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A CONCEPTUAL DESIGN OF NEUTRON COLLIMATOR IN THE THERMAL COLUMN OF KARTINI RESEARCH REACTOR FOR IN VITRO AND IN VIVO TEST OF BORON NEUTRON CAPTURE THERAPY

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Absract

A CONCEPTUAL DESIGN OF NEUTRON COLLIMATOR IN THE THERMAL COLUMN OF KARTINI RESEARCH REACTOR FOR IN VITRO AND IN VIVO TEST OF BORON NEUTRON CAPTURE THERAPY. Studies were carried out to design a collimator which results in epithermal neutron beam for IN VITRO and IN VIVO of Boron Neutron Capture Therapy (BNCT) at the Kartini research reactor by means of Monte Carlo N-Particle (MCNP) codes. Reactor within 100 kW of thermal power was used as the neutron source. The design criteria were based on recommendation from the International Atomic Energy Agency (IAEA). All materials used were varied in size, according to the value of mean free path for each material. MCNP simulations indicated that by using 5 cm thick of Ni as collimator wall, 60 cm thick of Al as moderator, 15 cm thick of ^{60}Ni as filter, 2 cm thick of Bi as γ-ray shielding, 3 cm thick of $^6Li_2CO_3$-polyethylene as beam delimiter, with 1 to 5 cm varied aperture size, epithermal neutron beam with maximum flux of 7.65 x 10^8 n.cm^{-2}.s^{-1} could be produced. The beam has minimum fast neutron and γ-ray components of, respectively, 1.76 x 10^{-13} Gy.cm^2.n^{-1} and 1.32 x 10^{-13} Gy.cm^2.n^{-1}, minimum thermal neutron per epithermal neutron ratio of 0.008, and maximum directionality of 0.73. It did not fully pass the IAEA's criteria, since the epithermal neutron flux was below the recommended value, 1.0 x 10^9 n.cm^{-2}.s^{-1}. Nonetheless, it was still usable with epithermal neutron flux exceeding 5.0 x 10^8 n.cm^{-2}.s^{-1}. When it was assumed that the graphite inside the thermal column was not discharged but only the part which was going to be replaced by the collimator, the performance of the collimator became better within the positive effect from the surrounding graphite that the beam resulted passed all criteria with epithermal neutron flux up to 1.68 x 10^9 n.cm^{-2}.s^{-1}.

Keywords—design, collimator, epithermal neutron beam, BNCT, MCNP, criteria

Abstrak

DESAN KONSEPTUAL KOLIMATOR NEUTRON DALAM KOLOM TERMAL REAKTOR RISET KARTINI UNTUK UJI IN VITRO DAN IN VIVO PADA BORON NEUTRON CAPTURE THERAPY. *Telah dilakukan penelitian tentang desain kolimator yang menghasilkan radiasi netron epitermal untuk uji in vitro dan in vivo pada Boron Neutron Capture Therapy (BNCT) di Reaktor Riset Kartini dengan menggunakan program Monte Carlo N-Particle (MCNP). Reaktor pada daya sebesar 100 kW digunakan sebagai sumber neutron. Kriteria desain berdasar pada rekomendasi dari IAEA. Setiap material divariasikan ukurannya berdasarkan mean free path radiasi di dalam material tersebut. Simulasi MCNP menunjukkan bahwa dengan menggunakan 5 cm Ni sebagai dinding kolimator, 60 cm Al sebagai moderator, 15 cm 60 Ni sebagai filter, 2 cm Bi sebagai perisai sinar-γ, 3 cm 6Li2CO3-polietilen sebagai penahan radiasi neutron, pada variasi bukaan sebesar 1 sampai 5 cm, dihasilkan fluks neutron epitermalmaksimum sebesar 7,65 x 10^8 n.cm^{-2}.s^{-1}. Radiasi neutron epitermal tersebut memiliki komponen neutron cepat sebesar 1,76 x 10^{-13} Gy.cm^2.n^{-1}, komponen sinar-γ sebesar1,32 x 10^{-13} Gy.cm2.n-1, rasio neutron termal per netron epitermal sebesar 0,008, dan direksionalitas maksimum sebesar 0,73. Hasil ini masih tidak memenuhi seluruh kriteria IAEA, karena fluks netron epitermal kurang dari 1,0 x 10^9 n.cm-2.s-1. Meski demikian, radiasi netron epitermal tersebut masih dapat digunakan karena fluksnya melebihi 5,0 x 108 n.cm-2.s-1. Pada saat diasumsikan bahwa bagian kolom termal yang tersisa di luar daerah kolimator tetap berisi grafit seperti semula, hasil keluaran kolimator menjadi lebih baik dengan fluks neutron maksimum mencapai 1,68 x 10^9 n.cm^{-2}.s^{-1}.*

