Indonesian Journal of Physics and Nuclear Applications
Volume 2, Number 2, June 2017, p. 75-82
ISSN 2549-046X, © FSM UKSW Publication

Analysis of Radiation Effects on Workers and Environment Pilot Plant Boron Neutron Capture Therapy (BNCT)

Nur Endah Sari[1]*, Yohannes Sardjono[2], Andang Widiharto[3]

[1]Physics, Faculty of Science and Technology, State Islamic University Sunan Kalijaga Marsda Adisucipto Street, Yogyakarta 55281 ,Indonesia
[2]Center of Science and Accelerator Technology – BATAN Babarsari Street, Depok, Yogyakarta 55281, Indonesia
[3]Physics Technic, Faculty of Technic, Gadjah Mada University Grafika No. 2 Street, Sinduadi, Yogyakarta 55281, Indonesia

Abstract BNCT is a new method in nuclear technology. The aim of BNCT application is to reduce human risk which used to kills cell targeting characteristic. The impact of using this technology should be considered before it is applied, among the effects of radiation on workers and the surrounding environment BNCT pilot plant. A research on modeling of BNCT pilot plant used a collimator for a 30 MeV cyclotron neutron sources which had been designed from the past research. Radiation shielding modeling for treatment room used MCNPX software. The radiation shielding was concrete baryte on each side that includes coated borated polyethylene 2 cm thick and it is featured with a sliding door with dimensions 220 × 87 × 200 cm coated with stainless steels 2 cm thick. Results obtained value equivalent dose rate of neutron and gamma of each 41.5 $\mu Sv.h^{-1}$ and 2.05 $\mu Sv.h^{-1}$. Effects of radiation received by workers in the form of deterministic effects did not have a significant are impact.

Keywords Radiation Protection, BNCT, MCNPX, Radiation Shielding

1. INTRODUCTION

BNCT is a combination of chemotherapy and radiotherapy which uses nonradioactive nuclides boron-10 to capture thermal and epithermal neutrons resulting in the prompt nuclear reaction $^{10}B(n,\alpha)^{7}Li$. The products of this reaction have a high linear energy transfer characteristic (α particles approximately 150 $keV.\mu m^{-1}$, ^{7}Li-nucleus approximately 175 $keV.m^{-1}$). The path lengths of these particles in water or tissues are in the range of 4.5-10 mm, hence resulting an energy deposition limited to the diameter of a single cell. Boron-11 has a half-life is very short around 10-12 s while Lithium-7 around 10-5 s. Theoretically, therefore, it is possible to selectively irradiate those tumor cells that have taken up a sufficient amount of ^{10}B and simulataneously spare normal cells (Saurwien, 2013; Saurwien and Ray Moss, 2009; Ilma, 2013). Research on BNCT treatment is being carried out in developed countries like America, Japan, Germany and others. This therapy chosen because it has many advantages including: effectively, reactions between neutrons and boron destroy cancer cells selectively, thermal and epithermal neutron energy used is low so as not to damage healthy cells around, a short treatment around 20-60 minutes and drugs containing boron compounds such as BPA and BSH not be toxic (poison) so there are no side effects to health (Holden et al, 2005; Moss et al, 2005).

BNCT treatment process carried out by method of injection (infusion) boron compounds into the brain tissue. There are two methods, namely intravenous infusion (i.v) and intracarotidly (i.c). An intravenous injection of boron compounds through the veins while injecting it intracarotidly boron compound is injected through the internal carotid artery (Saurwien et al, 2013; Wahyuningsih, 2014). After the injection of boron compounds then patient is irradiated with neutrons in the treatment room..

In a mixture of boron compounds, also included Scavanger highly reactive to lithium-7 so that lithium will be bound and exit the body through metabolism mechanisms. This is important because therapiutic dose of lithium approach to toxic dose. While the α particles would turn into helium after getting electrons through the reaction of ionization and excitation. Because helium is an inert noble gases, helium will be out of the body without reacting chemically (Saurwien and Ray Moss, 2009; IIma, 2013).

The effects of radiation will occur if there were not used safely, it can be somatic effects, genetic effects, stochastic effects and deterministic effects. So the worker must be used personal protective equipment and should also be made of radiation shielding that is able to withstand neutron radiation and gamma to keep from treatment room. (Chamber, 2009; Wiryosimin, 1995).

