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Optimization of double layered beam shaping assembly using genetic algorithm

BILALODIN[1,2,a], KUSMINARTO[1], Gede Bayu SUPARTA[1], Arief HERMANTO[1], Dwi Satya PALUPI[1], Yohannes SARDJONO[3]

[1]Department of Physics, Faculty of Mathematics and Natural Sciences, GajahMada University, Indonesia
[2]Department, of Physics, Faculty of Mathematics and Natural Sciences, Jenderal Soedirman University, Indonesia
[3]Centre for Accelerator Science and Technology, National Nuclear Energy Agency, Indonesia
[a]E-mail address: bilalodin.unsoed@gmail.com

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Abstract

The genetic algorithm method is a new method used to obtain radiation beams that meet the IAEA requirements. This method is used in optimization of configurations and compositions of materials that compose double layered Beam Shaping Assembly (BSA). The double layered BSA is modeled as having two layers of material for each of the components, which are the moderator, reflector, collimator, and filter. Up to 21[st] generation, the optimization results in four (4) individuals having the capacity to generate the most optimum radiation beams. The best configuration, producing the most optimum radiation beams, is attained by using combinations of materials, that is by combining Al with either one of CaF_2 and $PbF_2$for moderator; combining Pb material with either Ni or Pb for reflector; combining Ni and either FeC or C for collimator, and FeC+LiF and Cd for fast and thermal neutron filter. The parameters of radiation resulted from the four configurations of double layer BSA adequately satisfy the standard of the IAEA.

Key words: optimization; double layered BSA; genetic algorithm; radiation beams; IAEA.

Introduction

Boron Neutron Capture Therapy (BNCT) is a method for cancer therapy which irradiates cancer cells previously injected with boron ^{10}B. Interaction of a thermal neutron and a ^{10}B nucleus will form a compound nucleus ^{11}B. The compound nucleus will subsequently decay, radiating gamma and alpha particles. This energy of alpha particles is utilized to destroy cancer cells in body tissue. The range of alpha particle is short, of the size of a cell, allowing it to be focused on the cancer cell and avoid negative effects on healthy cells [1]. Cancer therapies using the BNCT methods are highly sensitive to the spectrum of the neutron being used [2].

Neutron source that facilitates a BNCT can be obtained from various sources, such as radioisotopes, nuclear reactors, and accelerators [3]. The downside of radioisotope neutron sources is its low neutron flux, causing the long duration of cancer therapy (more than an hour). This long period of therapy will cause exhaustion in patients and require more amount of Boron ^{10}B [4]. Utilization of a reactor for neutron source is constrained by several factors, such as the need of high security for the reactor facility, the existence of radiation waste from fission reactions, and high establishment cost and difficulties in acquiring sanctions [5,6]. To overcome such problems, neutron sources from an accelerator are currently being developed.

A type of accelerator is the cyclotron. Cyclotrons are intensively developed in various countries, such as Japan and Korea. Japan develops Cyclotron-Based Epithermal Neutron Source(C-BENS), and Korea develops Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT). Both types of cyclotrons uses a proton source with the energy of 30 MeV. Neutrons will result from interactions of protons with beryllium targets [7,8].

A part of the cyclotron that is yet to be developed is double-layered BSA. The BSA is a system that transforms fast neutrons into epithermal neutrons and concurrently reduce contaminants accompanying the beams [9,10]. The design of BSA currently being used is in the form of double and multilayer configuration [2].

To have an optimal radiation beam from the BSA, optimization is required about configurations of components that constitute the BSA, in a graduated or step-by-step way [9,11]. However, graduated optimization most frequently does not yield radiation beams as required by the IAEA. It can be caused by failure to select the right materials and by the incompatibility of the geometry of the BSA, considering that constituent materials of the BSA influence each other in the generation of radiation beams. Graduated optimization also takes a long time because it needs to simulate every component and different configurations of BSA [12].

