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The Optimization of Collimator Material and In Vivo Testing Dosimetry of Boron Neutron Capture Therapy (BNCT) on Radial Piercing Beam Port Kartini Nuclear Reactor by Monte Carlo N-Particle Extended (MCNPX) Simulation Method

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Abstract Boron Neutron Capture Therapy (BNCT) on radial piercing beam port Kartini nuclear reactor by MCNPX simulation method has been done in the National Nuclear Energy Agency Yogyakarta. BNCT is a type of therapy alternative that uses nuclear reaction ^{10}B (n, α) ^{7}Li to produce 2.79 MeV total kinetic energy. To be eligible IAEA conducted a study of design improvements and variations on some parameters to optimum condition which are Ni-nat thickness of 1.75 cm as collimator wall, Al_2S_3 as thick as 29 cm as moderator, Al_2O_3 0.5 cm thick as filter, Pb and Bi thickness of 4 cm as the end of the gamma shield collimators and Bi thickness of 1.5 cm as the base gamma shield collimators. The total dose was accepted in the tumor tissue 900×10^{-4} Gy/s. Radiation dose on the tumor tissue is 50±3 Gy with time irradiation of 9 minutes and 10 seconds. That dose was given into skin tissue and healthy liver tissue consecutively $(6.00\pm0.05) \times 10^{-2}$ Gy and $(10.00\pm0.05) \times 10^{-2}$ Gy. It shows the dose received by healthy tissue is still within safe limits.

Keywords Boron Neutron Capture Therapy, Kartini Reactor, in vivo testing, Dosimetry

1. INTRODUCTION

Various diseases threaten human health worldwide. According to data from the WHO (World Health Organization) in 2014, the total number of human deaths worldwide was 56 million during 2012, of which 36 million were deaths from non-communicable diseases, or non-communicable diseases (NCDs). There are four predominant types of NCDs, namely cardiovascular diseases, chronic respiratory diseases, diabetes and cancer. The number of deaths caused by cancer cases in the world is 8.2 million people. This is 21.7% of the total cases of NCDs mortality data making cancer the second deadliest after heart disease (Anonymous A, 2014).

Cancer is a group of diseases characterized by the growth of cells in the body that are abnormal and uncontrollable spread. Uncontrolled spread of these can lead to death so a therapy is needed to inhibit and eliminate cancer cells (Siegel et al, 2014). Some cancer treatment therapies include surgery, chemotherapy and radiotherapy. All three have weaknesses for conditions such as tumors at an early stage, using drugs which have side effects and also using high-dose radiation. To overcome some of these weaknesses Boron Neutron Capture Therapy (BNCT) which is selective against cancer cells (B Anonymous, 2014) has been developed. Kartini reactor neutron source research facility has been used for BNCT. Beam translucent port is used for in vivo tests because the beam port closest to the reactor core giving it a high neutron flux at the base (Widarto, 2002).

2. MATERIALS AND METHODS

2.1 Collimator System Optimization

Collimator system optimization in this study consists of three parts, namely a moderator, filter and shield gamma. Moderator serves to decrease the energy of fast neutrons for the epithermal neutron energy, so that the parameters used are $\dot{D}_f/\Phi_{epi}$ namely fast neutron dose rate per epithermal neutron flux (Soppera et al, 2012). A good criterion moderator material is a material that has a value $\dot{D}_f/\Phi_{epi} < 2 \times 10^{-13}$ Gy cm^2/n but the neutron flux values > $1{,}0 \times 10^9$ n/cm2 s. The filter serves to reduce the thermal neutron flux and fast neutron flux, so that only the epithermal neutron flux is passed. A good criteria filter material is a material that has a high absorption cross section which serves to shield gamma in order to minimize and absorb the gamma rays coming out of the aperture. The criteria for a good gamma shield material are having a density, atomic number and high attenuation coefficient great. Materials that effectively absorb gamma are Pb-nat and ^{209}Bi.

2.2 Object Design in Vivo Testing BNCT

Simulation geometry test sample used laboratory rats objects already injected with cancer cells. Mouse model which is the reference for the design of in vivo test with specified MCNP Konijnenberg et al (2004) is shown in Figure 2.1. Modeling is done with rats awake approach ellipsoid. Tumor samples used are part of the liver of mice that modeled the ellipsoid shape as well. The geometry modeling agency elipsoida mice with a mouse model is the most simple compared to the BNCT plan models or models Xplan as on research conducted by Liu et al (2014).

