

RADIATION SAFETY ANALYSIS OF NEUTRON COLIMATOR BASED ON NICKEL MATERIAL FOR PIERCING RADIAL BEAMPORT UTILIZATION OF KARTINI RESEARCH REACTOR

Widarto¹, T. Trikasjono², F. Akbar²

¹Center for Accelerator Science and Technology-National Nuclear Energy Agency of Indonesia

²Nuclear Technology School of Higher Learning-National Nuclear Energy Agency of Indonesia

Received: 2 May 2016. Accepted: 15 June 2016 . Published: July 2016

ABSTRACT

Radiation safety analysis of nickel material neutron collimator (as requirement) for piercing radial beamport utilization of Kartini research reactor has been done before the neutron collimator installed. The neutron collimator made of nickel material with cylindrical geometry which is 156 cm length. The inside and outside diameter are 16 cm and 19 cm respectively with mean cylindrical thickness is 1.5 cm. Irradiation process to the neutron collimator begin when the reactor being operated for 6 (six) hours per day and assumed optimum at 100 kW power level. Results of the analysis showed that gamma dose rate which was generated by collimator at a distance of 50 cm from the end of the collimator is $1.5328e^{-03}$ mr/hours. The dose rate is still below the dose limit value which was required by Nuclear Energy Regulatory Agency (BAPETEN) is 1 mr/hours. It can be concluded that utilization neutron collimator of nickel material which installed at the radial piercing beamport of Kartini Reactor is safely.

ABSTRAK

Telah dilakukan kajian analisis keselamatan paparan radiasi terhadap kolimator neutron (sebagai persyaratan) sebelum dipasang pada beamport tembus radial reaktor kartini. Kolimator neutron terbuat dari bahan nikel berbentuk silinder panjang 156 cm dengan diameter dalam 16 cm dan diameter luar 19 cm sehingga tebal silinder 1.5 cm. Proses iradiasi terhadap kolimator neutron terjadi pada saat reaktor dioperasikan pada suatu daya dan diasumsikan optimal pada daya 100 kw selama 6 jam dalam satu hari. Hasil analisis menunjukkan laju dosis gamma yang dihasilkan kolimator pada jarak 50 cm dari ujung kolimator sebesar $1.5328e^{-03}$ mr/jam. Laju dosis tersebut masih dibawah nilai batas dosis yang ditetapkan oleh bapeten sebesar 1 mr/jam, sehingga penggunaan kolimator tersebut dalam batas aman

© 2016 Jurusan Fisika FMIPA UNNES Semarang

Keywords: dose rate; neutron collimator; piercing radial beamport; radiation

INTRODUCTION

The development of nuclear technology utilization is increasing in various field such as industry, medicine, agriculture and research. Besides the benefit of nuclear technology utilization contained potential risk to human live and environment. So that it need to maintain and analyze radiation safety for workers, society, and environment. There are two methods

for monitoring to provide protection to human live by exposure of radiation, namely the monitoring of radiation exposure on the workplace and the monitoring of radiation exposure to personnel who work in potential radiation facility (Trikasjono, 2008).

Research reactors are used as neutron generators in contrast to power reactors in which energy production is the prime issue. Detailed radiation transport calculations are performed using Monte Carlo neutral particle transport code (MCNP) to optimise the nuclear

*Correspondence Address:

Jl. Babarsari, Depok, Sleman, Yogyakarta, 55281
E-mail: widarto_widarto@yahoo.com

facility shield design. Neutron and capture gamma dose rates at the accessible areas are estimated (Sunny & Subbaiah, 2014). To make neutrons available outside the reactor core, beam ports are designed around the core. These beam ports can be characterized by neutron flux level which is useful for neutron beam application in a reactor. The neutron and gamma flux variation was studied as a function of different orientations of beam tubes and optimally minimum information is produced to understand neutron beam design and use (Yasmeen & Mahmood, 2016). The advantage of using a TRIGA reactor for BNCT is its stability and reliability in addition to the high neutron intensity and low background radiation of the treatment beam (Savolainen et al., 2013)

For radiation safety purpose, requires radiation personal dose limit value assigned by Nuclear Energy Regulatory Agency (BAPETEN). According to regulation by The Head of BAPETEN State No. 4 2013, the personal radiation dose limit value is average effective dose of 20 mSv of five-year period, so the dose accumulated in 5 years should not exceed 100 mSv. While effective radiation dose limit value for community is 1 mSv per year (BAPETEN, 2013).

To improve the utilization of the Kartini research reactor, one of irradiation facility that is radial piercing beamport will be used for in vivo/in vitro neutron irradiation test facility as a basic research for developing Boron Neutron Capture Therapy (BNCT) method. By installing neutron collimator of nickel material in the radial piercing beamport to optimizing the neutron flux (Wahyono et al., 2012). Boron Neutron Capture Therapy (BNCT) has been advocated for many decades as an innovative form of radiotherapy that, in principle, has the potential to be the ideal form of treatment for many types of cancers (Moss 2014). The BNCT has been performed using research reactors which are usually located at place far from hospitals. At Kyoto University Research Reactor Institute (KURRI), more than 450 clinical studies of boron neutron capture therapy (BNCT) have been performed using a research reactor as of December 2013 (Tanaka et al., 2014). In BNCT method, it is needed a neutron source which is produced neutron flux that is suitable for BNCT system. BNCT neutron flux may be produced from a neutron Beam Shaping Assembly (BSA) design. BSA is a system tool that is used to produce the neutron flux corresponding to the flux of neutrons for BNCT therapy (Rasouli,

Masoudi, & Kasezas, 2012; Faghihi & Khalili, 2013).

Before the neutron collimator inserted in the radial piercing beamport, it should be carried out to analysis especially radiation safety aspect, because assume when the collimator in the beamport will be radioactive material because of neutron interaction when the reactor operated at power level. By the analysis of radiation safety aspect it can be used for basic requirement developing utilization of the Kartini research reactor (Karmanto, 2016).

A major release of radioactivity to the environment is always of concern, owing to potential acute and long-term health effects. Evidence from historic events confirms that any major uncontrolled release of radiation should be cause for immediate response and scientific assessment of potential health effects (WHO, 2013).

Radiation Effect to Human Live

The main biological effects of radiation is damaging the cells and tissues of the human body. Type the biological effects of radiation can be classified into two types, namely (Umbara, 2011):

1. Stochastic radiation effects severity is not dependent on the size of the dose and the probability of no specific threshold dose.
2. Deterministic radiation effects severity is dependent on large doses.