An attempt to overcome the weakness of graduated optimization method is to use the genetic algorithm (GA). The method has been used in dealing with modeling and optimization problems [13], optimizing beam components in accelerators [14]. Other achievements in the application of GA are the determination of optimum thickness in moderator design [15] and gamma shielding design to determine the best composition of some materials [16]. The latest achievement is the use of Multi-Objective Genetic Algorithm (MOGA) and Monte Carlo optimization method in optimizing the beam port of ITU reactor to produce epithermal neutron beams for BNCT purposes [11].

Such capabilities of GA open the possibility for use in the optimization of components of BSA in cyclotrons. This article discusses the optimization of components of BSA in the form of double layer configuration, namely that the components consist of two materials in combination.

Materials and methods

Conceptual Design of Double Layered BSA

The proton source that is modeled in the design of double layered BSA is protons having the energy of 30 MeV, resulted from a 30 MeV accelerator developed by the KURRI institute of Japan, i.e., C-BENS [7]. 30 MeV protons are exposed on ^{9}Be target to produce fast neutrons, subsequently processed by double layered BSA.

A double layered BSA has four main components, i.e. moderator, reflector, collimator, and filter. Each component is formed as a combination of two materials. The moderator is selected from combinations of aluminum (Al) material with eight other materials, i.e., Al_2O_3, LiF, AlF_3, MgF_2, CaF_2, BiF_3, PbF_2, and CF_2. The reflector is selected from combinations of lead (Pb) material with bismuth (Bi), carbon iron (FeC), Nickel (Ni) and graphite (C). The best material for moderator and reflector are then combined with collimator material, which is a combination of Ni material and borated polyethylene (B-Poly), FeC, C and Ti. The materials for moderator, reflector, and collimator used as components of double layered BSA are chosen based on their capability to produce the largest number of epithermal neutrons. At the last stage, it is selected combinations of filter for fast and thermal neutrons. Combinations of fast and thermal neutron filter are accomplished by combining FeC+LiF with Cd, Ti, Li, B_4C, and ^{10}B materials. Best performing filters are chosen by their capability to reduce fast and thermal neutrons. Also, at the end of double layered BSA is Pb material to reduce gamma rays [12].

The Monte Carlo N Particle X (MCNPX) 2.7 software is used to optimize the double layered BSA [17]. An MCNPX program is run with particle history of 106and multiplication factor of 6.25 x 10^{15} n/s in n p h Mode and tally F5 to compute beam parameters of the thermal neutron, epithermal neutron, fast neutron. A dose rate of gamma and fast neutron ware tallied by employing DE and DF tally. The configuration of double-layered BSA is shown in **Figure 1**.

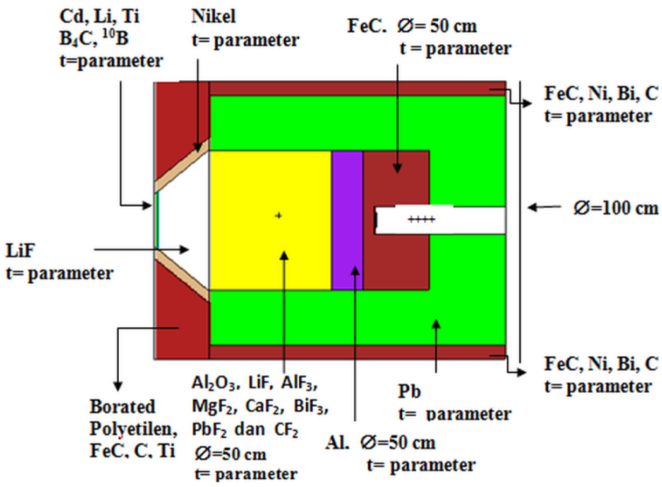

Figure 1. The configuration of double layered BSA

Implementation of Genetic Algorithm(GA)

The Genetic Algorithm is an optimization method that imitates natural biological evolution determining high quality chromosomes or individuals. The selection process of individuals from a population comprises the representation of chromosomes, fitness evaluation, crossover, mutation, and selection [18]. The implementation of GA in the optimization of double-layered BSA can be explained in the following: representation of chromosomes of double-layered BSA, calculating fitness function, conducting selection, conducting crossover and mutation, and convergence test.

