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ARTICLE

Radiation shielding experiments for composites based on pb-shot and boride

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We have developed a new type of shielding material called as “Double Shield” which consists of Pb-shot 0.5 mm in diameter and boride for shielding both neutron and gamma rays effectively. The transmission neutron measurements were performed with the neutron time-of-flight technique using a BF_3 detector and the neutron attenuation rate of the new product was compared with those of other shielding materials for each energy region. Moreover, the slab attenuation experiments were performed up to 30 cm for the new product, Pb and polyethylene mixed with boron oxide by measuring the leakage neutron and gamma-ray dose rates behind the materials. Based on the results of those experiments, it was verified that the new product has a higher shielding performance with respect to the total amount of neutron and gamma-ray dose rates.

Keywords: ***shielding material; Pb-shot; boride; transmission neutron; KURRI-Linac; Time-of-flight measurement; leakage neutron and gamma rays dose rate***

1. Introduction

Radiation shielding material is an important component in nuclear facilities such as nuclear plants and accelerator facilities. Particularly it is an important issue to minimize the healthy tissue dose rate from all radiations such as neutron, primary and secondary gamma rays in the Boron Neutron Capture Therapy (BNCT) [1]. As the space of radiation shielding is restricted in the case of BNCT, shielding materials with a high attenuation of both neutron and gamma rays are required. The contamination of absorbed dose by fast-neutron and gamma-ray components under the free-air condition was shown in Ref. [2]. The ratios of the gamma-ray dose to the fast-neutron dose were reported as about 26 and 13 % in the cases of mixed radiation fields for BNCT with reactor-based and accelerator-based neutron sources, respectively. Therefore, it is important to develop the appropriate shielding material for the mixed radiation fields where the gamma-ray dose occupies more than 10 % of the total dose. Moreover, the flexibility of material shape is also required for the shielding leakage radiations by streaming.

In this work, a new type of shielding material called as “Double Shield” which consists of Pb-shot 0.5 mm in diameter and boride (H_3BO_3) has been developed. To glue the particles of Pb-shot and boride, $C_6H_{10}O_5$ is mixed with the composite. The hydrogen content of the material is 3.7×10^{22} /cm^3. Inelastic scattering by lead and elastic scattering by hydrogen are effectively slowing down the velocity of fast neutron and ^{10}B can reduce thermal neutrons as an absorber. The primary gamma rays from the neutron source and the secondary ones emitted from the neutron capture reactions in the shielding materials are attenuated by Pb. Therefore, the material contains elements of lead and boride is expected to have high-performance shielding properties in the neutrons and gamma-rays mixed radiation fields. The specific gravity is 4.1 which is equivalents to twice of that of concrete. The construction cost is not much expensive compared with polyethylene and lead blocks. The “Double Shield” also has a flexibility of shapes such as board, brink and sealant.

We have carried out the transmission neutron and the slab attenuation measurements by using the 46-MeV electron linear accelerator at Research Reactor Institute, Kyoto University (KURRI-Linac) as a photo-neutron source [3]. The neutron and gamma-rays shielding performance of the new shielding material was obtained

2. Experiment

2.1. Transmission neutron measurement

The experimental arrangement is shown in **Figure 1**. Pulsed fast neutrons were produced in a water-cooled photo-neutron target [3], which was 5 cm in diameter and 6.1 cm long and composed of 12 sheets of Ta plates

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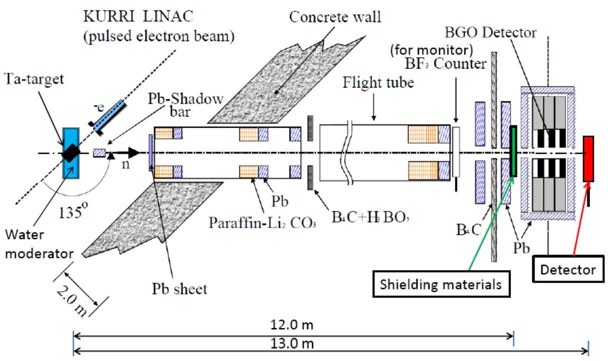

Figure 1. Experimental arrangement for the transmission neutron TOF and the slab attenuation measurement with the KURRI-Linac

with the total thickness of 29 mm. The fast neutrons were moderated in an octagonal water tank, 30 cm in diameter and 10 cm thick, placed besides the target. The intense bremsstrahlung was also produced at the Ta target. Consequently, the moderated neutrons and intense gamma-rays mixed radiation fields were provided in the source.