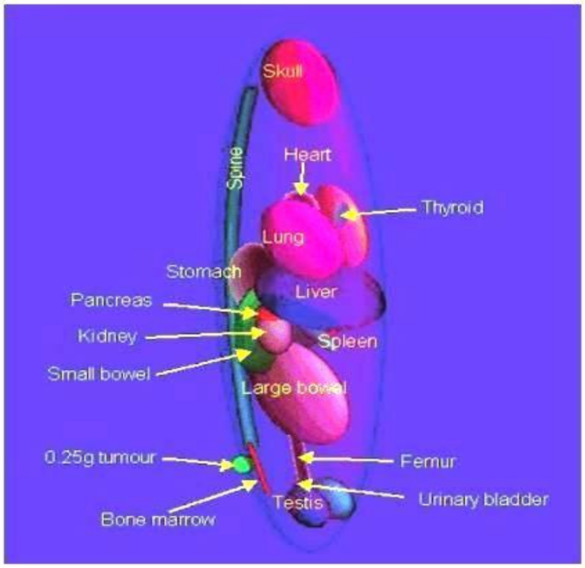


Figure 2.1 Visualization of the model mice (Konjinenberg et al, 2004)

The output generated from MCNP calculations include gamma dose rate, neutron dose rate, neutron flow and neutron flux values that have been written on the tally code MCNPX. The values resulting from the calculation MCNPX will be used in the calculation of the dose. Boron dose is the dose calculation; dose gamma interacts with matter, dose and dose proton neutron scattering.

3. RESULTS AND DISCUSSION

3.1 The Optimization of Collimator in Radial Piercing Beam Port

The parts that are used in the optimization of collimator include collimator wall (reflector), moderator, filter and shield gamma. In this study collimator wall using Ni-nat 156 cm long and having a thickness of 1.75 cm Data is derived from previous studies that produced quite high epithermal neutron flux values (Wahyuningsih, 2014) and a diameter of 3 cm aperture.

a. Moderation

Parameters taken into consideration to choose a good moderator were epithermal high flux value, the value of fast neutron component $\dot{D}_f/\Phi_{epi}$ epiwere small ($<2\times10^{-13}$) and epithermal neutron flux ratio with fast neutron flux (Φ_{epi}/Φ_{fast}).