Collimator

Determination of mass the collimator of nickel is useful for determining of radiation exposure when the collimator activated by neutron since inserting in the beamport and being activation process when the reactor is operated at power level. Figure 1. Indicate dimension of cylindrical collimator form with with size of length is 156 cm, outside diameter (r_o) is 19 cm and inside diameter (r_i) is 16 cm, mean the thickness of collimator is 1,5 cm (Arrozaqi, Widiharto, & Sardjono, 2013).

Neutron Activation.

Neutron activation is reaction between material atomic nuclei with neutron when the material put on the neutron field. By neutron activation the nuclei will nucleus in an excited state condition and radioactive emit particles weather α , β , γ or α and γ , β and γ simultaneously. Activities of material that has been activated can be determined using equation (1) (Suparman, 2011).

$$A = \sum_{act} \phi V (1 - e^{-\lambda t_i}) \quad (1)$$

A = activity (Bq)
 \sum_{act} = macroscopic crosssection (cm^{-1})
 ϕ = neutron flux ($\text{n cm}^{-2} \text{s}^{-1}$)
 V = volume of materials (cm^3)
 λ = decay time (s^{-1})
 t_i = irradiation time (s)

After irradiation process the nuclei material will emit radiation activity with specific decay time and value of activity as formula (2) follow (Awaludin, 2009).

$$A_t = A_0 e^{-\lambda t_d} \quad (2)$$

A_t = decay activity (Bq)
 A_0 = initial activity (Bq)
 λ = decay time (s)
 t_d = delay time (s)

Dose Rate

Figure 1. is indicate the neutron collimator which will be inserted to radial piercing beamport with cylindrical form. When the neutron collimator inserted to beamport while reactor operated, it can be assumed that the collimator will be radioactive material. Radiation activity of the collimator should be determine for safety analysis report related with radiation workers, public and environment.

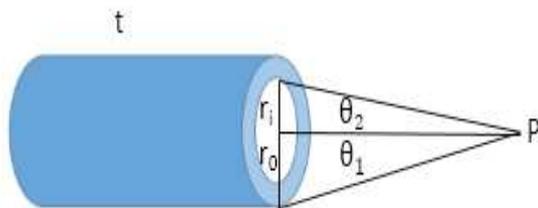


Figure 1. cylindrical neutron collimator.

Determination dose rate assume that closed position at the distance of point P where area worker done can be calculated by formula (3) follow (Stabin, 2007):

$$D = \Gamma C_v 2\pi \{ [-\ln(\cos\theta_1)] - [-\ln(\cos\theta_2)] \} \quad (3)$$

where :

Γ = gamma factor ($\text{R.m}^2/\text{Ci.hours}$)
 C_v = activity (Ci/m^3)
 t = length of cylinder (cm)
 r_i = cylinder inside diameter (cm)
 r_o = cylinder outside diameter (cm)

METHOD

Research Materials.

Figure 2 indicate dimension and technical specification of neutron collimator made of nickel material with total length 156 cm separated to 12 segments as follow,

Neutron collimator made of nickel material with cylindrical dimension and size specification as follow (Mujiyono, Mukhamad, & Leman, 2014):

Total length	(h)	= 156 cm
Inside diameter	(r_i)	= 16 cm
Outside diameter	(r_o)	= 19 cm
Segmen length	(p)	= 13 cm
Total segmen	(n)	= 12 segmen
Mass each segmen (m)		= 8 kg
Total mass	(m_t)	= 96 kg

Neutron collimator made of nickel material with cylindrical dimension and size specification as follow (Mujiyono et al., 2014):

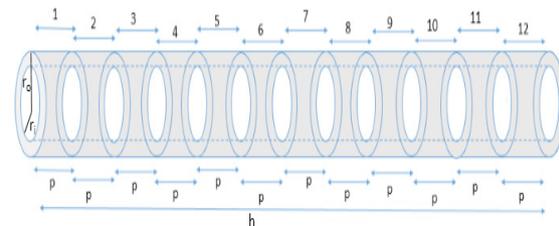


Figure 2. Dimension of neutron collimator

Total length	(h)	= 156 cm
Inside diameter	(r_i)	= 16 cm
Outside diameter	(r_o)	= 19 cm
Segmen length	(p)	= 13 cm
Total segmen	(n)	= 12 segmen
Mass each segmen (m)		= 8 kg
Total mass	(m_t)	= 96 kg

The nickel purity data of collimator material is around 95 % which used to manufacture the neutron collimator obtained from studies conducted by KKhoirunisa & Widarto (2015) with the title "Analysis of Type And Elements Content In Neutron Collimator Materials Before And After Manufacturing Using Neutron Activation Analysis Method (NAA)" (Khoirunisa & Widarto, 2015).

Neutron Flux

Neutron flux data along the radial piercing beamport of Kartini Research Reactor which is operates at 100 kW was studied by Sardjono et al, (2014) titled "Current Status of Boron Neutron Capture Therapy Technology Development and Application With Compact

Neutron Generator” (Widarto, 2014).

Data Analysis Technique

Equation (1) was used to determined the activity of each collimator elements when irradiation process take place. In determining the activity of each collimator elements after irradiation process was stopped we used equation (2). In determining the dose rate generated by collimator used equation (3).

RESULT AND DSCUSSION

Elements of Neutron Collimator

Research conducted by Khairunnisa, (2015) with the title “ Analysis of Type And Elements Content In Neutron Collimator Materials Before And After Manufacturing Using Neutron Activation Analysis Method (NAA)” were obtained the collimator elements before and after manufacturing. Table 1 shows the concentration of constituent elements of neutron collimator after manufacturing.

Tabel 1. Collimator Elements Concentration

Elements	Concentration (mg/g)
Ni-65	6.6506E-02
Mn-56	3.8558E-03
Cr-51	5.3670E-04
Hg-197m	1.5047E-04
W-187	1.6252E-05
Co-60	4.4206E-05
Cu-64	1.7392E-05

Based on neutron collimator homogeneity, the mass of each neutron collimator elements in each segment is same. By using equation (1), it will obtain the mass of each neutron collimator elements in each segment. Table 2 shows the mass of each neutron collimator elements in each collimator segment.

Neutron Flux of The Piercing Radial Beamport

Research conducted by Widarto et al, (2014) titled “Current Status of Technology Development and Application of Boron Neutron Capture Cancer Therapy With Compact Neutron Generator” calculated that the quantity of the thermal and fast neutron flux along the piercing radial beamport when the reactor Kartini operated at a power of 100 kW shown in Table 3. Figure 3 shows the dimensions of the

neutron collimator (Novitasari, 2015).