The measurements of transmission neutrons for the shielding material were performed with the neutron time-of-flight (TOF) technique under the following Linac conditions: the electron energy, about 30 MeV; pulse repetition rate, 50 Hz; pulse width, 100 ns; and average electron current, about 17 μA. The flight path used in the experiment is in the direction of 135° to the electron beam. The neutron beam was collimated to 2 cm in diameter with the collimation system composed of B_4C, Li_2CO_3 and Pb materials. A sample was placed at a distance of 12.0 m from the neutron source and the transmission neutrons were measured with a BF_3 detector placed at a distance of 13.0 m from the neutron source. Blocks (10 cm wide, 20 cm height and 5 cm thick) of the Double Shield, Pb and polyethylene mixed with 10 % boron oxide were used as samples. The element content of Double Shield is shown in **Table 1**. The output signals from the detector and the trigger signals from the accelerator were stored with the list mode using the Yokogawa's WE7562 multi channel analyzer. The transmission neutron TOF spectra were obtained by gating on the pulse-height region for the $^{10}B(n,\alpha)$ reaction.

Table 1. Element content of the Double Shield

Element	Number of density $\times 10^{22}$(/cm^3)
Pb	0.814
B	0.546
O	4.10
H	3.69
C	0.150

2.2. Slab attenuation measurement

The leakage neutron and gamma-ray dose rates were measured behind the materials, respectively. A neutron remcounter (ALOKA TPS-451C) was used for the measurement of neutron dose equivalent. An ionization chamber (ALOKA ICS-313) was used for the measurement of gamma-ray dose equivalent. The positions of sample and detector were same as the transmission neutron measurement. Thickness of shielding material was increased by 5 cm up to 30 cm.

3. Calculation

In order to estimate the neutron shielding effect due to the elements included in Double Shield, calculations with a Monte Carlo code MCNP-4C [4] were performed. A simplified model was used: a neutron source is located at the center of a sphere. In the sphere, we set two material regions with a thickness of 10 cm as shown in **Figure 2**. Those regions were filled with the shielding materials, respectively. The radius of the outer sphere is 150 cm and the neutron flux was estimated on the outer surface of the sphere. A Maxwell fission spectrum was used as a source. We performed three kinds of calculations as shown in **Table 2**. The densities of Pb and H_3BO_3 used in the calculation-2 and 3 were adjusted as the effective thickness of each nucleus was equal to that of Double Shield in the calculation-1.

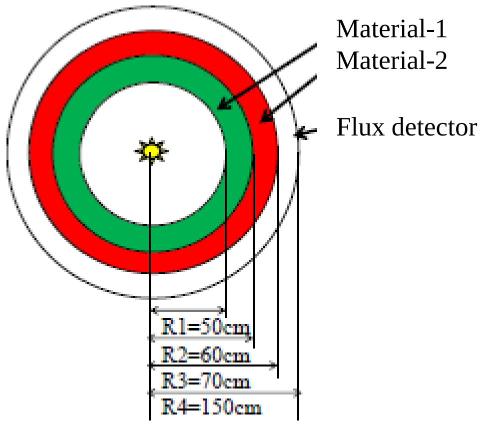

Figure 2. Schematic representation of the Monte Carlo model

Table 2. Geometric conditions of the calculations

Calculation	Material-1(Inside)	Material-2(Outside)
1	Double Shield	Double-Shield
2	Pb	H_3BO_3
3	H_3BO_3	Pb

4. Results and discussion

4.1. Neutron transmission rate

The TOF spectra obtained by measuring transmission neutrons are shown in **Figure 3**. The TOF spectrum without sample (Blank), which means an incident neutron spectrum on the sample, is represented by black open circle in Fig. 3. The neutron attenuation rate was obtained for each energy region by comparing with the incident neutron flux as shown in **Figure 4**. Below 1 eV, there are no differences between Double Shield and polyethylene mixed with 10 % boron oxide. In the epithermal region, the attenuation rate of Double Shield with a thickness of 5 cm was better than that of Pb with a thickness of 10 cm.

