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Assessment of the Absorbed Dose Components of BNCT Method at the Dalat Research Reactor

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Abstract:

At the Dalat Nuclear Research Reactor (DNRR) in Vietnam, some calculations and experiments of the Boron Neutron Capture Therapy (BNCT) method have been performed at horizontal channel No. 2 of the DNRR using a phantom. This research used the Monte Carlo N-Particle version 5 (MCNP5) code to simulate and calculate the distribution of absorbed dose components of the BNCT method. The collimator of horizontal neutron channel No. 2 of the DNRR was changed from cylindrical to conical to increase the flux of the neutron beam. Simultaneously, neutron crystal filters corresponding to 20 cm Si and 3 cm Bi are also employed to produce high-purity thermal neutron beams. The thermal neutron flux and absorbed dose components have been computed in a water phantom. The gamma dose from the reactor core of the DNRR can be omitted when calculating the total absorbed dose in the BNCT method.

Keywords **—BNCT, water phantom, absorbed dose,MCNP, collimator**

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1. INTRODUCTION

Boron Neutron Capture Therapy (BNCT) will selectively damage cancer cells that are difficult to achieve with other treatments. Therefore, BNCT was suggested as a possibility to treat brain tumors in 1951 [1-3]. So far, the neutron sources for BNCT are a thermal nuclear research reactor or an accelerator [4–5]. For example, the HANARO reactor in Korea [3] used a combination of single-crystal Si and Bi filters to generate a thermal neutron beam for BNCT research because single-crystal Si and Bi have a relatively small total cross-section for thermal neutrons. Furthermore, single-crystal Bi reduces gamma rays mixed in the neutron beam from the reactor core as well as secondary gamma rays created by the single-crystal Si filter. As a result, they are often used to generate pure thermal neutron beams.Before conducting clinical trials, preclinical studies are often simulated and tested on models (phantoms). Two types of materials commonly used to design phantoms for BNCT research are water and polyethylene because the densities of these two materials are almost similar to that of tissue. Water phantom has been used experimentally at the Tehran research reactor (TRR) in Iran[6]. For the last ten years, simulation calculations and experiments related to the absorbed dose of the BNCT method have been performed at horizontal channel No. 2 of the DNRR in Vietnam. However, the gamma dose (including the dose of gamma rays from the reactor and gamma rays produced by the reaction of the phantom material with neutrons) has not been calculated in detail. This study provides information about assessing the absorbed dose components of the BNCT method using the MCNP5 code. These include improvements in the shape of the collimator to increase the thermal neutron flux and detailed calculations of component gamma doses.

2. MATERIALS AND METHODS

2.1. Confirm the simulated values for cylindrical collimator by experiments

The DNRR is a 500 kW pool-type research reactor with four horizontal neutron channels. Three of the neutron channels (Nos. 1, 2, and 4) are oriented radially toward the reactor core's center, whereas channel No. 3 is tangential to the reactor core's outer edge [7-8].

Currently, the horizontal channel No.2 design includes a cylindrical collimator with a total length of 240.3 cm made upof two parts. The first part is 150.3 cm long and 9 cm in diameter. It installs neutron filters made of Si and Bi crystals with thicknesses of 20 cm and 3 cm, respectively. The second part is 90 cm long with an outer diameter of 20.1 cm and a inner diameter of 3cm. The current configuration of horizontal channel No. 2 is seen in Figure 1.

An aluminum plate is used to stop water leaks, while the lining layers around the collimators are composed of Pb and WWX-277 (a neutron shielding material from the Shieldwerx company) as gamma and neutron absorption materials, respectively [9].

