 3 (NR+Fe$_2$O$_3$) | Sample 2 (NR+Boron) |
| 6          | Sample 1 (NR)      | Sample 2 (NR+Boron)    |
| 6.1        | Sample 2 (NR+Boron) | Sample 1 (NR)         |
| 7          | Sample 1 (NR)      | Sample 3 (NR+ Fe$_2$O$_3$) |
| 7.1        | Sample 3 (NR+ Fe$_2$O$_3$) | Sample 1 (NR) |

* Layer1 is adjacent to neutron source.

2.2. Fabrication of neutron shielding

Material compositions which were the optimum compounds, that got from MCNP simulation were fabricated by semi-efficient vulcanization system including with appropriate rubber chemicals. All
compositions were mixed in a two-roll mill, then an electrically heated hydraulic mold at 150±2 °C was used to vulcanize and fabricate the rubber compound into slab shape.

2.3. Mechanical properties test
All vulcanizing materials both before and after aging at 70 °C for 72 h were investigated the mechanical properties consisting of hardness (Durometer type A: ASTMD2240) and tensile properties (ISO37) that consist of Tensile strength and Elongation at the break.

3. Results and discussion
3.1. MCNP simulation
The MCNP simulation results showed that the sample No.6 (2 layers) exhibited the best neutron shielding efficiency as shown in Figure 1. The initial neutron intensity remaining after being attenuated with shielding material was represented by % neutron transmission which its small value is considered as excellent shielding performance. Although both of sample No.6 and No.6.1 were made by the same compositions, their layers arrangement was difference. Figure 2. Illustrated neutron dose equivalent rate spectra. In fast neutron region (above 1E-2 MeV), neutron dose rate of all samples was similarly attenuated. This was due to the fast neutron slowing down by the elastic scattering with hydrogen atoms which contained in NR, then thermal neutron was produced. For sample No.6 as shown by pink dash-dotted line (Figure 2.) , the 2 cm layer1 of NR which was adjacent to neutron source works as both fast neutron moderator and thermal neutron attenuator because there are the highest hydrogen density, then lower neutron energy as thermal neutron (1E-8 – 1E-2 MeV) was effectively absorbed by boron content which contained in another 2 cm layer2 of NR+Boron. On the other hand, when material of NR+boron become to layer1 as the sample No. 6.1, boron cannot properly absorb neutrons as exhibited by the blue dashed line in Figure 2.

![Figure 1](image1.png)

**Figure 1.** % Neutron transmission (I/I0) of neutron dose equivalent rate.

![Figure 2](image2.png)

**Figure 2.** Neutron dose equivalent rate spectra for various materials.

A simulation of sample No.6 with varying boron amounts of layer2 was carried out to determine the optimized amount of boron. Result reveals that the most appropriate boron amounts were 20 phr as illustrated in Figure 3., it was exhibited that as the amount of boron added to layer2 of sample No. 6 increased, the neutron shielding performance was not increase due to hydrogen atom plays a key role in a wide energy neutron shielding more than that of boron that can only shield against thermal neutron. From MCNP calculation of neutron attenuation, the 4 cm shielding material No.6 having 2 layers of NR and NR with 20 phr boron can reduce the neutron dose by 17.91 ± 0.09 % with the total macroscopic cross section of 0.042 cm⁻¹.
3.2. Mechanical properties test

From MCNP simulation, the optimized neutron shielding designs were fabricated into 2 mm slab sheets. Because of the neutron shielding material unnecessary to stretch and impact, the standard mechanical properties of rubber flooring was considered. The results of mechanical properties are shown in Table 2. Both layers, the elongation at break value were more than 150% and the difference of tensile strength and hardness values of shielding materials between before and after heating (aging) tests were less than 25% and 5, respectively which found to meet the requirement of Thai Industrial Standard (TIS 2377-2551 Rubber flooring).

![Figure 3. %Neutron transmission of sphere neutron shielding at different amount of boron contents (phr)](image)

Table 2. Mechanical properties of NR and NR+20 phr boron before and after aging at 70 °C for 72 h.

| Properties               | NR of Layer1 Before Aging | NR of Layer1 After Aging | Difference | NR + 20 phr boron of Layer2 Before Aging | NR + 20 phr boron of Layer2 After Aging | Difference |
|--------------------------|---------------------------|--------------------------|------------|----------------------------------------|-----------------------------------------|------------|
| Tensile strength (MPa)   | 22.9±1.6                  | 25.3±1.1                 | +10.5%     | 24.5±2.6                               | 25.2±1.4                                | +2.8%      |
| Elongation at break (%)  | 645±14                    | 641.0±12                 | -0.6%      | 727±11                                 | 712.0±16                                | -2.1%      |
| Hardness (Shore A)       | 36.8±0.5                  | 39.4±0.3                 | +2.6       | 33.3±1.3                               | 35.8±0.5                                | +2.5       |

4. Conclusions

The optimized neutron shielding materials were designed using the MCNP transport code. For 4 cm thickness of shielding material, 2 layers of NR and NR with 20 phr boron powder (2 cm each) was the most appropriate for a wide energy range of neutron shielding. The designed shielding materials were well fabricated, and their mechanical properties meet the requirement of TIS 2377-2551 Rubber flooring. The thickness of shielding material should be considered to achieve a desired attenuation level.

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