Kata kunci : desain, kolimator, radiasi neutron epitermal, BNCT, MCNP, kriteria

INTRODUCTION

Boron Neutron Capture Therapy (BNCT) is another form of radiotherapy for healing tumour. In BNCT, ^{10}B and its carrier drug are administered to the patient. This carrier will take these compounds to the location of the tumour cells, where ^{10}B is supposed to be accumulated. Then, the tumour area is to be irradiated by neutron beam. ^{10}B in the tumour cells would capture the thermal neutron resulting in a prompt nuclear reaction $^{10}B(n,\alpha)^{7}Li$. Both α-particle and ^{7}Li have relatively high Linear Energy Transfer (LET) values (175 keV.μm^{-1} and above) and short path lengths (approximately 4.5 to 10 μm), hence the energy deposition is locally limited around the tumour cells. [1,2,3]

In TRIGA MARK-II type research reactor in Yogyakarta, which has also been known as Kartini Research Reactor, the facility for BNCT is going to be built for an advanced study which uses tumour-injected animals as the object. The thermal column of this reactor is planned to be implanted with a device which is capable of narrowing the neutron beam, called as *collimator*. Due to the tendency of epithermal neutron beams usage for BNCT, the collimator must contains materials needed to produce epithermal neutron beam which fulfill some particular characteristics recommended by the International Atomic Energy Agency (IAEA). Thus, a proper collimator has to be designed.

LITERATURE REVIEW

Table 1 shows the beam criteria recommended by the IAEA. The energy limits of 5 x 10-7, 10-2, and 20 MeV were used which, respectively, denoted the upper limit for thermal, epithermal, and fast neutrons energy spectrums. In this table, Φepi, Φth, and J are epithermal neutron flux, thermal neutron flux, and neutron current, respectively. Moreover, $\dot{D}$f and $\dot{D}$γ stand for dose rates due to the fast neutrons and gamma rays.

Table 1. Beam criteria recommended by the IAEA **[4]**

Φ_{epi} (n.cm^{-2}.s^{-1})	> 1.0 x 10^{9}
$\dot{D}_f$ / Φ_{epi} (Gy.cm^{2}.n^{-1})	< 2.0 x 10^{-}
$\dot{D}_\gamma$ / Φ_{epi} (Gy.cm^{2}.n^{-}	< 2.0 x 10^{-}
Φ_{th} / Φ_{epi}	< 0.05
J / Φ_{epi}	> 0.7

Several experiences in designing collimator for BNCT have been conducted both based on the materials selection and the geometry optimisation. A collimator consists of 5 components: collimator wall, moderator, filter, γ-ray shielding, and aperture.

Collimator wall should reflect neutrons back into the inner part of collimator. Suitable reflector materials for this are those with high scattering cross section and high atomic mass, such as Pb, Bi, PbF_2, and Ni. Part of wall which located at the end point of collimator should absorb neutrons rather than scatter. This part is made of $^{6}Li_2CO_3$-polyethylene or B_4C. Epithermal neutrons striking the wall of the collimator are thermalised and captured. For moderator, widely used materials are Al or its composites, Al_2O_3 and AlF_3. Materials such as Pb and Bi may be placed in the beam to reduce γ-rays. These will nonetheless reduce neutron beam intensity. For epithermal neutron beams, it is desirable to limit thermal and fast neutron contamination by filtering. Filter materials for thermal neutrons require ^{6}Li, ^{10}B or Cd. For filtering out the fast neutrons, ^{60}Ni isotope can be placed.