4.2. Dose rate of leakage neutron and gamma rays

Figures 5 and **6** show the comparison of leakage neutron and gamma-ray dose rate changes among shielding materials. The gamma-ray dose rate is about 10 % of the neutron dose rate without the shielding material. It is worth noting that the mixed radiation field used in the experiment reproduces a BNCT irradiation field in the viewpoints of balance between neutron and gamma-ray doses.

The dose rate of leakage neutron for Double Shield was converging on the background level at the thickness of 30 cm. The thickness is about 1.5 times that of the polyethylene mixed with 10 % boron oxide. The dose rate of leakage gamma ray for Double Shield was decreasing with thickness exponentially. On the other hands, the dose rate for polyethylene mixed with 10 % boron oxide was converging on the level higher than background around the thickness of 25 cm. It seems that primary and secondary gamma rays cannot be reduced. The comparison of leakage total dose rate changes is shown in **Figure 7**. It was found that the total dose rate of Double Shield was effectively decreasing compared with Pb and polyethylene mixed with 10 % boron oxide.

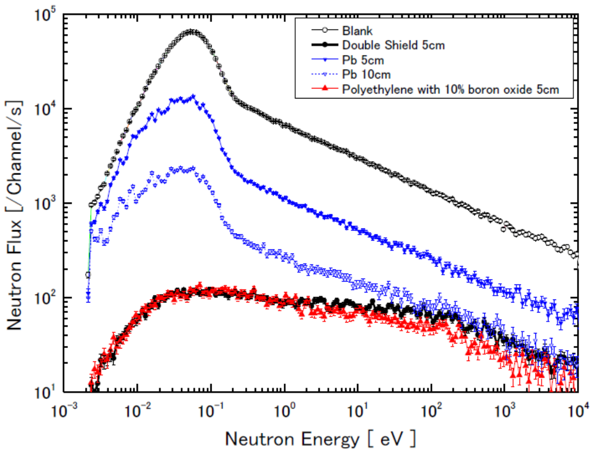

Figure 3. Transmission neutron TOF spectra for shielding materials

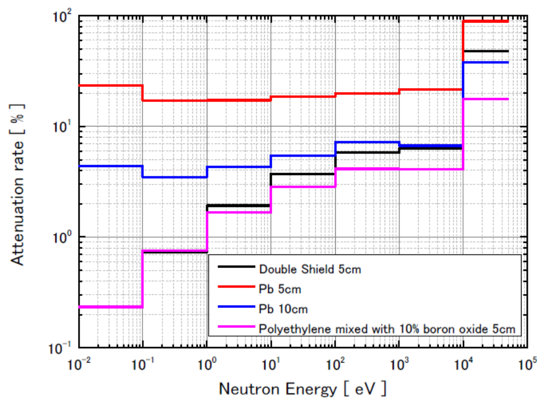

Figure 4. Comparison of neutron attenuation rate among shielding materials

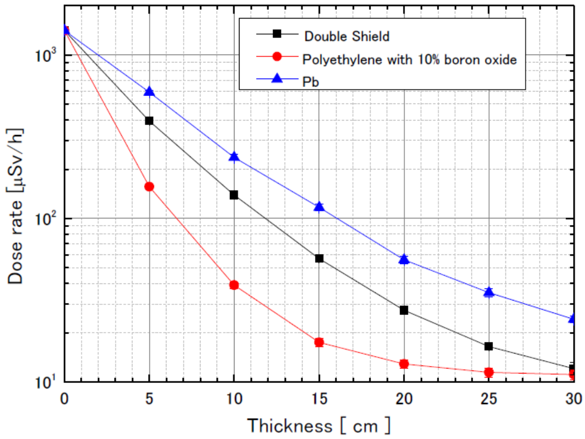

Figure 5. Comparison of leakage neutron dose rate changes among shielding materials