Table 2. Mass of Collimator Elements in Each Segment

Elements	Mass (gram)
Ni-65	5.3205E-01
Mn-56	3.0846E-02
Cr-51	4.2936E-03
Hg-197m	1.2037E-03
W-187	1.3002E-04
Co-60	3.5365E-04
Cu-64	1.3913E-04

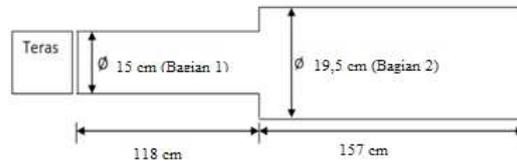


Figure 3. Radial Dimension Translucent Beamport

Table 3. Thermal And Fast Neutron Flux Along The Piercing Radial Beamport

Distance (cm)	Neutron Flux (n cm ⁻² s ⁻¹)	
	Thermal	Fast
0	1.3264E+09	1.3130E+09
25	4.1366E+08	3.3393E+08
50	4.0303E+08	3.9220E+08
75	1.0511E+08	8.3272E+07
100	2.0128E+07	1.4682E+07
120	8.3678E+06	3.3553E+06
140	8.3082E+06	1.5311E+06
160	3.0194E+06	3.1597E+06
180	5.9255E+06	4.5900E+05
200	5.2844E+06	4.7344E+05
220	3.6433E+06	1.2849E+06
240	4.4010E+06	5.2958E+05
260	3.0691E+06	9.8243E+05

Based on Table 3 data, it can be made a relationship between the beamport length and neutron flux. Figure 4 shows the relationship between the beamport length and thermal neutron flux, while Figure 5 shows the relationship between beamport length with fast neutron flux.

Equation (4) shows the distribution of thermal neutron flux, where the thermal neutron flux expressed in y-axis and x-axis specifies the beamport length.

$$y = 1.298 \times 10^9 e^{-0.0342x} \tag{4}$$

Based on Figure 5, it was obtained the equation (5) where fast neutron flux expressed in y-axis and x-axis specifies the beamport length.

$$y = 1.283 \times 10^9 e^{-0.0384x} \tag{5}$$

Thermal Neutron Flux Mapping

Collimator will be placed on the piercing radial beamport at a 118 cm distance from the reactor core. Figure 6 shows the placement of the neutron collimator in piercing radial beamport of Kartini Research Reactor.

Neutron flux which is interacting with the neutron collimator are thermal neutron flux (Ger-

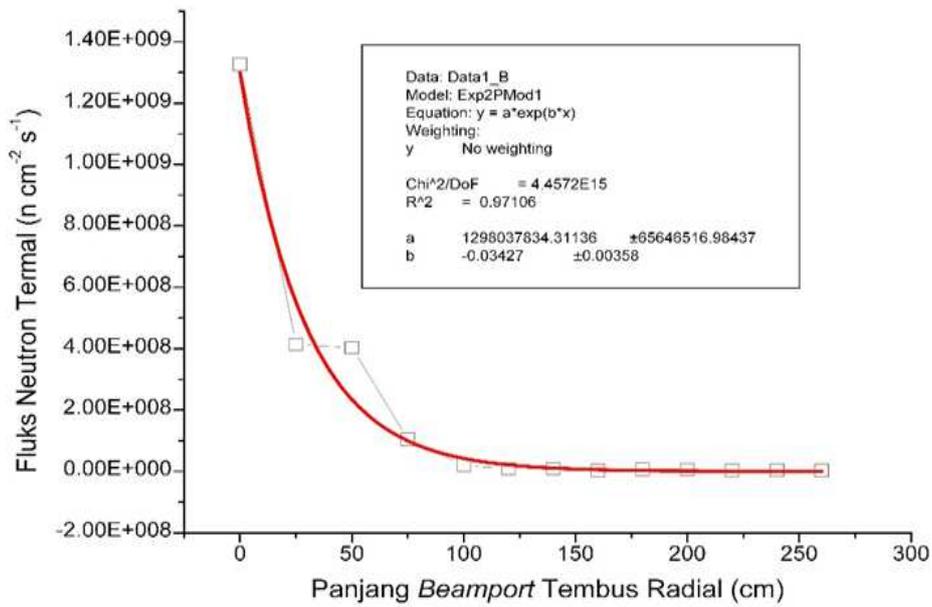


Figure 4. Graph Of Relationship Between The Beamport Length And Thermal Neutron Flux

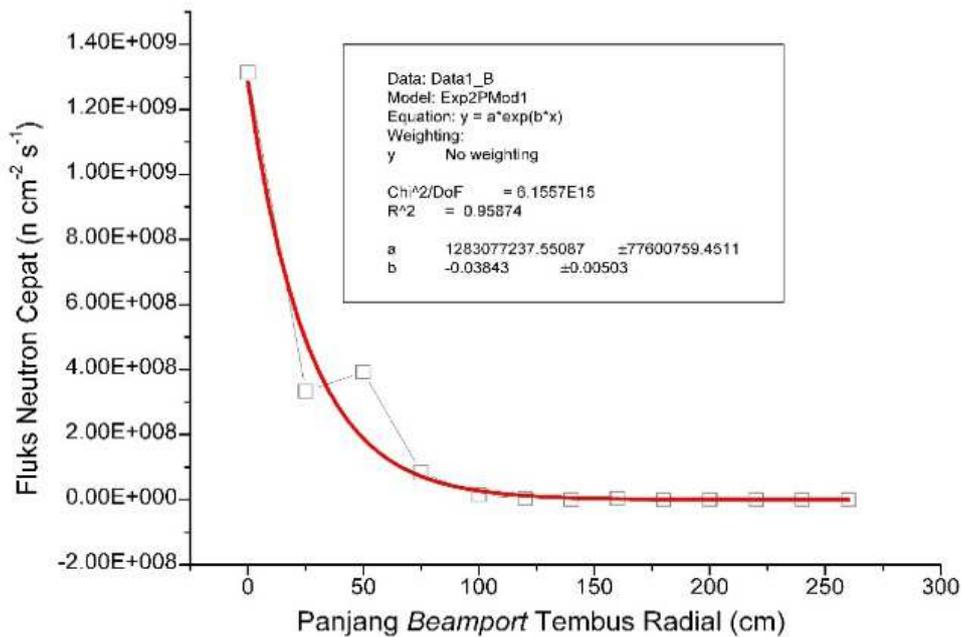


Figure 5. Graph of Beamport length Vs Fast Neutron Flux

hard, 1976). The magnitude of the thermal neutron flux which interacts with neutron collimator vary in each neutron collimator segments. The magnitude of the thermal neutron flux which interacts in each segments of collimator can be determined using equation (4). Table 4 shows the magnitude of the thermal neutron flux which interacts with each collimator segments (where length of each collimator segment separated with X_1 and X_2). So, each collimator segment length is $X_2 - X_1 = 13$ cm, and number of collimator segment is 12 segment. It mean that the total of collimator length is 12×13 cm = 156 cm.