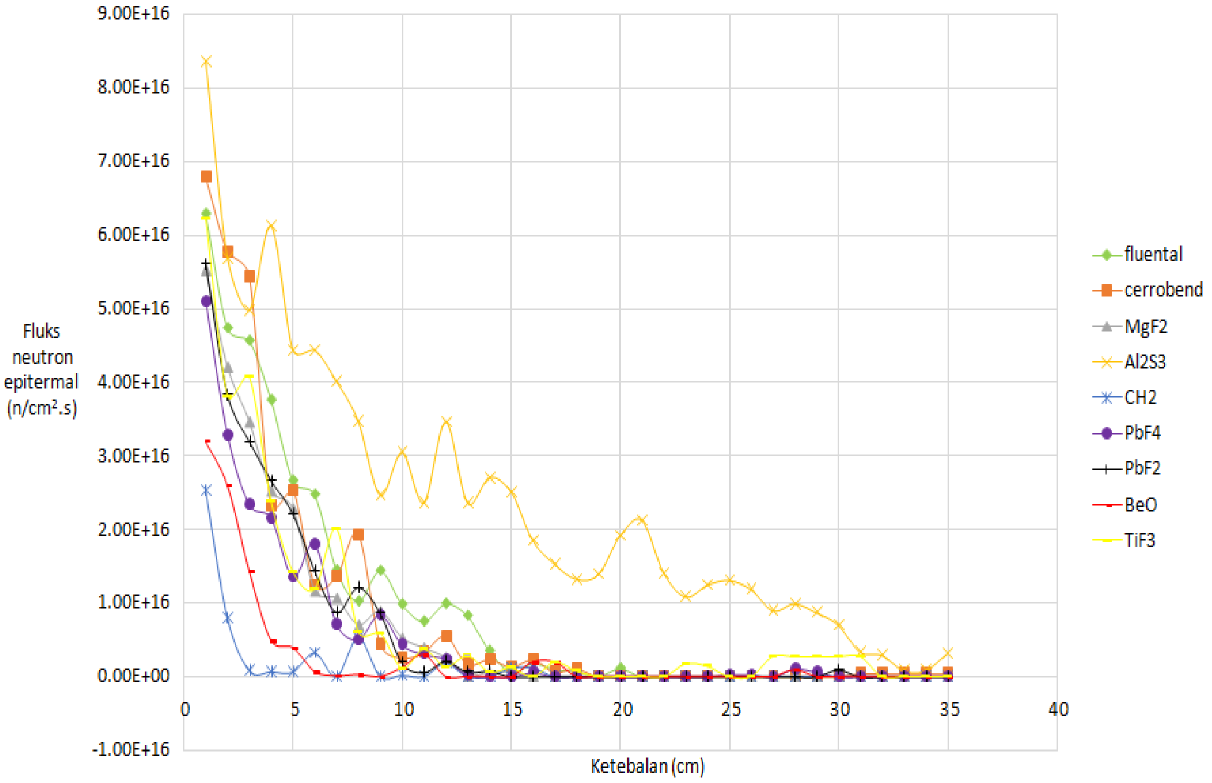


Figure 3.1 Epithermal neutron flux values versus material thickness moderator

Figure 3.1 shows the epithermal neutron flux values for some of the material versus the thickness of the material. As seen in the graph, the material with high value of the thickness, Al2S3 has increased thickness epithermal flux values compared to other moderator materials.

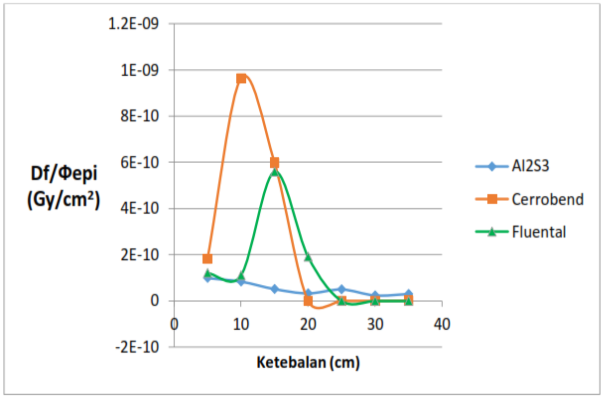


Figure 3.2 Value D_f/Φ_{epi} vs thickness of the material best moderator

Figure 3.2 shows the value D_f/Φ_{epi} to three different materials versus thickness, the three materials being Al_2S_3, Fluental and Cerrobend. The third election is because the material has a third epithermal neutron flux values higher than in other materials as shown in Figure 3.1. The elements that make up Al_2S_3 have a small mass number. Fluental material is a material consisting of (Al 30% + 69% + LiF AlF_3 1%), and Cerrobend consists of (Bi 50%, 31.8% Pb and Sn 18.2%). Criteria for selection of the best material are when the value D_f/Φ_{epi} decreases with the value of D_f/Φ_{epi}. From these criteria only Al2S3 still has a high value D_f/Φ_{epi} for large thicknesses of data while the other material values D_f/Φ_{epi} are already zero. Al_2S_3 is better as a moderator than the other two materials.

b. Filtering

Filtering is done to reduce the thermal neutron flux and fast neutron flux, so that only the epithermal neutron flux is passed. Material chosen as the filter was a material that has the look of the reaction (n, 2n) high. The type of filter used is a band pass filter, intended to effectively skip the epithermal neutron, including Ni, Fe and Al_2O_3. Using Al_2O_3 is intended to determine the effectiveness fast neutron flux filter.

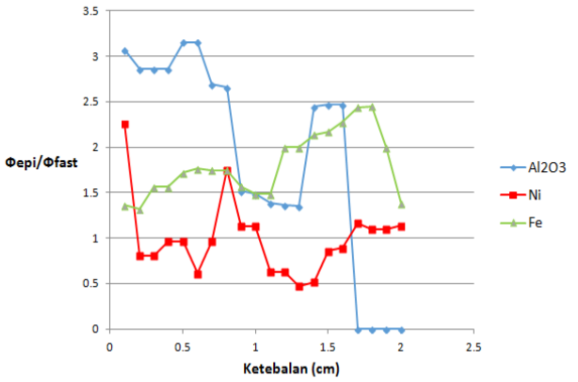


Figure 3.3 Value Φepi/Φfast vs the thickness of the filter material

Figure 3.3 shows materials effective in producing a ratio Φ_{epi}/Φ_{fast} high are the materials Al_2O_3 and ^{56}Fe. Low thickness Al_2O_3 having highest value of Φ_{epi}/Φ_{fast}, while ^{56}Fe is much lower. But for a much larger thickness value Φ_{epi}/Φ_{fast} ^{56}Fe material is much higher compared with Al_2O_3. This is because the material ^{56}Fe has the ability to filter out the most excellent fast neutrons, but because it is easily corrosive it cannot be used for a relatively long time. Therefore, the use of Al_2O_3 with a small thickness is more effective than the use of ^{56}Fe for high thickness. In part the filter material that is most effective is Al_2O_3 with a thickness of 0.5 cm.

c. Gamma shielding

Gamma shield serves to absorb the gamma rays so that magma that comes out of the aperture can be minimized. Two effective materials that absorb gamma-nat is Pb and ^{209}Bi. The following are shown in Table 3.1.