Chromosome representation of double-layered BSA

A double-layered BSA consists of 4 components, i.e., moderator, reflector, collimator, and filter. This configuration is represented as a chromosome or individual. Material arrangements and thicknesses of each component are denoted as a gene. The first material composing the component of BSA is called superior gene and the second is non-superior. A superior gene is always involved in every process of the formation of new generations. The materials used in the design and optimization of double-layered BSA are shown in **Table 1**.

Moderators and reflectors are composed of two materials with the maximum thickness of 50 and 50 cm, respectively. Collimators and fast and thermal filter are composed of the material with the maximum thickness of 15 cm and 39.04 cm, respectively.

Table 1. Chromosome and gene representation of double-layered BSA

No.	Moderator				Reflector				Collimator			Filter			
	m_1	t_1	m_2	t_2	m_3	t_3	m_4	t_4	m_5	t_5	m_6	m_7	t_7	m_8	t_8
1	Al	10	Al_2O_3	40	Pb	40	Ni	10	Ni	5	FeC	FeC+LiF	22	Cd	1
2	Al	20	LiF	30	Pb	30	C	20	Ni	10	Ti	FeC+LiF	22	B_4C	2
3	Al	30	AlF_3	20	Pb	20	FeC	30	Ni	15	C	FeC+LiF	22	Li	3
4	Al	40	MgF_2	10	Pb	10	Bi	40	Ni	20	B-Poly	FeC+LiF	22	^{10}B	4
5	Al	10	CaF_2	40	Pb	40	Ni	10	Ni	5	FeC	FeC+LiF	22	Cd	1
6	Al	20	BiF_3	30	Pb	30	C	20	Ni	10	Ti	FeC+LiF	22	B_4C	2
7	Al	30	PbF_2	20	Pb	20	FeC	30	Ni	15	C	FeC+LiF	22	Li	3
8	Al	40	CF_2	10	Pb	10	Bi	40	Ni	20	B-Poly	FeC+LiF	22	^{10}B	4

Where the t = thickness of material, m = type of material, t_1, t_2, t_3, t_4, t_5, t_7 in cm and t_8 = mm.

Fitness and Selection Function

To find the ability of individuals to survive each is assigned a positive fitness value. The fitness function is expressed in **Equation 1**.

$$F_i = (\Delta\varnothing_{epithermal} + \Delta\varnothing_{thermal}^{epi} + \Delta\varnothing_{fast}^{epi} + \Delta D_{fast\ neutron\ dose} + \Delta D_{gamma\ dose})/10^8 \qquad \text{Eq. 1}$$

where:

$$\Delta\varnothing_{epithermal} = (\varnothing_{epi} - 10^8)$$

$$\Delta\varnothing_{thermal}^{epithermal} = (\varnothing_{thermal}^{epithermal} - 100)$$

$$\Delta\varnothing_{fast}^{epithermal} = (\varnothing_{fast}^{epithemal} - 20)$$

$$\Delta D_{fast\ neutron\ dose} = (D_{fast\ neutron\ dose} - 10^{-13})$$

$$\Delta D_{gamma\ dose} = (D_{gamma\ dose} - 10^{-13})$$

Selection is subsequently conducted to find the probability of surviving individuals and is going to be used in the succeeding generation. Selection of individuals is carried out proportionally using the equation [19]:

$$F_s = \frac{F_i}{\sum F_i} N \qquad \text{Eq. 2}$$

Where F_s = selection function, F_i = fitness function, N = number of chromosomes/individuals in a generation. Another point to consider in selecting chromosomes to cross-over and mutate in the next generation is their having epithermal neutron flux of ≥ 1.0 x 10^9 n/(cm^2·s).