In the document No. 60 ICRP (International Commission on Radiological Protection) in 1990 who pursue the field of radiation safety, also mentioned that need to be applied system of dose limitation which comprehensively include: any use of radioactive substances and or other sources of radiation based only on the principle of benefit and must first be approved by the Agency Supervisors (principle of Justification), all radiation should be kept as low as possible (As low As Reasonably Achievable-ALARA), taking into account economic factors and social (principle Optimization), equivalent dose received by a person shall not exceed the Value limit dose (NBD) (The principle of limitation) (BAPETEN, 2016). So that workers who were in the control room safe, survived during the work and objectives of radiation protection can be applied.

2. MATERIALS AND METHODS

2.1 Radiation Protection

Nuclear Energy Regulatory Agency Of Indonesia (BAPETEN) Chairman’s Regulation Number 4 Year 2013 on Radiation Protection and Safety in Nuclear Energy Utilization" section 15 states that the Dose Limit Values for Radiation Workers assigned with the provision (BAPETEN, 2013):

a. Effective dose average is 20 mSv per year in the period of 5 (five) years, so the dose accumulated in five (5) years shall not exceed 100 mSv.

b. Effective dose is 50 mSv in 1 (one) particular year.

c. Equivalent dose to the eye lens by an average is 20 mSv per year in the period of 5 (five) years and 50 mSv in 1 (one) particular year.

d. Equivalent dose to the skin is 500 mSv per year.

e. Equivalent doses for the hands or feet is 500 mSv per year.

Dose limiting value must be below 20 mSv in a year that is the amount of NBD average in one year. NBD supervision carried out by (Widyaningsih and Sutanto, 2013; Darsono et al, 2013):

1. Monitoring individual dose is done externally and internally. External monitoring is done by using individual dosimeters and internal

monitoring conducted in-vivo or in-vitro.

2. Work area monitoring radiation exposure monitoring of radiation exposure to the work area to prevent exceeding NBD, the monitoring of radiation exposure work area, setting time (work hours) and management radiation workers. For the control room does not exceed 25 μSv.h^{-1} (2.5 mrem.h^{-1}).
3. Limiting the dose (Dose Constraint) for the application of optimization of radiation protection and radiation safety.

Determination of the dose limiting can be done in two ways by calculating workload with maximum dose rate and based on the evaluation of effective dose in a specified period. Then, assuming the calculation of working hours/workload radiation workers used by BAPETEN:

$$8\frac{hours}{day}\times 5\frac{days}{week}\times 4\frac{weeks}{month}\times 12\frac{months}{year}=1920\frac{hours}{year}\approx 2000\frac{hours}{year}$$

Rounding above will make the limit allowable radiation dose rate is getting smaller. While National Nuclear Energy Agency of Indonesia (BATAN) start applying the dose limiting. Dose limiting value prevailing at the Training Center from 2007 until today is 10 mSv in a year. It is derived from the assumption of a maximum working load as follows:

$$4\frac{hours}{day}\times 5\frac{days}{week}\times 4\frac{weeks}{month}\times 12\frac{months}{year}=960\frac{hours}{year}\approx 1000\frac{hours}{year}$$

The maximum working load of radiation workers in BATAN in one year is 1000 hours (Wiyuniati and Indragini, 2015). Furthermore, the maximum dose rate values calculated in the work area as follows:

1. Consideration BAPETEN

$$\dot{D}=\frac{20mSv}{2000hours}=10\mu Sv/hour$$

2. Consideration BATAN Dose Constraint

$$\dot{D}=\frac{10mSv}{1000hours}=10\mu Sv/hour$$

Based on above, the value of the dose rate of radiation received by workers should be less than 10 μSv/h in order to achieve the purpose of radiation protection.

2.2 Problem description

The study began by searching for references and literature studies related BNCT pilot plant will be designed. Designing and simulation process using MCNPX and displayed by Vised. Geometry, material, thickness and resources data input were use as code based on literature.

The collimator specification is based on optimization calculation by Made. The collimator consist of collimator wall, moderator, reflector, aperture, gamma shielding and filter. Defining the input code in the form of cell card, surface card and data card. Neutron sources used comes from 30 MeV cyclotron with a strong current of 1 mA. Here collimator design and dimensions of each:

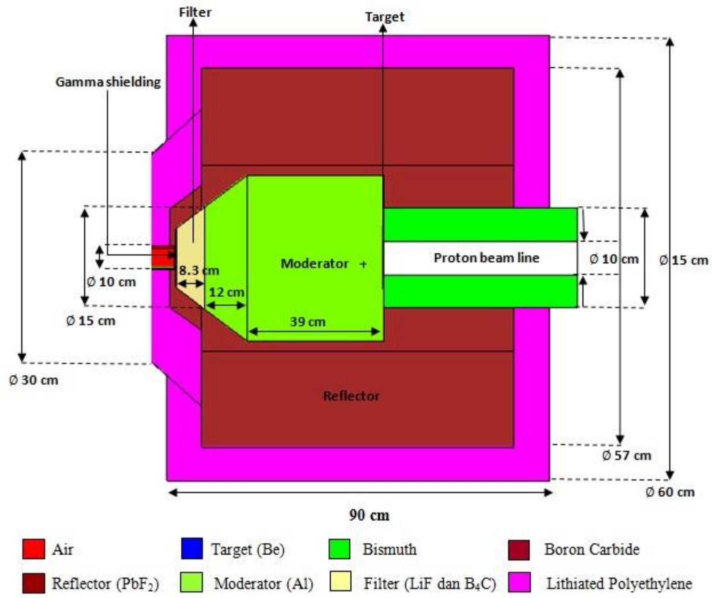

Figure 1. Top view geometry collimators with dimensions

Moderator of collimator design composed of thick aluminum 39 cm, 8.2 cm lithium fluoride as fast neutron filter and a 0.5 cm boron carbide as a thermal neutron filter. Each section aperture, reflector and gamma shield composed of bismuth, lead and timbale fluoride. Epithermal neutron flux generated by the collimator design amounted to 2.83×10^9 $n.cm^{-2}s^{-1}$ and has met all the parameters of neutron flux corresponding BNCT system established by the IAEA (Made, 2015).

Designing the radiation shield also by defining input code first. Design of the room created the dimensions 4 × 4 × 3 m. Radiation shields in the form of a wall thickness of 1 and 1.5 m to the concrete baryte material on each side that includes borated polyethylene coated with 2 cm (Kobayashi et al, 2000). Design is equipped with sliding doors the dimensions 220 × 87 × 200 cm coated with a 2 cm thick stainless steels outside (Chen et al, 2007). Once everything is completely defined, then a pilot plant design systems of BNCT was created. The overall design of the pilot plant BNCT is shown by the image below:

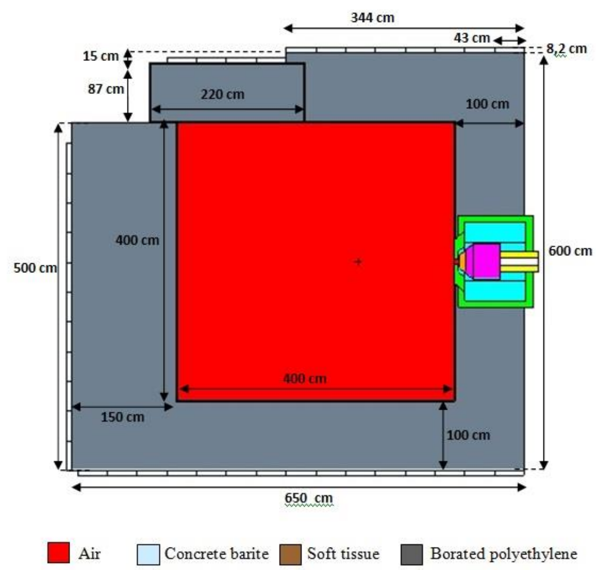

Figure 2. Top view design pilot plant BNCT

Design above surrounding the radiation shield there is soft tissue that each measuring 170 × 43 × 8.208 cm with a volume of 60,000 cm3 body adjusted to the recommendations of asia (Tanaka et al, 2000). Simulations using MCNPX takes 7-10 days with a number of nps 500 million. Simulations carried out by making the assumption that there are no people in the treatment room and workers were in the control room. Calculations using tally 4 is added to the function of the dose to calculate the rate of neutron dose and photons. In these calculations require Kerma to convert from the energy released by neutron and gamma radiation dose to function. The data used from Kerma coefficient used in the Dosimetry System 2002 (DS02) (Kerr et al, 2005). Program MCNPX use DEn and DFn ,DEn to determine where the energy to be converted and DFn to determine the results of the dose of energy. Further dose multiplied by the quality factor Q to obtain the value of equivalent dose. Then the value of equivalent dose compared to NBD by BAPETEN to determine deterministic effects that might be experienced by workers on the basis of the dose received. The following table is based on the effects of gamma radiation dose received:

Table 1. Acute Radiation Syndrome for Gamma Radiation

Dose (Gy)	Description
0-0.25	No clinically significant effects
0.25-1	Bone marrow damaged; decrease in red and white blood-cell counts and platelet count Lymph nodes and spleen injured; lymphocyte count decreases
1-3	Hematologic damage more severe. Recovery probable though not assured.
3-6	Fatalities will occur in the range 3.5 Gy without treatment
>6	Death expected.