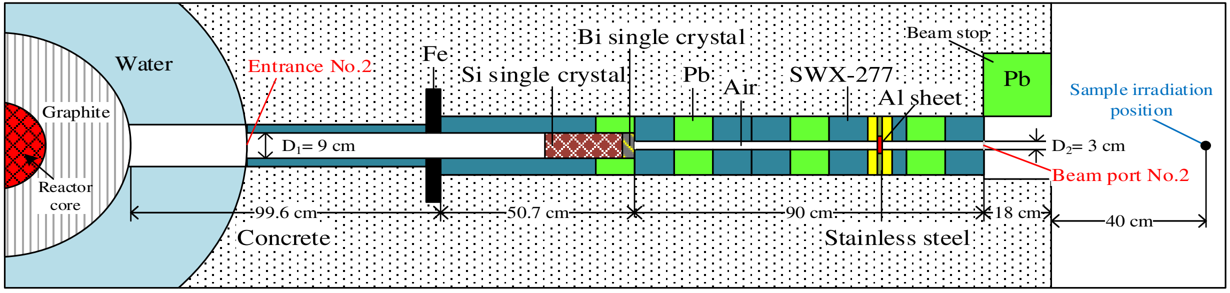

Fig.1. Structure of horizontal channel No.2 with the cylindrical collimator

As shown in Figure 1, a thermal neutron beam will be generated after passing through a single-crystal filter assembly made up of 20 cm Si and 3 cm Bi, which will be used for a variety of applications such as nuclear data measurement, neutron activation analysis, and BNCT research.

First, the MCNP5 code is used to simulate the structure of horizontal channel No. 2 in Figure 1, and then the thermal neutron flux and gamma dose rate in the water phantom were calculated using tally F4 with the DE4/DF4 cards of MCNP5. The following equations [10] are used to compute these values:

$$\phi_{th} = \int_{1\,\mathrm{meV}}^{E_{Cd}=0.5\,\mathrm{eV}} \varphi_n(E)dE \qquad (1)$$

$$\dot{D}_\gamma = \int_{E_1}^{E_2} \varphi_n(E)R(E)dE \qquad (2)$$

where $\phi_{th}$is the thermal neutron flux, and φ_n(E)is the neutron flux. In this paper, the energy range of thermal neutrons (0.025 eV) is calculated from 1.0×10^{-3} eV to 0.5 eV, $\dot{D}_\gamma$ is the gamma dose rate and R(E) is the conversion factor of neutron flux to gamma dose rate.

Second, we used the activation foils and Thermoluminescent Dosimeters to measure thermal neutron flux and gamma, respectively, to validate the above-simulated and computed values. The results showed that there was a good agreement between experimental and simulation results for the thermal neutron flux and gamma dose rate, as reported by us [11].

2.2. Change the shape of the collimator to increase the neutron flux

Finally, we utilized the MCNP5 code to simulate modifying the form of the neutron collimator to increase the flux of the neutron beam, which also increases the total absorbed dose of the BNCT method, as shown in Eq. (3). The conical collimator design of horizontal channel No. 2, which was simulated to increase the neutron flux and calculate the total absorbed dose for the BNCT application, is seen in Figure 2. The simulated result of thermal neutron flux at 2 cm depth in the phantom supplied by the conical collimator may be enhanced by a factor of 8.35, as shown in Table 1.

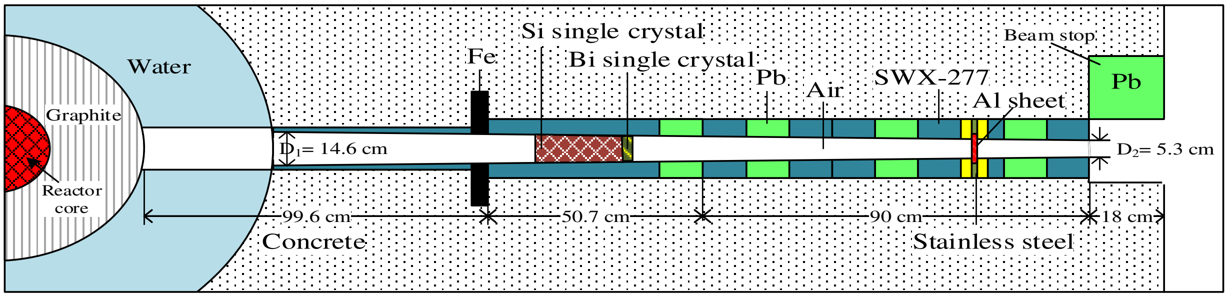

Fig.2. Structure of horizontal channel No.2 with the new collimator (conical shape)