Crossover and mutation

To obtain new generations, crossovers are conducted. A one point crossover is used in the process of gene transfer combination from parents to offspring. In this case, type or thickness of material from one chromosome is exchanged with another chromosome. To increase variations within the population mutation process is conducted. The mutation process is conducted regarding a change in gene values. In this case, mutation is conducted in the process of altering the type and thickness of material randomly in a particular chromosome [20]. Cross-over and mutation process carried out manually at each generation.

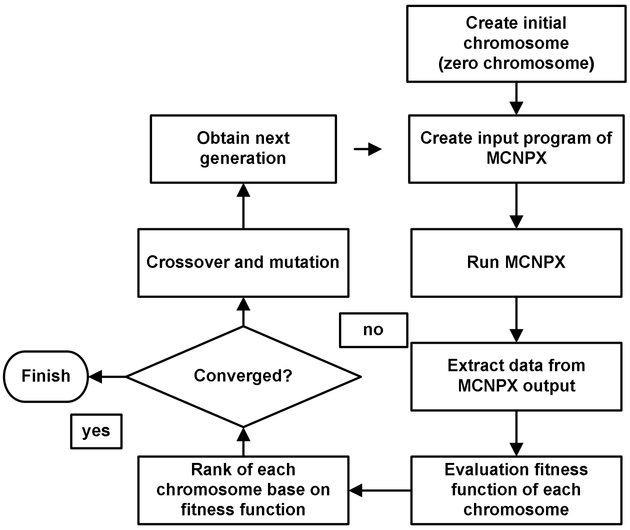

Figure 2. Flow chart of optimization of double layered BSA using the GA method

Convergence

Convergence criterion, in this case, is chosen when the fitness function is homogeneous and remains unchanged [11]. It indicates that the solution being sought is obtained. The flow chart of overall steps in the formation of new generations to obtain the optimal configuration of double-layered BSA is shown in **Figure 2**.

Results

Characteristics of the radiation beam of initial stage population

Characteristics of the radiation beams of eight individuals as early population measured at the end of the collimator (aperture) are shown in **Table 2**. Many of the values of the radiation beam component still deviate from those of the IAEA standard [21]. The highest epithermal neutron flux is 1.40E+09 n/(cm^2·s) and the lowest is 1.30E+08 n/(cm^2·s). Many values of other four beam parameters do not meet the IAEA criteria as yet. It implies that the epithermal neutron beam still contains many contaminants. According to the data, the first generation double-layered BSA is not adequate to be a source for BNCT therapies.

Table 2. Comparison of characteristics of the first generation beam to the desirable solution (IAEA standard)

No	Chromosome	Epithermal Flux ($n/cm^2.s$)	Φepi/Qther	Φepi/Φast	Dfast/Qepi ($Gy \cdot cm^2$)	Dγ/Qepi ($Gy \cdot cm^2$)
1	K1	1.02E+09	405	23	3.82E-12	5.88E-13
2	K2	1.46E+08	122	3	9.32E-12	4.11E-12
3	K3	6.30E+08	203	8	8.89E-12	7.30E-13
4	K4	1.34E+08	71	4	3.06E-11	1.72E-12
5	K5	1.40E+09	667	15	7.14E-12	2.29E-13
6	K6	3.60E+08	50	5	2.78E-11	8.89E-13
7	K7	6.87E+08	137	69	1.15E-12	9.46E-13
8	K8	1.30E+08	43	2	3.46E-11	5.00E-12
	IAEA (2001)	≥ 1.0E+9	> 100	> 20	< 2.0E-13	< 2.0E-13

B. Optimization of double-layered BSA

Figure 3 shows the relation between fitness function and generation during the genetic process. The triangle symbol (▲) denotes the average fitness value of eight chromosemes at 0^{th} to 21^{st} generation. According to **Figure 3**, fitness value increases with generation. The fitness value tends to be constant from generation 19 to 21. It suggests that the iteration has reached its convergence [11]. It means that some optimum solutions are reached.