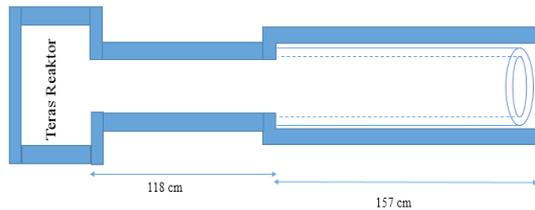


Figure 6. Placement of Collimator in Piercing Radial Beamport

Table 4. Thermal Neutron Flux in Each Collimator Segments

Segments	Length (cm)		Thermal neutron flux (ncm ⁻² s ⁻¹)
	x_1 (cm)	x_2 (cm)	
1	118	131	2.2942E+07
2	131	144	1.4708E+07
3	144	157	9.4289E+06
4	157	170	6.0447E+06
5	170	183	3.8751E+06
6	183	196	2.4843E+06
7	196	209	1.5926E+06
8	209	222	1.0210E+06
9	222	235	6.5454E+05
10	235	248	4.1961E+05
11	248	261	2.6901E+05
12	261	274	1.7245E+05

Collimator Dose Rate While Irradiation

The activity of each collimator elements is an activity accumulation of each collimator segments. Table 5 shows the amount activity of every collimator elements in the irradiation time.

The results are shown in Table 5 shows that the longer irradiation time, so that the activity of each collimator elements will be greater.

When the collimator is irradiated, each collimator elements will be activated. It will

become radioactive and emit radiation. Table 6 shows the magnitude of the dose rate produced by the collimator at a 50 cm distance from the end of the collimator. The total dose rate which is produced from neutron collimator is accumulated dose rate from each neutron collimator elements.

Table 5. Collimator Elements Activities in the Irradiation time

Elements	Activities (Ci)		
	ti = 2 hours	ti = 4 hours	ti = 6 hours
Ni-65	5,4251E-06	8,5547E-06	1,0360E-05
Mn-56	4,4649E-07	7,0749E-07	8,6006E-07
Cr-51	2,1143E-08	4,2242E-08	6,3297E-08
Hg-197m	4,3165E-08	8,3888E-08	1,2231E-07
W-187	1,5413E-09	2,9957E-09	4,3682E-09
Co-60	6,9119E-12	1,3824E-11	2,0735E-11
Cu-64	1,0606E-09	2,0119E-09	2,8651E-09

Table 6. Collimator Dose Rate in Irradiation Time

Ele-ments	Dose rate (mR/hours)		
	ti = 2 hours	ti = 4 hours	ti = 6 hours
Ni-65	6,3609E-04	1,0030E-03	1,2147E-03
Mn-56	1,6256E-04	2,5759E-04	3,1314E-04
Cr-51	1,9492E-07	3,8943E-07	5,8353E-07
Hg-197m	1,2964E-06	2,5195E-06	3,6734E-06
W-187	1,9978E-07	3,8831E-07	5,6621E-07
Co-60	3,7335E-09	7,4669E-09	1,1200E-08
Cu-64	5,5171E-08	1,0465E-07	1,4903E-07
Total	8,0040E-04	1,2640E-03	1,5328E-03

The results are shown in Table 6 shows that the longer irradiation time, dose rate generated by neutron collimator will be greater.

Based on Table 6 data, it can be made the relationship between the irradiation time and the dose rate. Figure 7 until Figure 13 shows the relationship between the irradiation time and the dose rate for each collimator elements.

Based on Figure 7, it was obtained the equation (6) where irradiation time expressed to x-axis and y-axis expressed the dose rate.

$$y = 1.5x10^{-3}(1 - e^{-0.275x}) \tag{6}$$

Based on Figure 8, it was obtained the equation (7) where irradiation time expressed to x-axis and y-axis expressed the dose rate.

$$y = 3.9x10^{-4}(1 - e^{-0.268x}) \quad (7)$$

Based on Figure 9, it was obtained the equation (8) where irradiation time expressed to x-axis and y-axis expressed dose rate.

$$y = 9x10^{-5}(1 - e^{-1.05x10^{-3}x}) \quad (8)$$

Based on Figure 10, it was obtained the equation (9) where irradiation time expressed to x-axis and y-axis expressed dose rate.

$$y = 2x10^{-5}(1 - e^{-0.029x}) \quad (9)$$

Based on Figure 11, it was obtained the equation (10) where irradiation time expressed to x-axis and y-axis expressed the dose rate.

$$y = 3.5457x10^{-6}(1 - e^{-0.029x}) \quad (10)$$

Based on Figure 12, it was obtained the equation (11) where irradiation time expressed to x-axis and y-axis expressed the dose rate

$$y = 1.2467x10^{-4}(1 - e^{-1.501.10^{-5}x}) \quad (11)$$

Based on Figure 13, it was obtained the equation (12) where the irradiation time expressed to x-axis and y-axis expressed the dose rate.

$$y = 5.3502x10^{-7}(1 - e^{-0.054x}) \quad (12)$$

Collimator Dose Rate after 6 Hours Irradiation

After irradiated for 6 hours was stopped, the activity of each collimator elements were decay. The total activity of each collimator elements are accumulation of each collimator elements activities. Table 7 shows the amount of every collimator elements activity after 6 hours irradiation time, whereas Table 8 shows the dose rate generated by a collimator at a distance of 50 cm from the end of the collimator after irradiated for 6 hours. The total dose rate which is generated by neutron collimator is accumulated dose rate of each collimators elements in each segments.

Table 7. Collimator Elements Activities After Irradiated for 6 Hours

Elements	Activity (Ci)		
	td = 3hours	td = 6hours	td = 9hours
Ni-65	4.5394E-06	1.9890E-06	8.7148E-07
Mn-56	3.8438E-07	1.7179E-07	7.6778E-08
Cr-51	6.3099E-08	6.2902E-08	6.2706E-08
Hg-197m	1.1207E-07	1.0270E-07	9.4105E-08
W-187	4.0042E-09	3.6706E-09	3.3647E-09
Co-60	2.0734E-11	2.0733E-11	2.0732E-11
Cu-64	2.4336E-09	2.0671E-09	1.7558E-09

The results are shown in Table 7 states that the longer delay time, the lower activity of each collimator elements.

Table 8. Collimator Dose Rate After Irradiated for 6 hours

Ele-ments	Dose rate (mR/hours)		
	td = 3 hours	td = 6 hours	td = 9 hours
Ni-65	5.3224E-04	2.3321E-04	1.0218E-04
Mn-56	1.3995E-04	6.2547E-05	2.7954E-05
Cr-51	5.8171E-07	5.7989E-07	5.7808E-07
Hg-197	3.3661E-06	3.0845E-06	2.8264E-06
W-187	5.1903E-07	4.7578E-07	4.3613E-07
Co-60	1.1200E-08	1.1199E-08	1.1199E-08
Cu-64	1.2659E-07	1.0753E-07	9.1333E-08
Total	6.7680E-04	3.0001E-04	1.3408E-04

The results are shown in Table 8 shows that the longer the delay time, the smaller the dose rate generated collimator elements.