Table 3.1 Value Φ_{epi} and D_γ/Φ_{epi} vs gamma shield material thickness of the end of the collimator

Thickness Pb and Bi (cm)	$\Phi_{epi} \times 10^9$ (n/cm² s)	$\dot{D}_\gamma/\Phi_{epi} \times 10^{-13}$ (Gy cm²/n)
1	4.4	286
2	7.5	99
3	6.9	82
4	5.4	50
5	2.2	60
6	2.1	81
7	2.1	48
8	2.1	44
9	2.1	21
10	0	0

Election of the end of the gamma shield collimators with Pb and Bi constituent material thickness of 4 cm are due to consideration of the high value Φ_{epi} and the value of D_γ/Φ_{epi} lowest. This value is still higher than the standard IAEA value doses of gamma which must be lower than 2×10^{-13} making it necessary to continue efforts to lower it by adding a shield gamma part at the base of the collimator using a type of the same material and varying the thickness of the material.

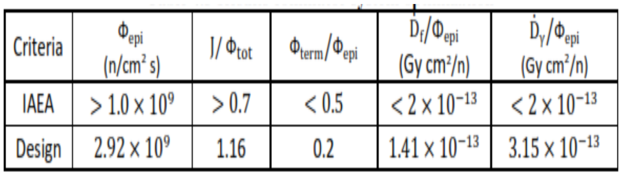
Table 3.2 shows the value D_γ/Φ_{epi} much smaller compared to the addition of gamma shield at the end of the collimator only. The result of adding gamma shield at the end of the collimator is a value of D_γ/Φ_{epi} approximately 50×10^{-13} Gy cm^2/n, but after adding a gamma shield at the base of the collimator the value D_γ/Φ_{epi} decreased to 3.1×10^{-13} Gy cm^2/n.

Table 3.2 Value $\dot{D}_\gamma/\Phi_{epi}$ vs Bi gamma shield material thickness at the base of the collimator

Thickness (cm)	$\dot{D}_\gamma/\Phi_{epi} \times 10^{-13}$ (Gy cm^2/n)
1	17.5
1.1	180
1.2	110
1.3	4.4
1.4	3.8
1.5	3.1
1.6	17.8
1.7	20
1.8	6.7
1.9	6.7
2.0	6.4

d. The optimization result

Table 3.3 Results collimator system optimization



Criteria	Φ_{epi} (n/cm^2 s)	J/Φ_{tot}	Φ_{term}/Φ_{epi}	$\dot{D}_f/\Phi_{epi}$ (Gy cm^2/n)	$\dot{D}_\gamma/\Phi_{epi}$ (Gy cm^2/n)
IAEA	$> 1.0 \times 10^9$	> 0.7	< 0.5	$< 2 \times 10^{-13}$	$< 2 \times 10^{-13}$
Design	2.92×10^9	1.16	0.2	1.41×10^{-13}	3.15×10^{-13}

Table 3.3 shows the optimum results from this study with a design specification for reflector collimator system using Ni-nat 156 cm and a thickness of 1.75 cm, a moderator using the material at a thickness of 29 cm Al_2S_3, filter using Al_2O_3 material with a thickness of 0.5 cm and a gamma shield at the tip of the collimator using Pb and Bi material with a thickness of 4 cm and gamma shield collimators at the base using a 1.5 cm thick Bi material as shown in Figure 3.4.

