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Optimization and designing collimator for boron neutron capture therapy at the thermal column of RTP

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Abstract. Boron Neutron Capture Therapy (BNCT) is a promising method to cure cancer by using interaction between boron compound and the slow neutron beam obtained from nuclear power reactor, nuclear research reactor and neutron generator. Based on the previous feasibility study shows that the thermal column can generate higher thermal neutrons for BNCT application at the TRIGA MARK II reactor. Currently, the facility for BNCT are planned to be developed at thermal column. Thus, the main objective was focused on the optimization of thermal neutron and epithermal neutron flux at the thermal column by designing collimator. This paper briefly goes through the characterization of collimator for the ideal neutron collimator design. Several collimators with variable geometries have been designed using Monte Carlo Simulation Codes of MCNPX. The results are then compared in term of thermal neutron, epithermal neutron and gamma fluxes yielded and the ideal collimator then optimize based on aperture size, shielding thickness and collimator condition This research is useful in the selection of neutron collimator design BNCT facility at the TRIGA MARK II reactor.

1. Introduction

BNCT is one of the promising methods in order to cure cancer that used the combination of low energy of neutron (slow neutron) irradiation and the targeting of a tumour site injected with a proper boron containing compound. Basically, the tumour cell was not directly destructed by neutron, but indirectly destroyed by the results of nuclear reaction between neutron and boron [1]. In theory, the BNCT also is one of the forms of radiotherapy which is selectively kills the cancer cells and less effect on other normal cell that used photon that will selectively deposited in tumour cell of Boron carriers such as BPA and BSH [2]. The standard Boron carries compound must be enriched by Boron-10 with about 20% natural abundance. The patient will be irradiated with slow energy of neutron to reach the ratio of high concentration of boron in the tumour cell [3]. The irradiation with slow neutron will cause the nuclear reaction of Boron -10 capture of the thermal neutron and, as a result, of production Boron-10 converts into Boron-11 which then decay into ^{7}Li and emits of an alpha particle [4] that destroy the cancerous cells.

The thermal column of TRIGA MARK II research reactor was believed to supply a sufficient proportion of neutron beam for developing BNCT facility [5]. The thermal neutron flux measurement at the thermal column showed that the thermal neutron flux inside the thermal column was 1.17 x

10^{10} neutron. $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.which is higher than the IAEA requirement for BNCT (1.0 x 10^9 neutron. $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) at 1000kW based on previous research [6]. Unfortunately, those thermal neutron fluxes were decreased to 8.58 x 10^8 neutron. $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ as per measurement at the thermal column door [7]. Thus, the optimization on the thermal neutron flux at the outside section of the thermal column is needed to get the optimize thermal neutron flux inside the thermal column for BNCT facility by designing a neutron collimator.

In order to optimize the neutron beam at RTP for BNCT research facility purpose, the modification for the thermal column must include the designing and installing the neutron collimator [7]. Collimator is well known as a beam limiting device that is widely used in various industries including optical, medical and nuclear [8]. Collimator or beam limiting device acts as a filter of the beam that just allows the beam in a specific direction to travel through. Generally, neutron collimator is composed of the combination of neutron collimating materials, neutron moderator materials and neutron shielding material [8].

2. Design selection

There are several design of collimators with different geometries and materials that have been simulated by using MCNPX Visual Editor as shown in Table 1 and Figure 1. All the collimators have a same total length for the simulation and, only aluminum is fixed as a casing for the collimator because of the low activation energy characteristic as compare to other material and is widely used in nuclear reactor and nuclear applications such as nuclear waste storage and other reactor application [9]. There are two parts of collimator of the thermal column, that is the inner part and outer part. Both parts have different diameter and length, as the inner part has small diameter which is 20 cm with 51.8 cm long while the outer part consist of 24 cm diameter and 54.8 cm of length. In fact, the collimators work based on the principle of radiation interaction with matter, by shifting or filtering methods. The shifting method uses a moderator to lower the neutron energy whereas the filtering method uses materials to absorb neutrons in certain energies [8]. Thermal neutron, fast neutron, and gamma flux were simulated using MCNPX simulation code at the end window of the collimator. The measured flux was divided into two regions which is the centre and outer region. The reason is to identify the difference of the flux values at both regions [10].

Table 1. Summarization of materials used in collimator design.