Based on Table 8 data, it can be made the relationship between the delay time and the dose rate of each collimator elements. Figure 14 until Figure 20 shows the relationship between the delay time and the dose rate of each collimator elements.

Based on Figure 14, it was obtained the equation (13) where delay time expressed to x-axis and y-axis expressed the dose rate

$$y = 1.21x10^{-3}e^{-0.275x} \quad (13)$$

Based on Figure 15, it was obtained the equation (14) where delay time expressed to x-axis and y-axis expressed the dose rate.

$$y = 3.1x10^{-4}e^{-0.268x} \quad (14)$$

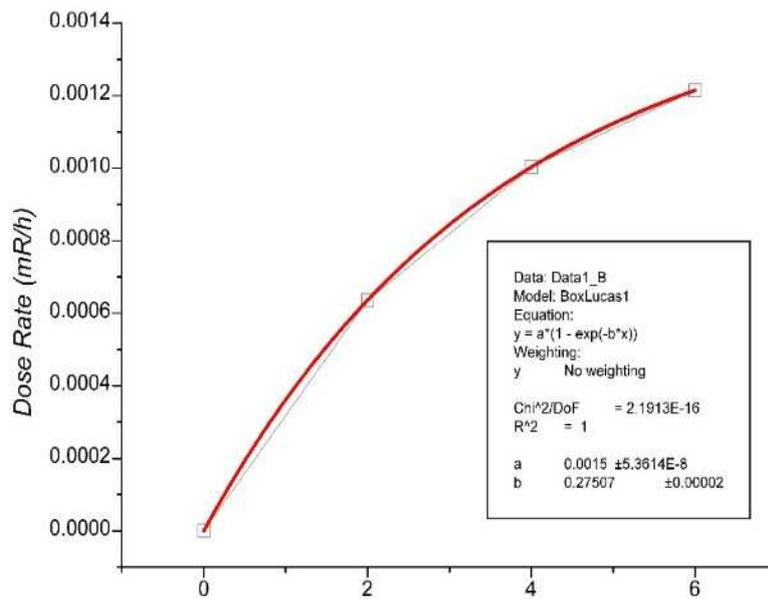


Figure 7. Graph of Irradiation Time Vs Dose Rate of Ni-65

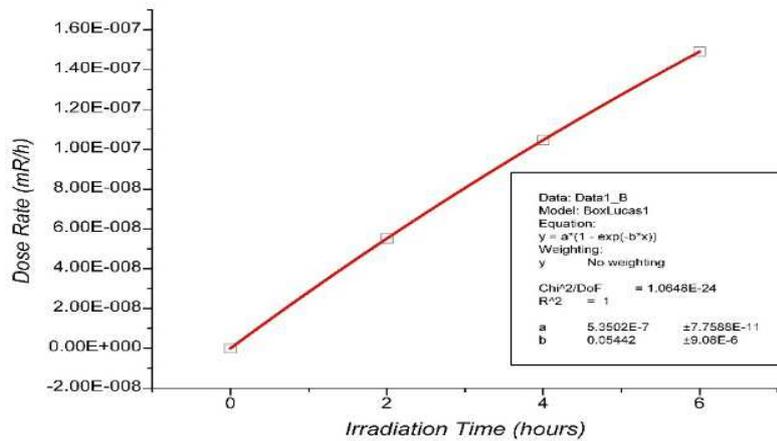


Figure 8. Graph of Irradiation Time Vs Dose Rate of Mn-56

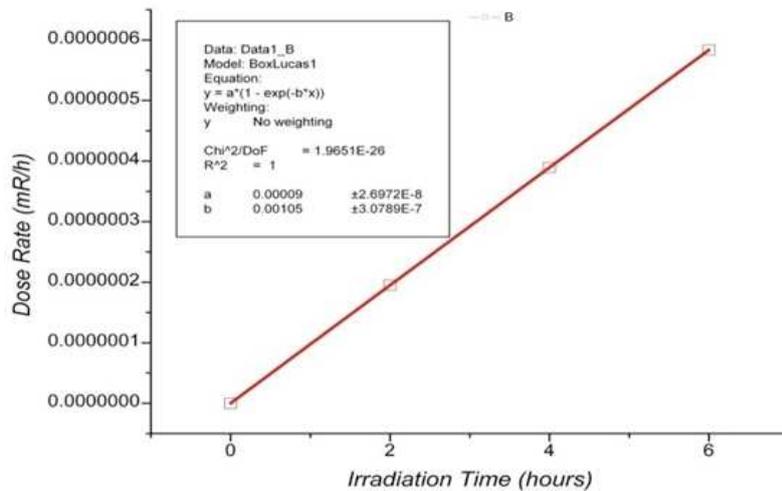


Figure 9. Graph of Irradiation Time Vs dose rate of Cr-51

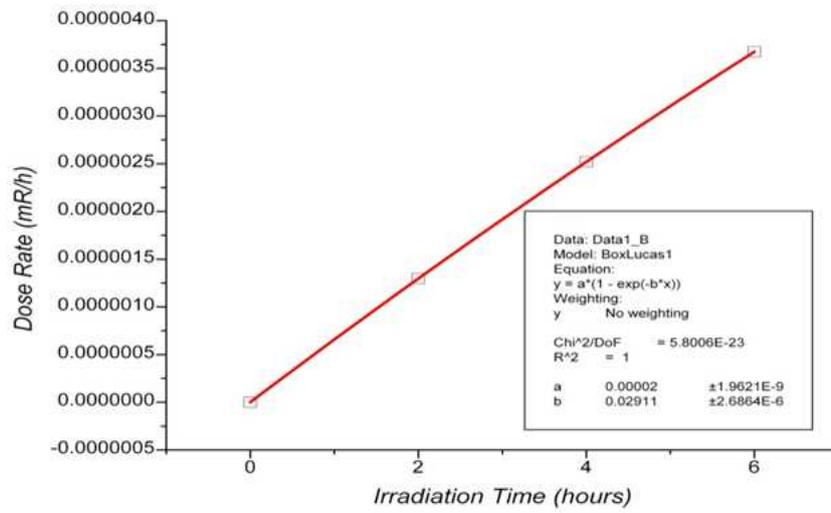


Figure 10. Graph of Irradiation Time vs dose rate of Hg-197m

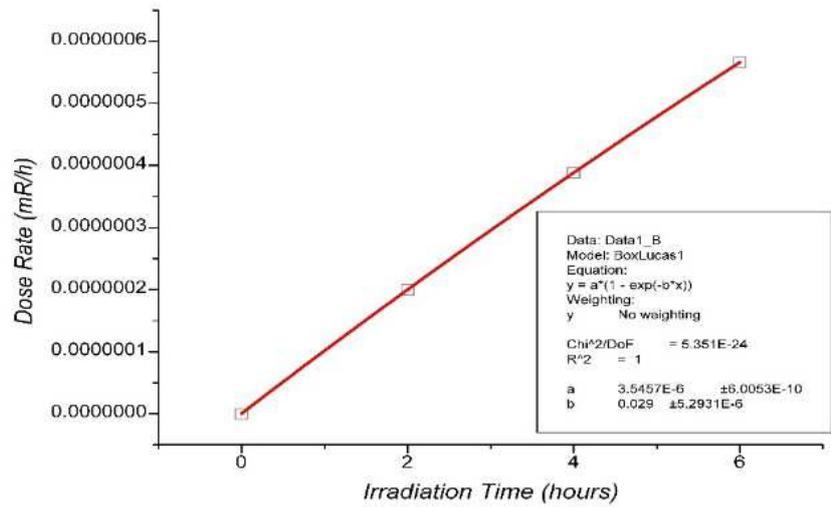


Figure 11. Graph of Irradiation Time Vs Dose Rate of W-187

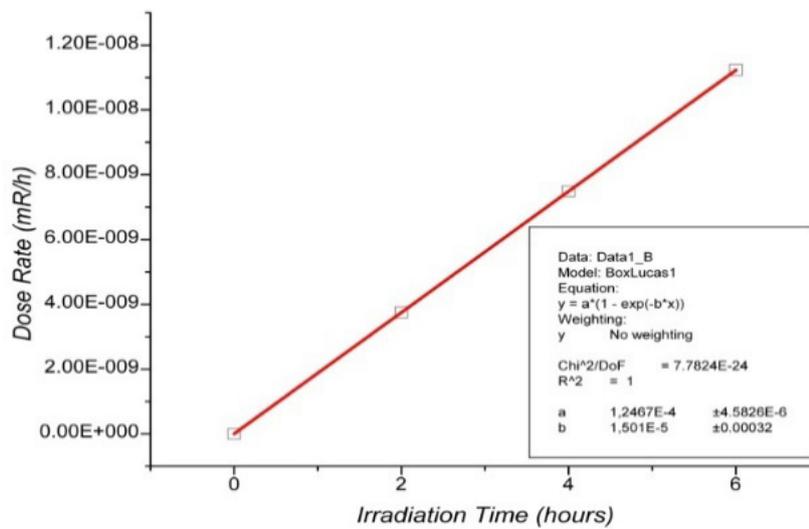


Figure 12. Graph of Irradiation Time vs Dose Rate of Co-60