Source: Thumer, 2007

3. RESULTS AND DISCUSSION

Results obtained in the form of the dose rate shown in the following table:

Table 3. Gamma dose rate equivalent

Cell	$\dot{D}$ (μSv.h^{-1})	Cell	$\dot{D}$ (μSv.h^{-1})	Cell	$\dot{D}$ (μSv.h^{-1})
149	0	201	0	300	0
150	0	202	0	301	0
151	0	203	0	302	0
152	0	204	0	303	0
153	58	205	0	304	0
154	0	206	0	305	0
155	0	207	0	306	0
156	0	208	0	307	0
157	0	219	0	308	9.47
158	0	210	0	309	0
159	0	211	0	310	0
160	0	212	0		
200	0	213	0		

The average gamma dose rate of 2.05 μSv.h^{-1}. Gamma dose equivalent worker in a year is 2.05 mSv

These data showed that the largest dose rate lies in the cells that are on the doorstep and a cell located in front collimator while for cells beside collimator received very small dose rate (almost zero). In the cells of soft tissue that is located in front of the door, the cell 153 received the biggest of dose rate of gamma above dose limit 58 μSv.h^{-1}. The cell dose rate value above is far from the threshold of the 10 μSv.h^{-1} compared with other cells that have met the requirements limiting doses for gamma dose. This is because the shield on the door thinner than the shield on the wall that is 72 cm while the wall thickness of 101 cm. The results showed concrete baryte shield with a thickness of 100 cm is more effective at absorbing neutron and photon radiation than the thickness of 68 cm. This was evidenced by the rate of the absorbed dose to the cells of soft tissue that is in a position outside the side collimator rate value of the dose is zero.

Then cell located in front collimator that 308 had the pace of the largest neutron doses are cells 303 while other cells are below the limiting dose, the dose rate of neutron 1370 μSv.h-1 although it was received dose rate of photon below the dose limits 9.47 μSv.h-1. This could be caused due to direction irradiation of neutron radiation that Vec and Dir protons are directed to the x-negative right in front of the shield. The probability of neutron movement were occurred randomly but the position causes increasing movement probability reach the point

Based on the simulation, the total dose received by workers in about 43.55 mSv a year is included doses of neutron and gamma. According to the table 1 above, gamma dose received were not go beyond the threshold (1 Gy = 1000 mSv) so that there is no significant effect caused. According to the document ICRP 60 of 1990 to prevent deterministic effects for radiation workers set dose limits is 0.5 Sv.year^{-1} for all tissues or organs except the lens of the eye 0.15 Sv.year^{-1} and prevent stochastic effects the effective dose limit is 50 mSv.year^{-1} for all body. The results showed that design meets requirements of ICRP recommendations about dose limit values received radiation workers.

Referring to above ICRP document, BAPETEN sets NBD 10 μSv.h^{-1} to avoid the possibility of stochastic effects, even in the design of this requirement has not been met perfectly. But the value of the dose rate that came out of the side shield collimators already meet the requirements, where the room next to the control room where a collimator is a radiation worker located. Preventive measures that can be done to minimize the workload of workers to radiation and when the instrument is being operated or used for the treatment of people not allowed to pass through the room. Then the room in front of a collimator is necessary to add shielding to reduce neutron and gamma dose rates in the area of being able to add or increase the thickness of the shield with other materials as needed. Based on the above data analysis obtained an average rate of neutron and gamma equivalent dose received by workers each 41.5 μSv.h^{-1} and 2.05 μSv.h^{-1}. The effects of radiation caused for deterministic effects no significant effects, while for stochastic effects are still unknown and unpredictable.

4. CONCLUSIONS AND REMARKS

It is important to design the radiation shield that sufficient to withstanding the dose rate of neutron and gamma, the design used today can still be used but it should be optimized so that the dose rate less than the dose limit set and meet Governing Terms safety of BAPETEN to minimize effects that may be experienced by workers.

Acknowledgment

The authors would like to thank Prof. Sardjono for introducing the MCNPX methodology, Dr. Andang Widiharto for his helpful suggestion about radiation protection and M. IIma Muslih,S.T for his helpful to teach MCPNX. The work is supported by Center of Science and Accelerator Technology-National Nuclear Energy Agency of Indonesia (PSTA-BATAN).