Figure 4 shows the effect of variation in the generation on changes in epithermal neutrons. The symbol (▲) denotes the value of epithermal neutron flux. The line indicates the limit of epithermal neutron flux required by the IAEA. The iteration (generation) required to produce a population with individuals that produce optimal Pareto (set of optimal solutions) is epithermal neutron flux ≥ 1.0 x 10^9 n/($cm^2 \cdot s$) [21]. Increase in generation engenders solutions that spread in the direction of the optimum solution, and all optimal solutions are reached from generation 15 to generation 21. The epithermal neutron flux as the solution to generation 21 varies between 1.0-1.47 x 10^9 n/cm^2. Such values of epithermal neutron flux have satisfied the IAEA requirement. It implies that the intensity of epithermal neutron beams produced by the double-layered BSA optimized by the GA method agrees with the requirement for BNCT purpose.

Figure 5 shows the effect of variation in the generation on the ratio of epithermal to thermal neutron flux (Φepi/Φther). The iteration (generation) required to produce a population with individuals that produce optimal pareto is ≥ 100 [21]. Increase in generation engenders solutions that spread in the direction of the optimum solution. All optimal solutions are reached from generation 17 to generation 21. The ratio Φepi/Φther as the solution to generation 21 varies between 200-900. Such values suggest that the flux of fast neutron, being perturbing radiation, is sufficiently low in intensity. Besides thermal neutron flux, fast neutron flux coming directly from the double-layered BSA must be restricted as well. The ratio of epithermal neutron flux to fast neutron flux (Φepi/Φfast) must be less than 20 in value [21].

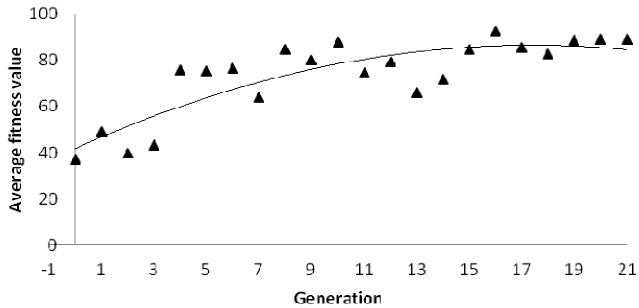

Figure 3. The relation between generation and average fitness value

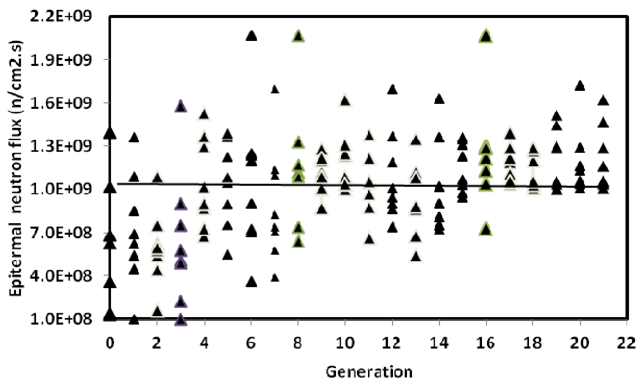

Figure 4. Effect of variation of generation on epithermal neutron flux.

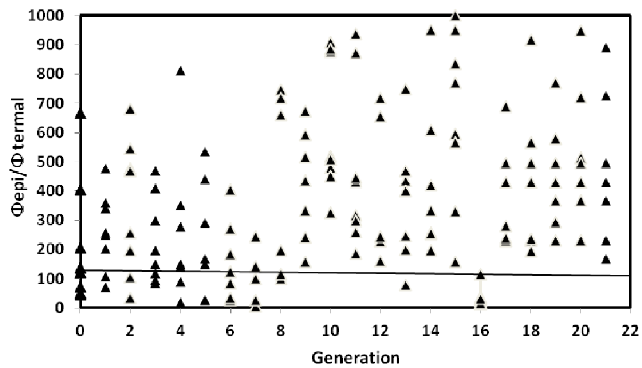

Figure 5. Effect of variation in the generation on the ratio of epithermal to thermal neutron flux.