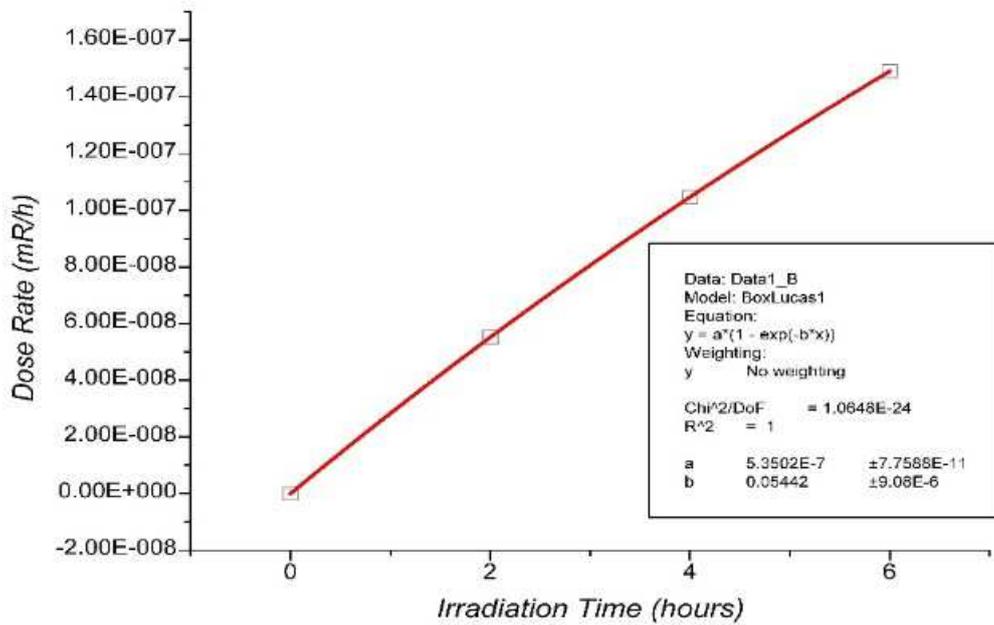


Figure 13. Graph of Irradiation Time Vs Dose Rate of Cu-64

Based on Figure 16, it was obtained the equation (15) where delay time expressed to x-axis and y-axis expressed the dose rate.

$$y = 5.8353 \times 10^{-7} e^{-1.04 \times 10^{-3} x} \quad (15)$$

Based on Figure 17, it was obtained the equation (16) where delay time expressed to x-axis and y-axis expressed the dose rate.

$$y = 3.6734 \cdot 10^{-6} e^{-0,029x} \quad (16)$$

total dose rate calculated at deley time (*td*) for 0 hours (suddenly irradiated), 3 hour, 6 hour and 9 hour. Further more for safety aspect such as requirement by regulatory, should be calculated by assumed that dose rate for distance 50 cm from the collimator . The result of Dose Rate of Collimator After Irradiated for 6 hour could be shaw as Table 9.

Total dose rate generated by the neutron collimator has ben calculated when irradiated by neutron for 6 (six) hour, assumed at 50 cm distance and with various delay time (*td*) for 0 hour (sudenly irradiated) is 1.5328E-03 mR/hour, for 3 hour is 6.7680E-04, for 6 hour is 3.0001E-04 and for 9 is 1.3408E-04 (Akbar, 2015).

Table 9. Dose Rate of Collimator After Irradiated for 3, 6, and 9 hours.