Aperture size should be made in accordance to the purpose of the design. In this study, the collimator which is going to be built is for trials with 1 to 2 cm sized tumour cell samples and tumour-

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injected animals as the object. For the tumour-injected animals, the size of tumour cells would be monitored. Once the tumour reaches the detectable size, it would be irradiated immediately. Hence the minimum detectable size of tumour should be known. James Michaelson (2003) used screening mammography to detect breast cancer. According to the result of the study, it was found that detectable size of tumour was approximately 30 mm. [4,5,6]

THEORETICAL BACKGROUND

In nuclear phenomena, each of the processes described by which neutrons interact with nuclei is denoted by a characteristic cross section. Cross section, denoted by σ, is equal to the number of collisions per second with one nucleus per unit intensity of the beam or, in other words, the effective cross sectional area of the nucleus. [1]

This study was conducted by doing simulations using MCNP5 program. It works based on the probability of interactions between radiations and materials which is derived from the microscopic cross sections. The individual probabilistic events that comprise a process are simulated sequentially. The probability distributions governing these events are statistically sampled to describe the total phenomenon. The statistical sampling process is based on the selection of random numbers. [7]

MATERIALS AND METHOD

This study was a simulation-basic experiment, using MCNP5 program. As the first step, it was needed to make a model of the reactor since it would be used as the neutron source. Several parts of the reactor, whose existence were considered to affect to the reactor criticality, were modelled, such as core, the radial reflector, rotary specimen rack, and piercing beam port. Reactor core configuration was made for thermal power of 100 kW. The thermal column was also built since it would become the point of interest; where the collimator would be built. Simulations was done to make sure that the criticality value was approximately 1, and the thermal neutron flux in the ring B was near (12.45 ± 0.23) x 10^{11} n.cm^{-2}s^{-1} [8]. The result should be *written* (recorded) for the next collimator conceptual designing process.

In an MCNP input file, *tallies* are the information that a user wants to obtain by Monte Carlo calculation. According to the beam criteria in Table 1, the tallies needed were those for resulting fluxes and current data. Neutron and gamma fluxes were calculated using F4 tally and corresponding dose values were determined using fluence to kerma conversion factors reported in ICRU 63 [9]. Moreover, neutron current was calculated using F1 tally. Normalization factors for each tally were calculated, used for normalizing the tallies for a reactor within 100 kW thermal power.

Then, the collimator designing was conducted. A rough collimator design was made by using MCNP5 codes: 100 cm length of collimator, 54 cm of outer collimator diameter, 3 cm thick of beam delimiter, and 3 cm sized aperture. Beam delimiter used was made of $^{6}Li_2CO_3$-polyethylene. In designing collimator, one should start with the varied size of collimator wall. Material used was Ni. The best thickness would be that the thickness which provided the highest epithermal neutron flux. Then, moderator, Al, was varied until the fast neutron component decrement no longer significant. In this point, ^{60}Ni as fast neutron absorber, which in fact also absorbed the thermal neutrons, was started to be used and varied until the fast and thermal neutron components desired reached. The next step was to employ Bi, as γ-ray shielding into the collimator and alter its thickness until the desired γ-ray component gained. The last parameter of beam quality, the directionality, was checked right after. If the directionality was less than desired, more beam delimiter would be added. The last step conducted was varying the aperture or the beam cross section size to find out the performance of the collimator design in different aperture size.