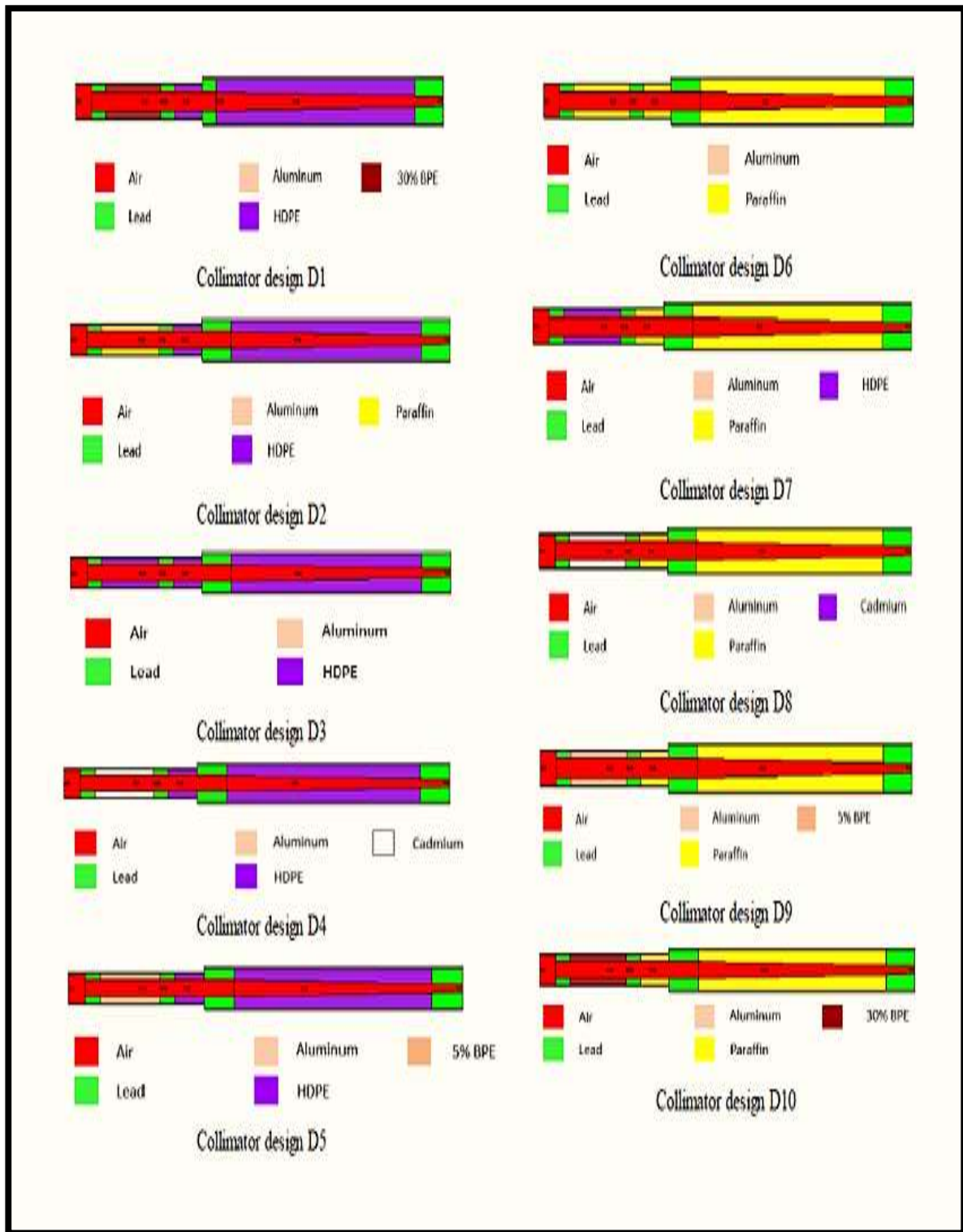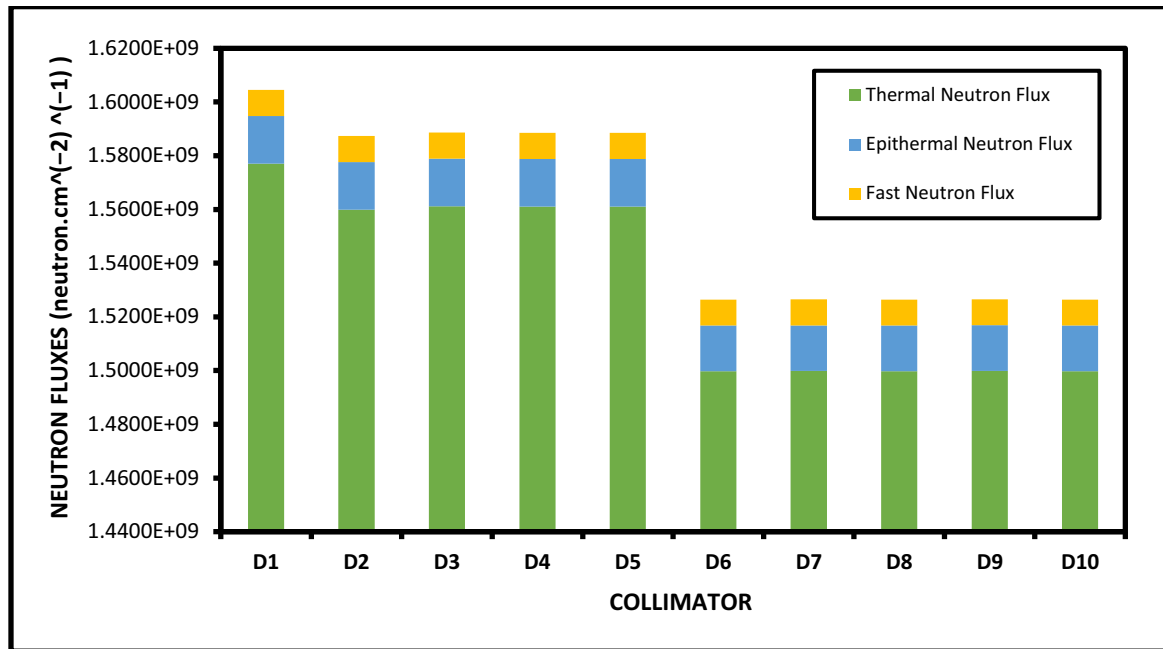| No. of Collimator Design	Material
D1	HDPE + Aluminium + Lead + 30% BPE
D2	HDPE + Aluminium + Lead + Paraffin
D3	HDPE + Aluminium + Lead
D4	HDPE + Aluminium + Lead + Cadmium
D5	HDPE + Aluminium + Lead + 5% BPE
D6	Paraffin + Aluminium + Lead
D7	Paraffin + Aluminium + Lead + HDPE
D8	Paraffin + Aluminium + Lead + Cadmium
D9	Paraffin + Aluminium + Lead + 5% BPE
D10	Paraffin + Aluminium + Lead + 30% BPE