Element	Dose rate (mR/jam)			
	td = 0 hour	td = 3 hour	td = 6 hour	td = 9 hour
Ni-65	1.2147E-03	5.3224E-04	2.3321E-04	1.0218E-04
Mn-56	3.1314E-04	1.3995E-04	6.2547E-05	2.7954E-05
Cr-51	5.8353E-07	5.8171E-07	5.7989E-07	5.7808E-07
Hg-197	3.6734E-06	3.3661E-06	3.0845E-06	2.8264E-06
W-187	5.6621E-07	5.1903E-07	4.7578E-07	4.3613E-07
Co-60	1.1231E-08	1.1230E-08	1.1230E-08	1.1229E-08
Cu-64	1.4903E-07	1.2659E-07	1.0753E-07	9.1333E-08
Total	1.5328E-03	6.7680E-04	3.0001E-04	1.3408E-04

According to safety aspect requiremet authorized by regulatory body (Badan Pengawas Tenaga Nuklir) is 1 mR / h). Its could be concluded that utilization of the neutron colimator made of Nickel when inserted in the radial piercing beamport is safely, because the dose rate which generated by neutron collimator is much lower than dose rate requirements regulatory.

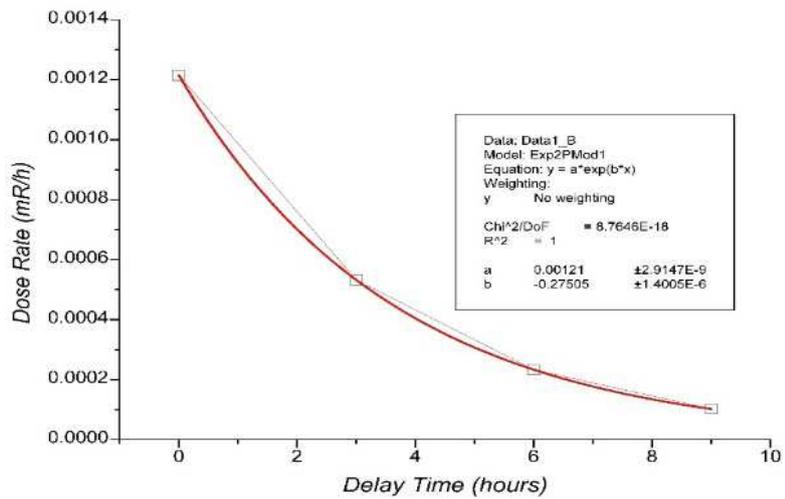


Figure 14. Graph of Delay Time Vs Dose Rate of Ni-65

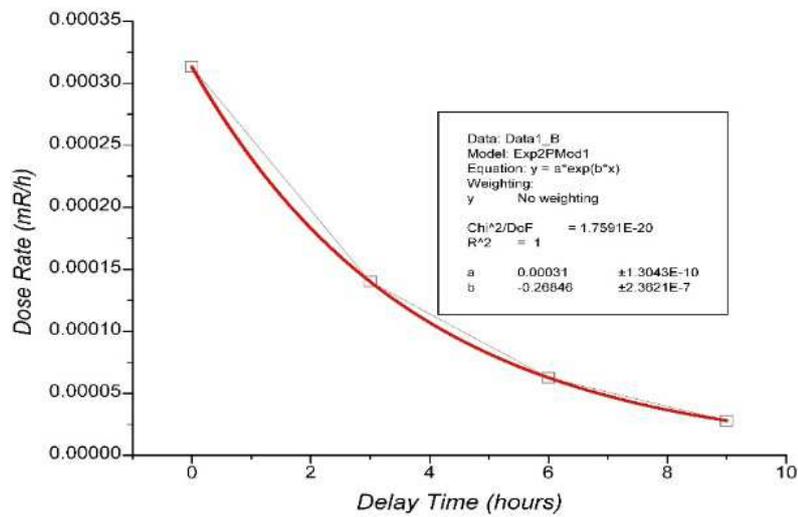


Figure 15. Graph of Delay Time Vs Dose Rate of Mn-56

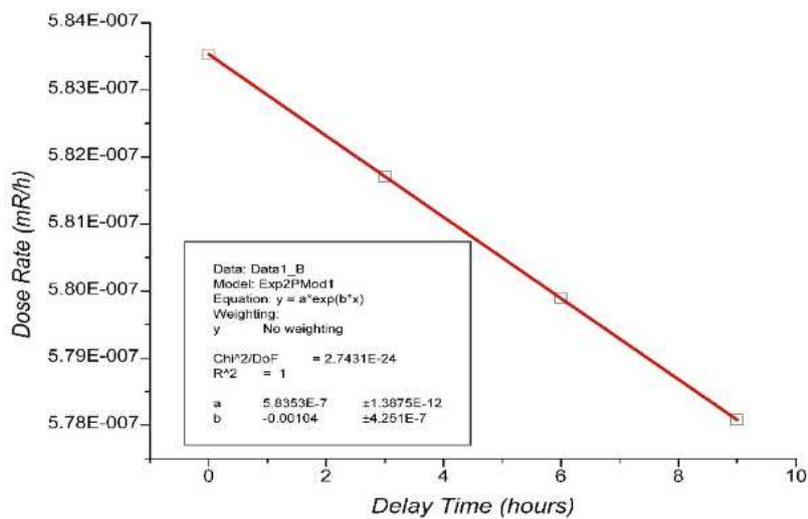


Figure 16. Graph of Delay Time Vs Dose Rate of Cr-51

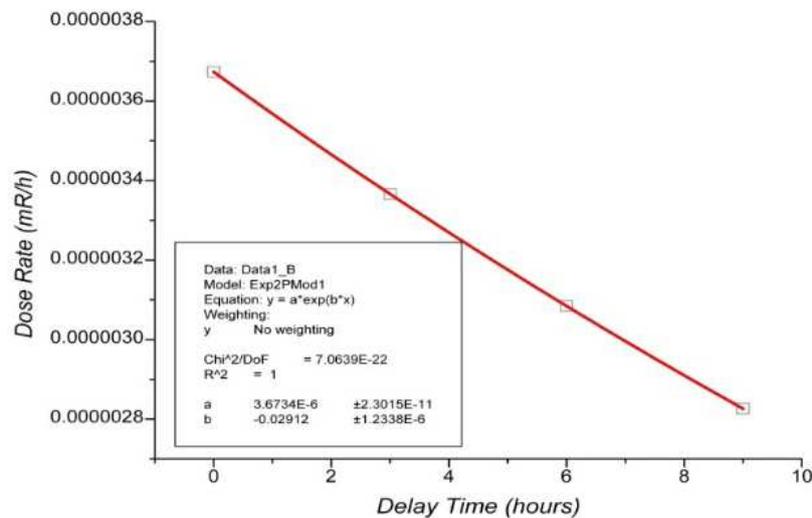


Figure 17. Graph of Delay Time Vs Dose Rate of Hg-197m

CONCLUSION

The total dose rate generated by neutron collimator at a distance of 50 cm from the end of the collimator after 6 (six) hours irradiation for delay time (td) 0 hour (suddenly irradiated) is $1.5328\text{E-}03$ mR/hour, for 3 hour is $6.7680\text{E-}04$, for 6 hour is $3.0001\text{E-}04$ and for 9 is $1.3408\text{E-}04$ mR / h. The dose rate are much lower than the dose limit which authorized by Nuclear Energy Regulatory Agency (BAPETEN) i.e. 1 mR / hour. $1.5328\text{E-}03$ its means that utilization of the neutron collimator is safely.