The search result for the optimal solution of ratio Φepi/Φfast is shown in **Figure 6**. At early generations, individuals/ chromosomes representing the configuration of double-layered BSA still contain fast neutrons. Despite the genetic process run against individuals up to the 21st generation, not all individuals have the optimal ratio of epithermal neutron flux. The ratio Φepi/Φfast varies between 10-53 and only five (5) individuals that satisfy the value of > 20.

The effects of variation in generations on the variation in the ratio of fast neutron dose and gamma dose to epithermal neutron flux are shown in **Figure 7** and **8**. The increase in generation yields some solutions in term of the ratio of fast neutron dose to epithermal neutron flux, which varies and tends to yield a solution towards a ratio of fast neutron dose to epithermal neutron flux (Dγ/Φepi) that approach 2×10^{-13} Gray·cm^2. The result of variation in gamma doses against epithermal neutron flux yields the ratio of gamma dose to epithermal neutron flux < 2×10^{-13} Gray·cm^2. Optimization of the ratio of gamma dose to epithermal neutron flux at the last generation (Gen-21) yields a result between 4.86-95.7 x 10^{-14} Gray·cm^2. It suggests that the double-layered BSA contains contaminant radiation in the form of very low gamma radiations.

Optimization of the double-layered BSA until 21st generation results in four (4) solutions that reach optimum condition. The value of beam radiation parameters of the BSA has satisfied the IAEA standard. The values of 21st generation radiation beam parameters are shown in **Table 3**, and the configuration of the optimum double-layered BSA is shown in **Table 4**.

Table 4 shows that an optimum configuration is attained by combining Al material with either one of PbF_2 or CaF_2 as moderator. The best reflector is made by combining Pb with Ni materials. The best collimator is made by combining Ni material with FeC and C materials. To reduce fast neutron, thermal neutron, and gamma contaminants it is recommended to use FeC+LiF, Cd, and Pb. The achievement of optimization using the genetic method is inescapably related to the use of superior genes, such as Al, Pb, Ni, FeC, and Cd, which are always involved in every process of the formation of new generations.

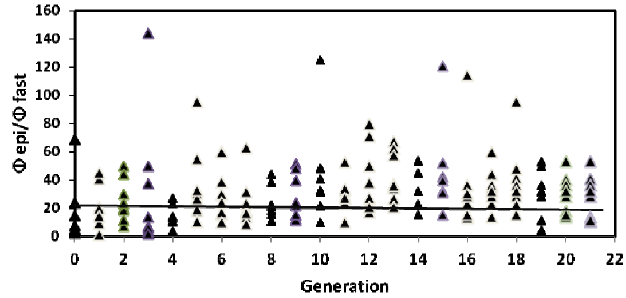

Figure 6. Effect of variation in the generation on the ratio of epithermal to fast neutron flux

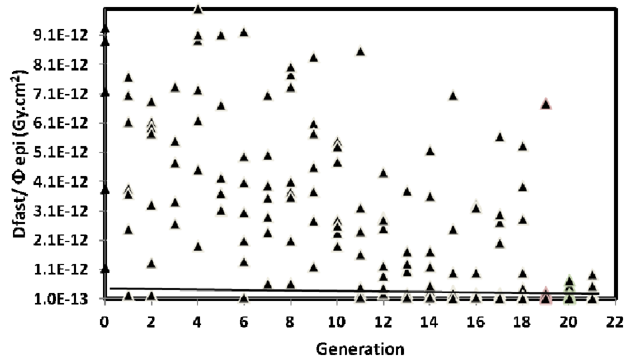

Figure 7. Effect of variation in the generation on the ratio of fast neutron dose to epithermal neutron flux.