Figure 1. The collimator design D1-D10.

3. Results and discussion

The results obtained from MCNPX code at the centre and outer part of collimator tube were displayed in Figure 2.

Figure 2. Graph of neutron flux across the beam line of collimator with different material.

Based on the geometries presented in Figure 1, the simulation results show that most of the collimator designs have the same range of neutron flux (thermal, epithermal and fast). For the thermal neutron flux, average flux obtained was $3.75 \times 10^9 \text{neutron.cm}^{-2}\text{s}^{-1}$ and the highest thermal neutron produced was from design D1 that comprise of lead, 30% borated polyethylene, HDPE and aluminium. All the design used HDPE as collimate material (D1, D2, D3, D4 and D5) give simulated result with higher thermal neutron compared to the paraffin-based design (D6, D7, D8, D9 and D10) with 7.8% of relative different between the averages. The presence of boron as the neutron absorber could control the nuclear reactions for all the materials contain boron in the design [11]. The design of collimator using HDPE obtained higher epithermal neutron flux compared to paraffin with 7% of different percentage. For epithermal neutron flux, the used of HDPE on D3 had resulted $1.77 \times 10^7 \text{neutron.cm}^{-2}\text{s}^{-1}$. The strong moderation characteristic from paraffin lead to most of the design used paraffin as neutron collimate material, obtained lower epithermal flux compared to the HDPE. Besides that, the effectiveness of HDPE as fast neutron shielding and moderator was proved on the fast neutron flux measurement. All the design from D1-D5 simulated low fast neutron flux compared to paraffin (D6-D10). In this conjunction, the design D1 was qualified for BNCT collimator based on the MCNPX resulted on highest thermal neutron flux and epithermal neutron flux compared to other designs even though there are less than 1% different of fast neutron with the highest design. The measurement of gamma flux on D1, D2, D3 D4, and D5 have same value of 5.9493 x $10^2 \text{gy.cm}^{-2}\text{s}^{-1}$ at the outer and $1.4762 \times 10^7 \text{gy.cm}^{-2}\text{s}^{-1}$ for center of collimator. The value of gamma flux for paraffin-based design also all the same from design D6-D10 had obtained highest the gamma flux on outer with 6.1646 x $10^2 \text{gy.cm}^{-2}\text{s}^{-1}$ and higher for the center of collimator compared to HDPE (D1, D2, D3 D4, and D5) which is negligible.