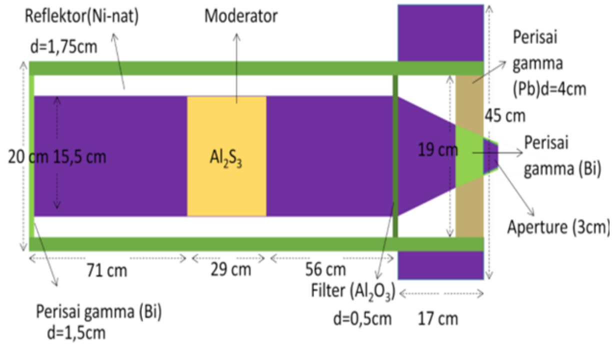


Figure 3.4 the system design collimators

3.1 The Optimization of Collimator in Radial Piercing Beam Port

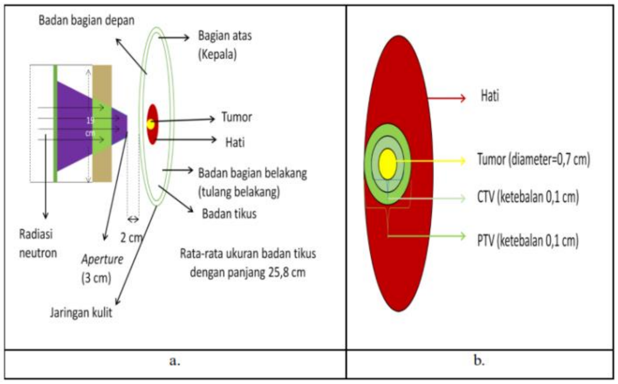


Figure 3.5 a. Design test radiation in vivo liver tumors in mice, b. Definition area of the tumor in the liver of mice

Irradiation techniques on using the technique in one direction, namely towards the front are shown in Figure 3.5. This technique aims to directly irradiate the part closest to the tumor. It will also reduce the radiation in other organs.

Dosimetry BNCT in vivo test on tumor tissue with a maximum dose of irradiation 50 Gy generate a simulated liver tumor tissue in the liver of mice with the irradiation times was ~ 9 min. A longer irradiation (radiation) in the tumor tissue is done so that the tumor tissue can be reduced but healthy tissue around it is still in safe dose of radiation.

Table 3.4 Time of irradiation on tumor tissue with the maximum dose

Tissue	Total dose (Gy/s)	Maximum dose standard (Gy)	Irradiation time tolerance (second)	Irradiation time
Tumor	900×10^{-4}	50	555	9 minutes 10 seconds

Table 3.4 shows the time of irradiation on tumor tissue with the maximum dose. The irradiation time threshold is obtained by using a maximum dose of 50 Gy to the tumor. The threshold values at the maximum dose of 3 Gy due to skin, when on top of that value, would result in signs of damage to the skin tissue. Exposure to radiation on the skin is more sensitive because the distance is closer to the source of radiation. Radiation maximum threshold dose in the tumor tissue is allowed at 50 Gy. The dose values are the dose to destroy tumor cells.

Table 3.5 Dose in other tissues when irradiated tumor tissue

Tissue	Maximum dose standart (Gy)	Radiation doses to other tissues to reduced tumor tissue (Gy) $\times 10^{-2}$
Skin	3	6.00 ± 0.05
Healty liver	35	10.00 ± 0.05

Table 3.5 shows the value of the dose in the skin tissue and the healthy liver tissue when BNCT therapy is done on tumor tissue for in vivo testing. This value is the maximum limit value with long time exposure dose irradiation on the network for 9 minutes 10 seconds to hopefully be able to kill tumor cells that exist in the liver of mice. Value dose to surrounding skin tissue $(6.00 \pm 0.05) \times 10^{-2}$ Gy and dose values for healthy liver tissue $(10.00 \pm 0.05) \times 10^{-2}$. Both of these values are far from the limit value of the maximum dose of radiation to the heart tissue and healthy skin of 3 Gy and 35 Gy (ICRU, 1989). This is still within the safe limits of radiation to tissue located around the tumor tissue. As a comparison, to reduce tumors in mice after 8 days of mice injected with tumor, it takes 1 hour 17 minutes after irradiation experiments with BSH as much as 35 mg boron/g (Fujii et al, 2011).

4. CONCLUSION AND REMARKS

Based on the results of this study it is concluded:

1. BNCT collimator material optimization for Kartini reactor have been successfully carried out and meet almost all the requirements of the

IAEA.

2. Results of each optimization components:
    a. $\Phi_{epi} = 2.92\times10^{9}$ n/cm^{2}s,
    b. $\Phi_{term} / \Phi epi = 0.2$,
    c. $J/\Phi_{tot} = 1.16$ cm^{-1},
    d. $\dot{D}_{f}/\Phi_{epi} = 1.41\times10^{-13}$ Gy cm^{2}/n,
    e. $\dot{D}_{\gamma}/\Phi_{epi} = 3.15\times10^{-13}$ Gy cm^{2}/n.

The maximum dose of radiation on the tumor tissue of 50 ± 3 Gy is irradiation time of 9 minutes 10 seconds. The radiation dose received in the skin tissue and the healthy liver tissues respectively are $(6.00\pm0.05)\times10^{-2}$ Gy and $(10.00 \pm 0.05)\times10^{-2}$ Gy. The dose values are still quite low compared to the value of the dose received by the tumor tissue. It shows the radiation exposure of healthy tissue around the tumor tissue is still within safe limits.

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