Remarks

It is required α and β spectroscopy to study both α and β radiation which is may occur from collimator elements activity.

ACKNOWLEDGEMENT

We would like to said thanks to INSIN-as Research Coordinator of BNCT (Prof. Ir. Y. Sardjono) and all members who is supporting the accomplishment of this project, especially for Center of Science and Accelerator Technology (PSTA-BATAN) for the opportunities given to perform this work.

REFERENCES

Akbar, F. (2015). Analisis Keselamatan Radiasi Kolimator Bahan Nikel Pada Beamport Tembus Radial Reaktor Kartini. Tugas Akhir Jurusan Teknik Fisika. Sekolah Tinggi Teknologi Nuklir.
Arrozaqi, M. I. M., Widiharto, A., & Sardjono, Y.

(2013). Perancangan Kolimator Di Beamport Tembus Reaktor Kartini Untuk Boron Neutron Capture Therapy. *Doctoral Dissertation*. Yogyakarta: Fakultas Teknik Universitas Gadjah Mada
Awaludin, R. (2009). *Pembuatan Nanopartikel Emas Radioaktif dengan Aktivasi Neutron*. Kawasan Puspipetek Serpong-Tangerang: PRR-BATAN
BAPETEN. (2013). *Peraturan Kepala Badan Pengawas Tenaga Nuklir Nomor 4 Tahun 2013 tentang Proteksi dan Keselamatan Radiasi Dalam Pemanfaatan Tenaga Nuklir*. Jakarta: Badan Pengawas Tenaga Nuklir.
Faghihi, F., & Khalili, S. (2013). Beam Shaping Assembly of a D-T Neutron Source for BNCT and its Dosimetry Simulation in Deeply-seated Tumor. *Radiation Physics and Chemistry*, 89, 1-13.
Gerhard, E. (1976). *Neutron Activation Tables*. Weinheim New York: Verlag Chemie
Karmanto, E. E. (2016). *Sistem Manajemen Pengoperasian, Perawatan, Modifikasi, dan Utilisasi Reaktor Kartini*. Yogyakarta: PSTA-BATAN
Khoirunisa & Widarto. (2015). *Analisis Kandungan Elements Pada Bahan Kolimator Neutron Sebelum Dan Setelah Manufaktur Menggunakan Metode AAN*. Yogyakarta: STTN-BATAN.
Moss, R. L. (2014). Critical review, with an optimistic outlook, on Boron Neutron Capture Therapy (BNCT). *Applied Radiation and Isotopes*, 88, 2-11.
Mujiyono., Mukhamad, A. F. H., & Leman, A. (2014). *Manufaktur Collimator BNCT Berbahan Nikel dengan Metode Gravity Casting dan Analisis Potensi Centrifugal Casting Sebagai Metode Alternatif*. Yogyakarta: Jogja Bangkit Publisher.
Novitasari., I. S. (2015). Analisis Fluks Neutron Pada Beamport Tembus Radial Reaktor Kartini Un-

- tuk Fasilitas Uji in Vivo Dan In Vitro Boron Neutron Capture Therapy (BNCT)*. Skripsi. Yogyakarta: Jurusan FMIPA Universitas Negeri Yogyakarta.
- Rasouli, F. S., Masoudi, S. F., & Kasesaz, Y. (2012). Design of a model for BSA to meet free beam parameters for BNCT based on multiplier system for D-T neutron source. *Annals of Nuclear Energy*, 39(1), 18-25.
- Savolainen, S., Kortensniemi, M., Timonen, M., Reijonen, V., Kuusela, L., Uusi-Simola, J., Salli, E., Koivunoro, H., Seppala, T., Lonroth, N., Valimaki, N., Hivonen, H., Kutiluoto, V., Seren, T., Kuronen, A., Heikkinen, S., Kosunen, A., and Auterinen, I. (2013). *Physica Medica. European Journal of Medical Physics*, 29, 233-248.
- Sardjono, Y., Widarto, Pudjorahardjo, J.S., Triatmoko, I.M., Susilowati, A.D. (2014). *Status Saat Ini Pengembangan Teknologi Dan Aplikasi Boron Neutron Capture Cancer Therapy Dengan Compact Neutron Generator, Buku Status Boron Neutron capture Therapy di Indonesia*. Yogyakarta: Jogja Bangkit Publisher.
- Stabin, M. G. (2007). *Radiation Protection and Dosimetry*. New York: Springer.
- Sunny, C. S., & Subbaiah, K. V. (2004). Shield structure optimisation studies for the west beam port of the KAMINI reactor. *Annals of Nuclear Energy*, 31(12), 1403-1413.
- Suparman, L. Y. (2011). Penentuan Karakteristik Distribusi Fluks Neutron Thermal Fasilitas Iradiasi Lazy Susan (LS) Arah Horizontal Reaktor Kartin. Skripsi. Yogyakarta: Jurusan FMIPA Universitas Negeri Yogyakarta.
- Tanaka, H., Y. Sakurai, M. Suzuki, S. Masunaga, T. Mitsumoto, Y. Kinashi, M. Narabayashi, Y. Nakagawa, T. Watanabe, N. Fujimoto, A. Maruhashi, N. Kondo, K. Ono. (2014). Evaluation of thermal neutron irradiation field using a cyclotron-based neutron source for alpha autoradiography, *Applied Radiation and Isotopes*, 88, 153-156
- Trikasjono, T. (2008). Studi Penerimaan Dosis Eksterna Pada Pekerja Radiasi di Kawasan Batan Yogyakarta, Prosiding Seminar Nasional IV SDM Teknologi Nuklir, Yogyakarta.
- Umbara, R. H. (2011). *Pedoman Keselamatan dan Proteksi Radiasi Kawasan Nuklir Serpong (Revisi 1)*. Tangerang Selatan: PUSPIPTEK Serpong.
- Yasmeen, R., & Mahmood, M. S. (2016). Design study of neutron beam facility around TRIGA research reactor core. *Annals of Nuclear Energy*, 91, 203-205.
- Wahyono, P. I. (2012). *Laporan Analisis Keselamatan (Rev.7)*. Yogyakarta: PTAPB-BATAN.
- WHO. (2013). *Health Risk Assessment: from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami*. Switzerland: WHO Press.