4. Collimator optimization

In order to select an ideal collimator for BNCT facility at the thermal column, there are several optimizations that were studied in this stage, based on design D1. The optimization of collimator included the aperture of collimator size and the lead thickness. Based on the Table 2, the D1 design still was an ideal collimator for BNCT with the sufficient number of thermal neutron and highly absorbing gamma flux compared to the 5 cm and 10 +5 cm. The 10 cm lead have sufficient quality in shielding gamma but do not give an optimal thermal neutron, as the function of collimator for BNCT is to maximize the thermal neutron. The result is given in Figure 3.

Table 2. The lead thickness result on gamma and thermal from centre and outer.

Lead Thickness (cm)	Thermal Neutron, $neuton.\,cm^{-2}s^{-1}$		Gamma, $\gamma cm^{-2}s^{-1}$	
	Outer	Centre	Outer	Centre
D1 (5+10)	5.42×10^7	1.58×10^9	5.95×10^2	1.48×10^7
5	3.19×10^7	1.56×10^9	7.81×10^2	1.49×10^7
10	6.47×10^6	3.71×10^8	5.95×10^2	1.48×10^7
10+5	3.20×10^7	1.56×10^9	7.81×10^2	1.49×10^7
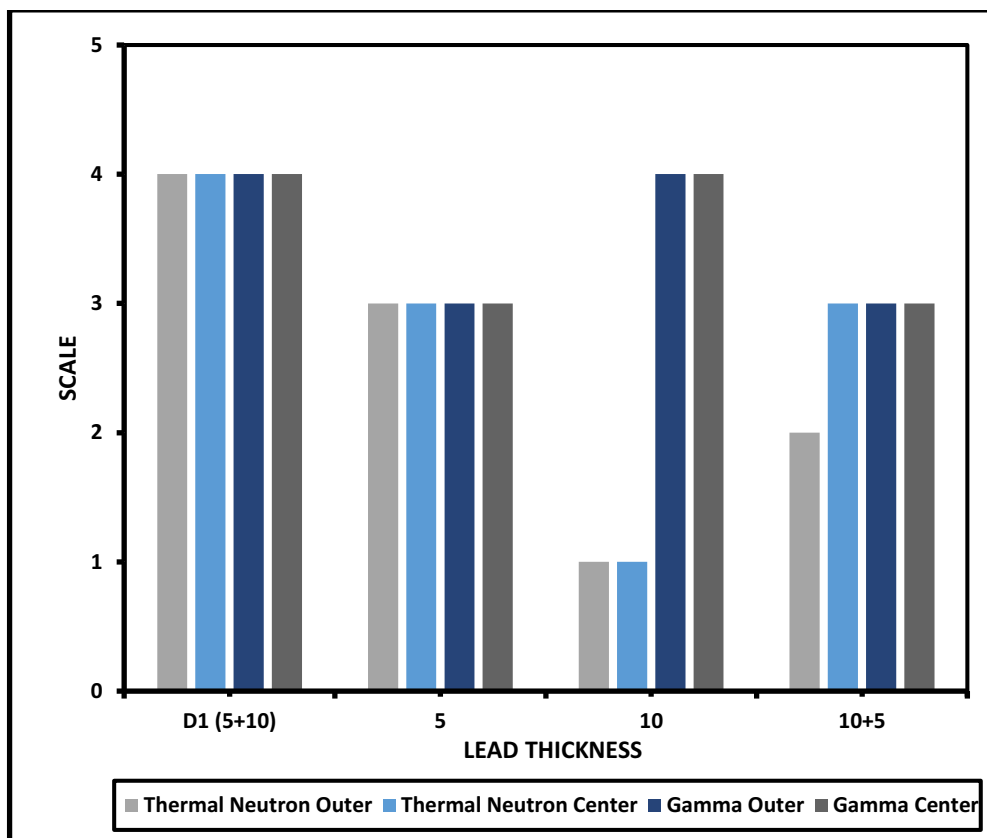
Figure 3. The different lead thickness result on gamma and thermal from centre and outer.