Table 1. Simulated results of the thermal neutron flux and gamma dose rate forthe cylindrical and conical collimators

Type of collimator	Thermal neutron flux ϕ_{th} $(n.cm^{2}.s^{-1})$	Gamma dose & rate D_γ $(Gy.h^{-1})$	Filters (cm)	
			Si	Bi
Cylinderical collimator (A)	1.12×10^{7}	1.89×10^{-3}	20	3
Conical collimator (B)	9.35×10^{7}	1.90×10^{-2}	20	3
Ratio B/A	8.35	10.05		

2.3. Calculation of absorbed dose components

There are four absorbed dose components that are often studied in BNCT: (i) boron dose, (ii) thermal neutron dose, (iii) gamma dose, and (iv) fast neutron dose [12-15]. However, with the current configuration of horizontal channel No. 2, the fast neutron dose is extremely low and may be negligible. Consequently, the following estimate of the total absorbed dose in BNCT is [13-14]:

$$\begin{aligned} D &= D_B + D_N + D_\gamma \\ &= (7.43\times10^{-14}\times C_B + 6.78\times10^{-14}\times C_N)\times\Phi_{th} + D_\gamma \end{aligned} \qquad (3)$$

where D is the total absorbed dose; D_B is the boron dose; D_N is the thermal neutron dose; D_γ is the gamma dose, including gamma from the reactor coreand gamma generated by the interaction of thermal neutrons with the hydrogen of the water phantom; C_B is the concentration of ^{10}B (the value chosen in this calculation is 30 ppm); C_N is the concentration of ^{14}N (chosen to be 2%)[14], and Φ_{th} is the thermal neutron fluence $(n.cm^{-2})$. When calculating dose in BNCT, the concept of thermal neutron fluence (Φ_{th}) is often used instead of the concept of thermal neutron flux (ϕ_{th}). The relationship between these two quantities is calculated as follow:

$$\Phi_{th} = \phi_{th} \times t \qquad (4)$$

where t is the time in seconds.

3. Results and Discussion

3.1. Neutron fluxes and gamma doses for the conical collimator

According to Table 1, when both the shape and the solid angle of the collimator are changed, the thermal neutron flux and gamma dose rate increase approximately 8.35 times and 10.05 times, respectively. Simulation results for the distribution of thermal neutron flux and gamma dose in the water phantom are presented in Tables 2 and 3, respectively.

Table 2. Thermal simulated neutron flux along the central axis of the phantom by MCNP5

No.	Position (cm)	ϕ_{th} $(n.cm^{-2}.s^{-1})$	
		Mean	Error (%)
1	0	1.46×10^{8}	1
2	0.5	1.78×10^{8}	1
3	1	1.49×10^{8}	1
4	2	9.35×10^{7}	1
5	3	5.69×10^{7}	1
6	4	3.53×10^{7}	1
7	5	2.20×10^{7}	1
8	6	1.42×10^{7}	1
9	7	9.32×10^{6}	1
10	8	6.15×10^{6}	2
11	9	4.05×10^{6}	2
12	10	2.70×10^{6}	2