RESULTS AND ANALYSIS

The criticality calculation by using MCNP5 gave result 1.007 $\pm$ 0.000, which was a good approximation to the criticality value of 1.000 $\pm$ 0.010. The thermal neutron flux in Ring B of the reactor core was (14.30 $\pm$ 0.00) x 10^{11} n.cm^{-2}.s^{-1}, meanwhile the real value, which was detected by a study, was approximately (12.45 $\pm$ 0.23) x 10^{11} n.cm^{-2}.s^{-1} [8]. This difference might be caused by the multiplication factor inputted into the MCNP codes that did not quite depict the real number of neutrons. With these results, collimator designing was then conducted.

The results of simulation for wall thickness variation are depicted in Figure 1.

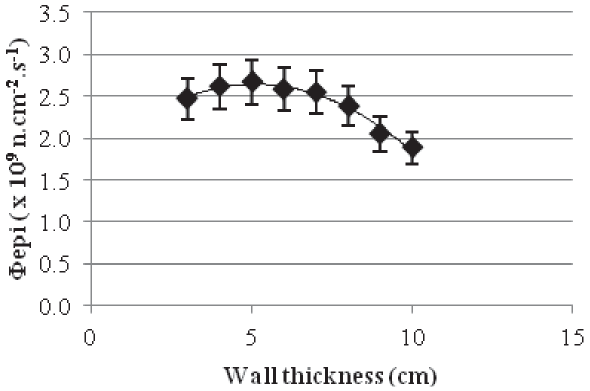

Figure 1. Epithermal neutron flux for various thickness of wall (Ni).

Natural nickel was a very good material to be employed as a neutron collimator wall. Its atomic mass which was not too small, that would make too much energy decrement of neutrons, and yet not too high, that only would slightly shift the energy spectrum of neutrons. Hence without moderator, the natural nickel itself already produce epithermal neutron-dominated beam, but still needed more materials to raise its quality. As shown in Figure 1, the flux reaches its highest value (2.67 n.cm^{-2}.s^{-1}) in thickness of 5 cm. At this point, the energy spectrum shifts of fast neutrons to become epithermal neutrons is optimum. In 6, 7, 8 cm of wall thickness and so on, epithermal neutron flux decreases monotonically. In fact, as the thickness of collimator wall increases, the inner diameter of collimator decreases, causing more collisions occurred between the neutrons and the wall. Thus the energy spectrum shift becomes further, and the epithermal neutrons more reduced, instead.

The results of simulations for varied moderator thickness are depicted in Figure 2. It shows nicely how the ratio between fast neutron dose rate per epithermal neutron flux decreases exponentially. With no moderator, the fast neutron component is 1.08 x 10^{-11} Gy.cm^2.n^{-1} or, approximately, 50 times higher than the desired value, 2.0 x 10^{-13} Gy.cm^2 n^{-1}.

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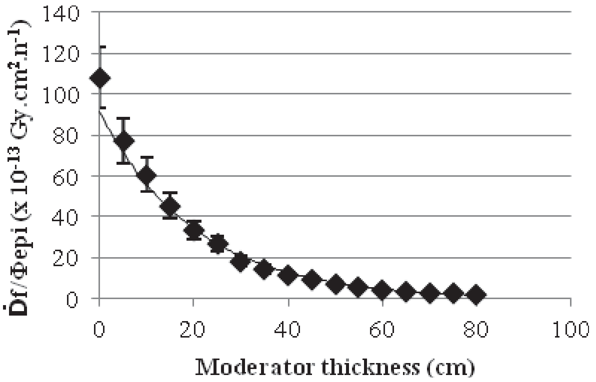

Figure 2. Fast neutron component for various thickness of moderator (Al).

Al performs very well moderation effect that it reduces the fast neutron dose more rapidly without much decrease of epithermal neutron flux up to 60 cm thickness. After that, the addition of moderator is no longer effective since the fast neutron component only slightly decreases. 60 cm thick Al is used as moderator, with fast neutron component of 4.07 x 10^{-13} Gy.cm^2.n^{-1} and 1.27 x 10^9 n.cm^{-2}.s^{-1} epithermal neutron flux.