In Figure 3, the scale was 0-4 which means the higher scale, the higher thermal neutron obtained. In contrast, the higher scale for gamma means the higher absorption of gamma for variable thickness. The D1 design still was an ideal collimator for BNCT with the sufficient number of thermal neutron and highly absorbing gamma flux compared to the 5 cm and 10+5 cm. The 10 cm lead have sufficient quality in shielding gamma but not to give an optimal thermal neutron as the function of collimator for BNCT to maximize the thermal neutron production for clinical research study.

In terms of sufficient thermal neutron production, the aperture size was studied in order to see the correlation between the aperture size and thermal neutron production based on simulation result. The result of D1 with 5cm aperture size was compared with different aperture size which is 3 cm, 7 cm and 9 cm. The data was shown on Figure 4.
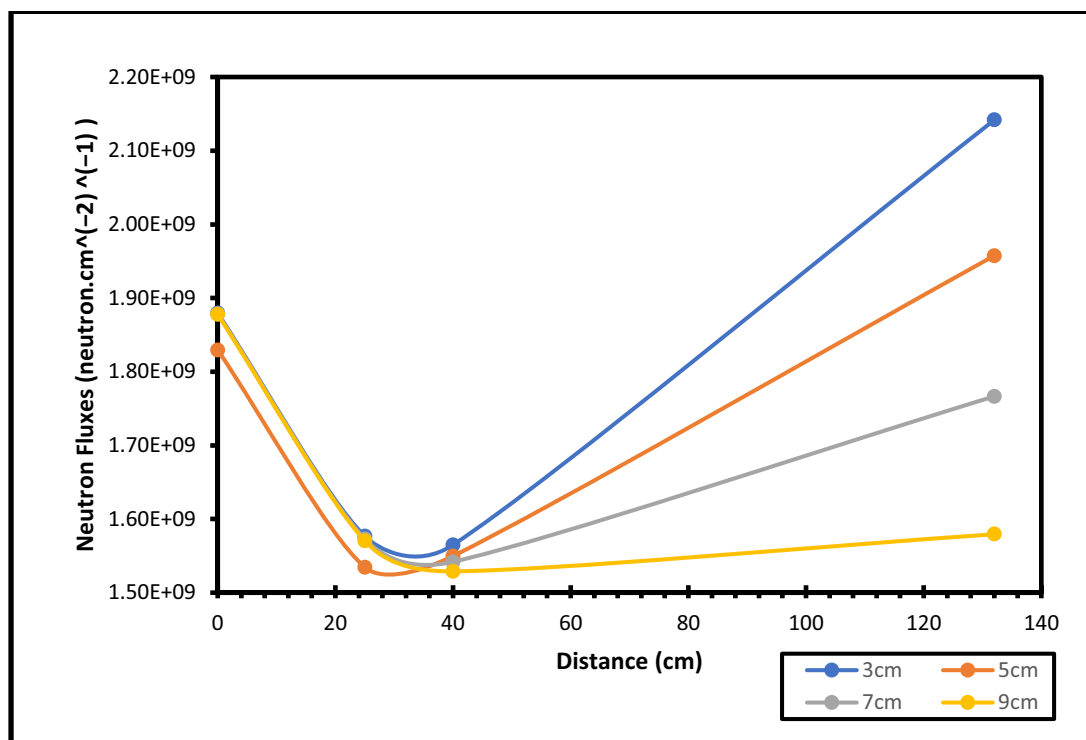
Figure 4. The graphical comparison between thermal neutron flux obtains from different size of aperture along the distance.

Based on Figure 4, neutron fluxes transmitted by the 3 cm of aperture show the higher thermal neutron obtained from MCNP simulation compared to the 5 cm, 7 cm and 9 cm of aperture size for BNCT collimator. At the distance of collimator on 30 cm to 40 cm, all of the aperture size shows the reduction of thermal neutron because of the thermal neutron transmission from the inner collimator (Part 1) to the outside collimator (Part 2). This simulation result shows that the smaller size of collimator aperture, the higher thermal neutron flux produced. At the end of collimator window, all of the thermal neutron was collimating and focusing the beam. The size of aperture gives implication towards of neutron production through collimator. As maximize the thermal neutron for BNCT application, the 3 cm of aperture has been selected to be used as an ideal collimator.

5. Conclusion

The characterization of suitable materials for collimator used in BNCT has been simulated and compared successfully using MCNPX computer code. As result, the collimator D1 which composed of 30% borated polyethylene, aluminum, HDPE and lead materials has been selected as the ideal design of collimator with the optimization of the same thickness and 3 cm of aperture size for BNCT collimator at RTP. The results obtained from this paper are expected to be useful for the construction of the new BNCT facility at TRIGA research reactor around the world.

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