Table 3. Gamma dose along the central axis of the phantom simulated by MCNP5

No.	Position (cm)	D_γ (Gy) from reactor, with phantom		D_γ (Gy) from reactor, without phantom	
		Mean	Error (%)	Mean	Error (%)
1	0	5.99×10^{-6}	1	4.56×10^{-8}	7
2	0.5	8.11×10^{-6}	1	4.64×10^{-8}	7
3	1	8.02×10^{-6}	1	4.93×10^{-8}	7
4	2	6.88×10^{-6}	1	4.47×10^{-8}	7
5	3	5.27×10^{-6}	1	4.36×10^{-8}	7
6	4	4.00×10^{-6}	1	4.47×10^{-8}	7
7	5	3.06×10^{-6}	1	4.43×10^{-8}	7
8	6	2.39×10^{-6}	2	4.21×10^{-8}	7
9	7	1.79×10^{-6}	2	4.41×10^{-8}	8
10	8	1.38×10^{-6}	2	4.23×10^{-8}	8
11	9	1.14×10^{-6}	2	3.98×10^{-8}	8
12	10	8.74×10^{-7}	2	4.22×10^{-8}	8

Table 2 and Figure 3 show that the maximum value of thermal neutron flux is 1.78×10^{8} n.cm^{-2}.s^{-1} at 0.5 cm depth and then decreases to 5.69×10^{7} n.cm^{-2}.s^{-1} at 3 cm depth in the water phantom.

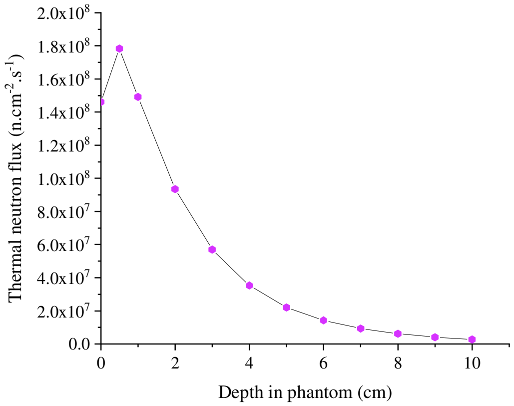

Fig. 3. Thermal neutron flux distribution in the phantom

Figure 4 displays the two-dimensional distribution of the thermal neutron flux in the phantom. The neutron flux area accounts for approximately 87% (with a value of 1.25×10^{8} n.cm^{-2}.s^{-1}) of the total neutron flux, which is dispersed mostly from the phantom surface to a depth of about 3 cm and drastically decreases at depths higher than 5 cm in the phantom.

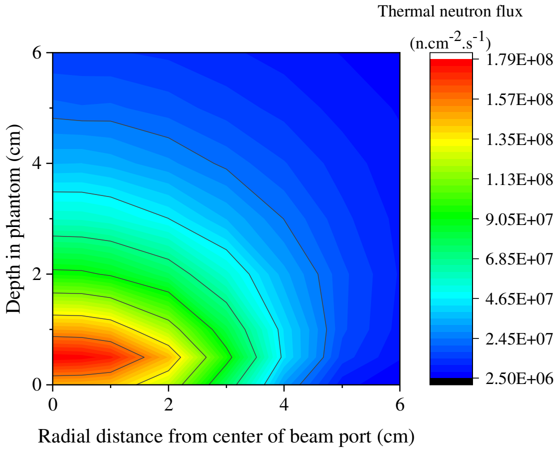

Fig. 4. 2-D thermal neutron flux distribution in the phantom

3.2. Absorbed dose components of BNCT method

After obtaining the simulated values of thermal neutron flux and gamma dose, as indicated in Tables 2 and 3, respectively, the total absorbed dose of the BNCT method has been calculated by applying Eqs. (3) and (4). The results of these calculations are reported in Table 4.