Usage of ^{60}Ni as filter gave results as shown in Figure 3 and 4. Figure 3 depicts that the fast neutron component, once again, decreases exponentially. 12 cm thick of filter is actually enough to decrease the fast neutron component below the upper limit recommended, to 1.84 x 10^{-13} Gy.cm^2.n^{-1}, but according to the simulations done it eventually increased exceeding 2.0 x 10^{-13} Gy.cm^2.n^{-1} when Bi as γ-ray shielding is added. Thus 15 cm thick of filter is preferred, with 1.70 x 10^{-13} Gy.cm^2.n^{-1} fast neutron component and 9.99 x 10^8 n.cm^{-2}.s^{-1} epithermal neutron flux.

Thermal neutron component also decreases exponentially as more ^{60}Ni added into the collimator, as shown in Figure 4. With 15 cm thick of ^{60}Ni, it is reduced from 0.061 to 0.008, which is far below the recommended maximum value, 0.05.

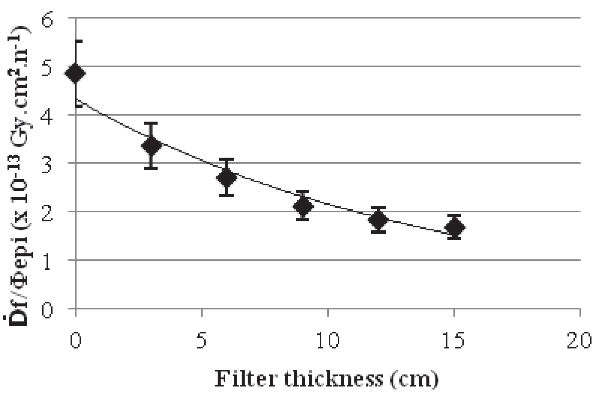

Figure 3. Fast neutron component for various thickness of filter (60Ni).

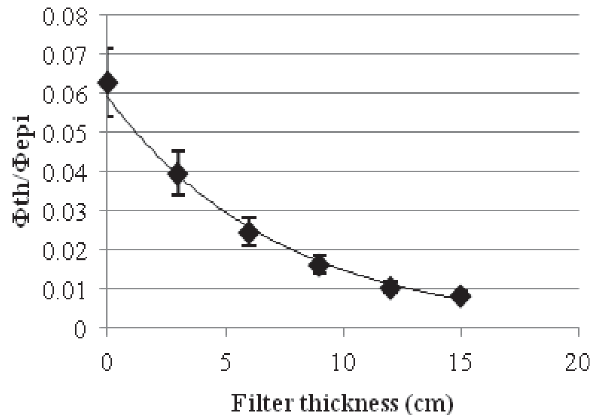

Figure 4. Thermal neutron component for various thickness of filter (60Ni).

The effects of Bi addition in the collimator are shown in Figure 5. The γ-ray component is reduced exponentially by using Bi. With thickness of 2 cm, the γ-ray component remains 1.44 x 10^{-13} Gy.cm^2.n^{-1}. The addition for more thickness will, of course, decrease the γ-ray component. 4 and 6 cm thick of Bi results in 0.79 x 10^{-13} and 0.40 x 10^{-13} Gy.cm^2.n^{-1} γ-ray components, respectively. Thus 2 cm thick of Bi is used rather than 4 or 6 cm. With 2 cm thick of Bi, the epithermal neutron flux decrease to 7.48 x 10^8 n.cm^{-2}.s^{-1}.

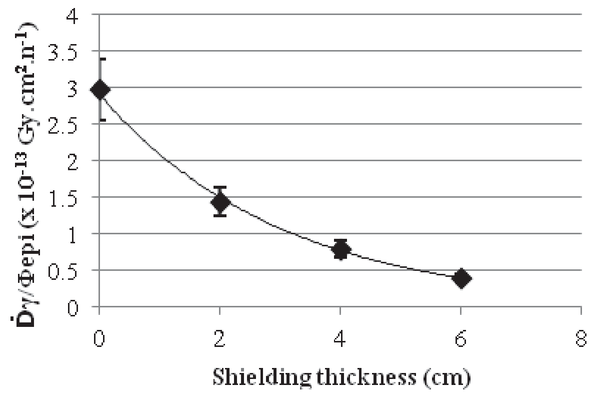

Figure 5. Gamma-ray component for various thickness of shielding (Bi).