REFERENCES

BAPETEN. (2013). BAPETEN Chairman's Regulation Number 4 Year 2013. Retrieved from http://jdih.bapeten.go.id/index.php/site/dokview/id/322

BAPETEN. (2015). Instrumentation Radiation Protection Document. Retrieved from http://ansn.bapeten.go.id/

Cember,Herman & Thomas E.Johnson. (2009). Introduction to Health Physics (4th edition). United States: The McGraw-Hill Companies.

Chen, A.Y., Y.W.H.Liu., & R.J.Sheu. (2008). Radiation shielding evaluation of the BNCT treatment room at THOR: A TORT-coupled MCNP Monte Carlo simulation study. Applied Radiation and Isotopes 66, 28-38. doi:10.1016/j.apradiso.2007.07.016

Darsono, Safirudin, & M.Toifur. (2013). Simulation For Radiation Shielding Design Of EBM-Latex Using MCNP5. Ganendra Journal Nuclear Science and Technology, Volume 16, Number 2, 87-96.

Holden,N.E & R.N.Reciniello. (2005). Radiation Dosimetry in the Patient Treatment Room at the BMRR. 12th International Symposium on Reactor Dosimetry ,Gatlinburg,TN ,New York.

Ilma, Muhammad. (2013). Design Of Collimator In The Radial Piercing Beam Port Of Kartini Reactor For Boron Neutron Capture Therapy. Gajah Mada University, Indonesia.

Kobayashi,T., Y. Sakurai., K.Kanda., Y.Fujita., & K.Ono. (2000). The Remodelling outline of neutron irradiation facility of the Kyoto University Research Reactor mainly for neutron capture therapy. Nuclear Technology, 131-141. Retrieved from http: //www.iaea.org/inis/collection/NCLCollectionStore/_Public/32/030/32030427.pdf

Kerr, George D., Joseph V. Pace,III., & Stephen D.Egbert. (2005). Survivor dosimetry Part A "Fluence to kerma conversion coefficients". Retrieved from http:// inis.iaea.org.

Made.A, I. (2015). Optimization Of Collimator Design For BNCT Based Cyclotron 30 MeV and Its Dosimetry Simulation in Head and Neck Soft Tissue Sarcoma Using Monte Carlo N Particle X Program. Gajah Mada University, Indonesia.

Moss,R.L., F.Stecher-Rasmussen., K.Appelman., A.Roca., & A.Wittig. (2005). Neutron Activation of Patients following BNCT at the HFR Petten. Retrieved from http: https://www.researchgate.net/profile/Finn_StecherRasmussen/publication/267799995_Neutron_Activation_of_Patients_following_BNCT_at_the_HFR_Petten/links/55c09d8308ae9289a09b8b6a.pdf

Saurwien, Wolfgang A.G. (2012). Principles and Roots of Neutron Capture Therapy. Neutron Capture Therapy Principles and Application, 1-16. New York: Springer-Verlag Berlin Heidelberg.

Tanaka, Gi-ichiro and Hisao Kawamura. (2000). Reference Man Models on Normal Data from Human Populations. Retrieved from http://www.irpa.net/irpa10/cdrom/00602.pdf

Turner,James.E. (2007). Atoms, Radiation, and Radiation Protection (3rd edition). Jerman: WILEY.

Wahyuningsih, Dwi. (2014). Optimation Of Collimator Design For In Vivo Testing Of Boron Neutron Capture Therapy (BNCT) On Radial Piercing Beam Port Kartini Nuclear Reactor Using Monte Carlo N Particle 5 (MCNP5) Simulation. Gajah Mada University, Indonesia.

Widyaningsih,Dewi & Heri Sutanto. (2013). Determination of External Radiation Dose Radiation On Workers At Radiation Room Unit Radiotherapy DR. KARIADI SEMARANG Hospital. Periodic Journal of Physics,Volume 16, Number 2, 57-62. Issn: 1410 – 9662

Wiyuniati,Slamet & Indragini. Proposal of Dose Constraint Value for Radiation Worker and Trainees in Center for Education and Training, National Nuclear Energy Agency.Widyanuklida, Volume 15, Number 1, 46-51.

Wolfgang Sauerwein & Ray Moss. (2009). Requirement for Boron Neutron Capture Therapy (BNCT) at a Nuclear Research Reactor. The European BNCT Project, Belanda.

Wolfgang A.G.Sauerwein, Pierre M. Bet, dan Andrea Wittig. (2012). Neutron Capture Therapy. Drugs for BNCT : BSH and BPA, Neutron Capture Therapy Principles and Application, 117-161. New York: Springer-Verlag Berlin Heidelberg.