Table 4. Calculated results of the total absorbed dose in the water phantom for the conical collimatior

No.	Position (cm)	Dose (Gy)				
		Boron dose D_B	Thermal neutron dose D_N	Gamma dose D_γ (with phantom)	Gamma dose D_γ (without phantom)	Total absorbed dose D
1	0	3.25×10^{-4}	1.98×10^{-5}	5.99×10^{-6}	4.56×10^{-8}	3.51×10^{-4}
2	0.5	3.97×10^{-4}	2.41×10^{-5}	8.11×10^{-6}	4.64×10^{-8}	4.29×10^{-4}
3	1	3.32×10^{-4}	2.02×10^{-5}	8.02×10^{-6}	4.93×10^{-8}	3.60×10^{-4}
4	2	2.08×10^{-4}	1.27×10^{-5}	6.88×10^{-6}	4.47×10^{-8}	2.28×10^{-4}

No.	Position (cm)	Dose (Gy) Boron dose D_B	Thermal neutron dose D_N	Gamma dose D_γ (with phantom)	Gamma dose D_γ (without phantom)	Total absorbed dose D
5	3	1.27×10^{-4}	7.72×10^{-6}	5.27×10^{-6}	4.36×10^{-8}	1.40×10^{-4}
6	4	7.87×10^{-5}	4.79×10^{-6}	4.00×10^{-6}	4.47×10^{-8}	8.75×10^{-5}
7	5	4.90×10^{-5}	2.98×10^{-6}	3.06×10^{-6}	4.43×10^{-8}	5.51×10^{-5}
8	6	3.17×10^{-5}	1.93×10^{-6}	2.39×10^{-6}	4.21×10^{-8}	3.60×10^{-5}
9	7	2.08×10^{-5}	1.26×10^{-6}	1.79×10^{-6}	4.41×10^{-8}	2.39×10^{-5}
10	8	1.37×10^{-5}	8.34×10^{-7}	1.38×10^{-6}	4.23×10^{-8}	1.60×10^{-5}
11	9	9.03×10^{-6}	5.49×10^{-7}	1.14×10^{-6}	3.98×10^{-8}	1.08×10^{-5}
12	10	6.02×10^{-6}	3.66×10^{-7}	8.74×10^{-7}	4.22×10^{-8}	7.30×10^{-6}

Note: The concentrations of boron (C_B) and nitrogen (C_N) used are 30 ppm and 2%, respectively.

The reactions captured thermal neutrons from hydrogen in the water phantom $^{1}H(n,\gamma)^{2}H$, which mainly contributed to the gamma dose in the water phantom, as shown in Table 3 and Figure 5.

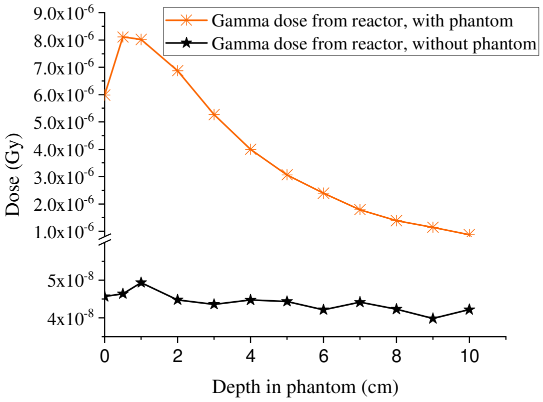

Fig. 5. Gamma dose distribution by in the phantom

The gamma radiation at the phantom's surface is enhanced approximately 130 times compared to that without the phantom (from 4.56×10^{-8} Gy to 5.99×10^{-6} Gy) but about three times lower than the thermal neutron dose, as presented in Figure 6.Furthermore, Figures 3 and 5 indicate that the curves of thermal neutron flux and gamma dose have the same shape, which means the thermal neutron capture reaction of hydrogen mainly contributed to the gamma dose.The MCNP5 calculation also revealed that the thermal neutron dose was approximately three times greater than the gamma dose (Figure 6). Our results also indicate that the gamma dose is the most significant difference when using the horizontal channel or the thermal column of the reactor for BNCT research. It is smaller than the thermal neutron dose for the horizontal channel at DNRR in Figure 7(a), but not for the thermal column of a reactor at TRR in Figure 7(b).