Diameter of aperture was altered in 1, 2, 3, 4, and 5 cm. The results are collected in Table 2. The data show that, generally, the aperture size apparently does not cause any certain effect to the beam. Almost all parameters show fluctuating results. Data in Table 2 show that, generally, the aperture size apparently does not cause any certain effect to the beam. Almost all parameters are varied fluctuate. This collimator design does not fully pass the IAEA's criteria, since the epithermal neutron flux is always below the recommended value, 1 x 10^9 n.cm^{-2}.s^{-1}.

Table 2. Beam characteristics for different aperture diameter.

Aperture diameter (cm)	1	2	3	4	5
Φ_{epi} (n.cm^{-2}.s^{-1})	7.55x10^8	7.61x10^8	7.48x10^8	7.65x10^8	7.57x10^8
$\dot{D}_f / \Phi_{epi}$ (Gy.cm^2.n^{-1})	1.80x10^{-13}	1.85x10^{-13}	1.80x10^{-13}	1.76x10^{-13}	1.81x10^{-13}
$\dot{D}_\gamma / \Phi_{epi}$ (Gy.cm^2.n^{-1})	1.47x10^{-13}	1.45x10^{-13}	1.44x10^{-13}	1.34x10^{-13}	1.32x10^{-13}
Φ_{th} / Φ_{epi}	0.010	0.010	0.009	0.009	0.008
J / Φ_{epi}	0.72	0.72	0.73	0.72	0.73

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Nonetheless, the beam is said to be usable with epithermal neutron flux exceeding 5 x 10^8 $n.cm^{-2}.s^{-1}$. When it is assumed that the graphite inside the thermal column is not discharged but only those parts which would be replaced by the collimator, the performance of the collimator become better, as shown in Table 3.

Table 3. Beam characteristics for different aperture diameter of graphite-surrounded collimator.

Aperture diameter (cm)	1	2	3	4	5
Φ_{epi} ($n.cm^{-2}.s^{-1}$)	$1.60x10^9$	$1.63x10^9$	$1.64x10^9$	$1.68x10^9$	$1.65x10^9$
$\dot{D}_f / \Phi_{epi}$ ($Gy.cm^2.n^{-1}$)	$1.56x10^{-13}$	$1.69x10^{-13}$	$1.61x10^{-13}$	$1.61x10^{-13}$	$1.59x10^{-13}$
$\dot{D}_\gamma / \Phi_{epi}$ ($Gy.cm^2.n^{-1}$)	$1.25x10^{-13}$	$1.18x10^{-13}$	$1.24x10^{-13}$	$1.26x10^{-13}$	$1.16x10^{-13}$
Φ_{th} / Φ_{epi}	0.006	0.007	0.007	0.007	0.007
J / Φ_{epi}	0.73	0.73	0.72	0.72	0.72

With the graphite thickness of about 8 cm, the epithermal neutron flux increases dramatically exceeding the recommended value up to 1.68 x 10^9 $n.cm^{-2}.s^{-1}$ for all size of aperture, accompanied by relatively better beam quality. The beam resulted passes all criteria.

Graphite apparently contributes to reflect more neutrons. Some neutrons leak from the collimator would then interact with the graphite which located exactly outside the collimator, and reflected back into the collimator area. This results in the enhanced epithermal neutron beam intensity.