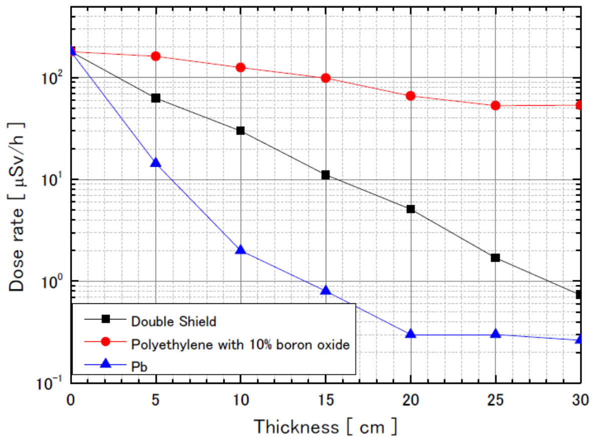

Figure 6. Comparison of leakage gamma-ray dose rate changes among shielding materials

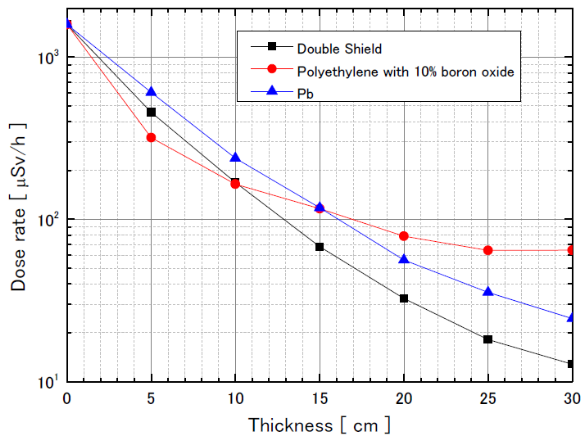

Figure 7. Comparison of leakage total dose rate changes among shielding materials

4.3. Calculation results

The comparison of neutron energy spectra obtained by calculation-1, 2 and 3 is shown in **Figure 8**. It is found that the high energy components above 100 keV are effectively reduced by locating lead inside. The results show that the inelastic scattering by lead has an important role to reduce the high energy components. In the case of calculation-1, the reduction rate for high energy neutron is close to that of calculation-2. In the case of calculation-3, the reduction rates in the high energy region (> 100 keV) and low energy region (<0.1 eV) are much smaller than those of the other cases since the slowing down is not sufficiently done in the material-1 region. Therefore, it is expected that the high-energy neutron can be effectively reduced by mixing Pb-shots to the shielding material for the neutron source with a Maxwell fission spectrum.

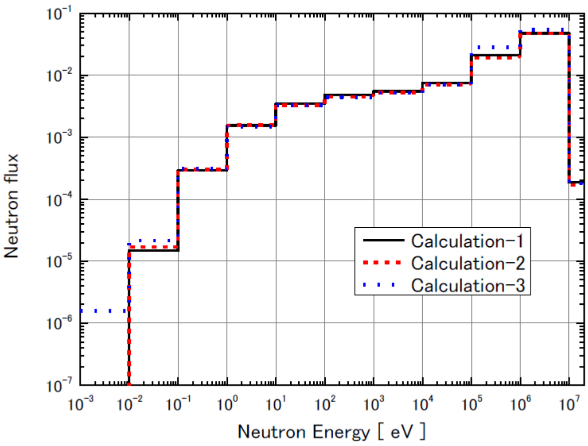

Figure 8. Comparison of neutron energy spectra obtained by calculation-1,2 and 3

5. Summary

We have carried out the transmission neutron measurement with the TOF technique and obtained the attenuation rate of the new shielding material called as “Double Shield” for each energy region. Moreover, the leakage neutron and gamma-ray dose rates were measured for several shielding materials. Based on the results of those experiments, it was verified that Double Shield has a higher shielding performance compared to usual shielding materials in the neutrons and gamma-rays mixed radiation fields.

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