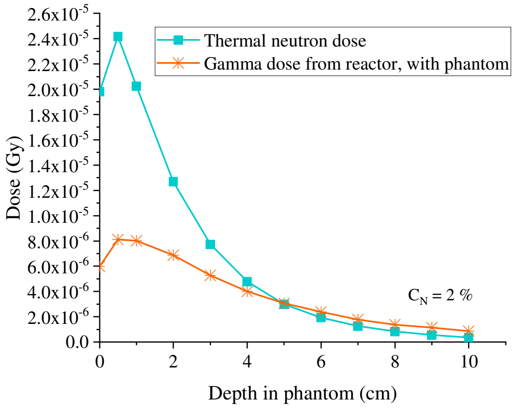

Fig. 6. Gamma and thermal neutron doses distribution in phantom

The absorbed dose components along the central axis of the water phantom at the DNRR are shown in Figure 7(a). The total absorbed dose, reaching a maximum of 4.24×10^{-4} Gy at 0.5 cm depth and rapidly decreasing to 1.36×10^{-4} Gy at 3 cm depth in the phantom, is mainly due to the boron and thermal neutron doses. Our results also show a relative agreement between the shapes of absorbed dose components in the phantom simulated at the DNRR and the results measured in the phantom at the TRR in Iran in Figure 7(b).

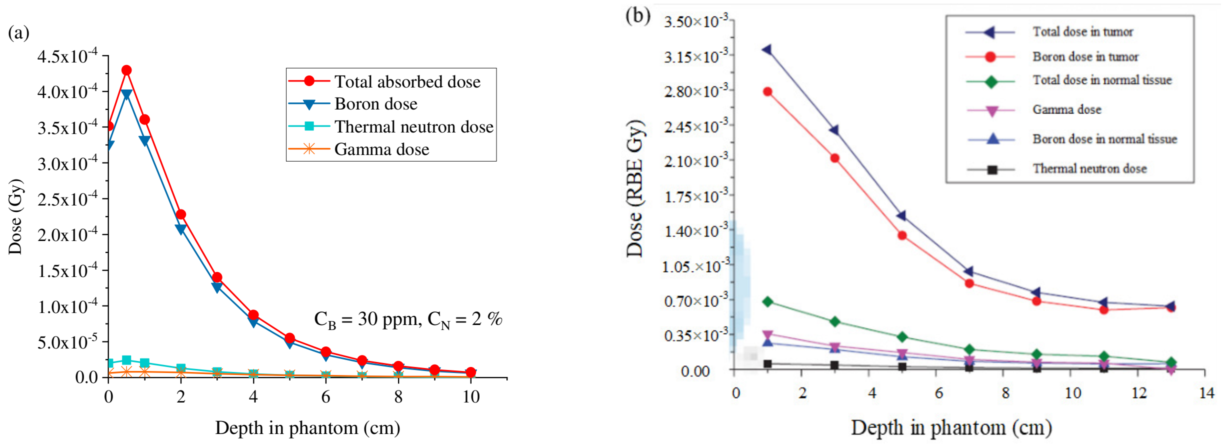

Fig. 7. Distribution of absorbed dose components in the phantom: (a) at DNRR; (b) at TRR

4. Conclusion

The MCNP5 code was used to assess the contribution of absorbed dose components in a water phantom of BNCT research at the DNRR. The total absorbed dose depends mainly on the boron and thermal neutron doses. The gamma dose from the reactor core of the DNRR contributes very little compared to the gamma dose generated from the phantom material, and it can be omitted when calculating the total absorbed dose in the BNCT method.

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Competing Interest: The authors have declared that no competing interest exists.

Ethical approval: This study does not contain any studies with human or animal subjects performed by any of the authors.

Author Contributions: The first draft of the manuscript was written by Pham Dang Quyet and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.