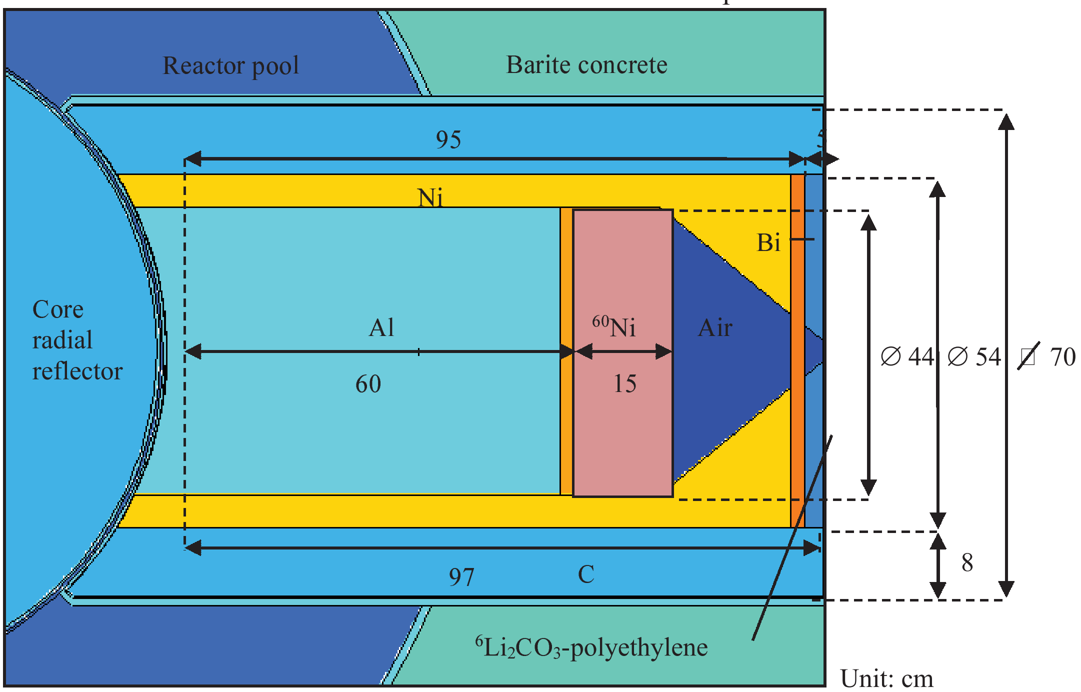

Figure 6. Collimator configuration.

VI. CONCLUSION AND RECOMMENDATION

A conceptual design of collimator which is proper to be implanted in the thermal column of Kartini Research Reactor has been made. It consists of:

1. 5 cm thick of Ni, as collimator wall,
2. 60 cm thick of Al, as moderator,
3. 15 cm thick of ^{60}Ni, as thermal and fast neutron filter,
4. 2 cm thick of Bi as γ-ray shielding, and
5. 3 cm thick of $^6Li_2CO_3$-polyethylene,

with configuration as depicted in Figure 6. With 1 to 5 cm varied aperture size, epithermal neutron beam with maximum flux of 7.65 x 10^8 $n.cm^{-2}.s^{-1}$, minimum fast neutron and γ-ray components of, respectively, 1.76 x 10^{-13} $Gy.cm^2.n^{-1}$ and 1.32 x 10^{-13} $Gy.cm^2.n^{-1}$, minimum thermal neutron per epithermal neutron ratio of 0.008, and maximum beam directionality of 0.73, could be produced. It does not fully pass the IAEA's criteria, since the epithermal neutron flux is below the recommended value of 1.0 x 10^9 n.cm^{-2}.s^{-1}. Nonetheless, it is still usable with epithermal neutron flux exceeding 5.0 x 10^8 n.cm^{-2}.s^{-1}. 8 cm thick of graphite surrounding the collimator could make the performance of the collimator become better that the beam resulted passes all criteria with epithermal neutron flux up to 1.68 x 10^9 n.cm^{-2}.s^{-1}.

As a recommendation, a further study about this BNCT-purpose collimator design might be needed for the safety assessment. In fact, radiations do not only emerge from the output hole of the collimator, but also around the collimator itself. These unwanted exposures would shower the patient. It should be reduced as low as possible. Some addition of shielding would be convenient.

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