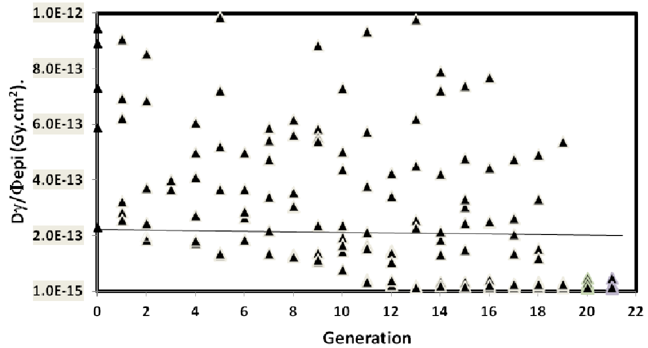

Figure 8. Effect on variation in the generation on the ratio of gamma dose to epithermal neutron flux.

Table 3. Parameters of radiation beam resulting from optimization of double-layered BSA using the GA.

No	21st Generation Chromosome	Epithermal Flux (n/cm^2.s)	Φepi/Φther	Φepi/Φfast	Dfast/Qepi (Gy·cm^2)	Dγ/Φepi. (Gy·cm^2)
1	K1	1.47E+09	1865	10	9.32E-13	2.46E-14
2	K2	1.16E+09	725	14	5.48E-13	4.86E-14
3	K3	**1.04E+09**	**231**	**28**	**1.98E-13**	**1.49E-14**
4	K4	**1.01E+09**	**367**	**53**	**1.71E-13**	**1.48E-14**
5	K5	1.62E+09	169	41	2.71E-13	9.57E-15
6	K6	**1.29E+09**	**496**	**36**	**1.75E-13**	**1.16E-14**
7	K7	1.06E+09	891	11	5.41E-13	1.41E-14
8	K8	**1.06E+09**	**431**	**32**	**1.34E-13**	**1.41E-14**
	IAEA (2001)	≥ 1.0E+9	> 100	> 20	< 2.0E-13	< 2.0E- 13

Table 4. The configuration of double-layered BSA optimized using the GA method resulting in optimal parameters of beam radiation

K	Moderator				Reflector				Collimator			Filter			
	m_1	t_1	m_1	t_2	m_3	t_3	m_4	t_4	m_5	t_5	m_6	m_7	t_7	m_8	t_8
K3	Al	32	PbF_2	18	Pb	40	Ni	10	Ni	5	FeC	FeC+LiF	26	Cd	1
K4	Al	28	CaF_2	22	Ni	10	Pb	40	Ni	5	FeC	FeC+LiF	24	Cd	1
K6	Al	20	CaF_2	30	Ni	20	Pb	30	Ni	15	C	FeC+LiF	24	Cd	1
K8	Al	20	CaF_2	30	Ni	20	Pb	30	Ni	10	C	FeC+LiF	39	B_4C	1

Discussion

The study shows that the parameters of neutron beams are in agreement with IAEA recommendation can be attained by optimizing a double-layered BSA using the genetic algorithm method. The parameters recommended by the IAEA are obtained at generation 21.

The quality of neutron beams created up to 21^{st} generation has the value of epithermal neutron flux of 1.01 x 10^9 - 1.47 x 10^9 n/(cm^2·s). Such values meet the standard recommended for cancer therapies using the BNCT method, which is > 1 x 10^9 n/(cm^2·s) [21]. The achievement of epithermal neutron beam quality that agrees with the standard is accounted for by the ability of double moderator in moderating fast neutrons to become epithermal neutrons. Aluminum, (Al) as the main moderator, has the high cross section to energies higher than ten keV [22]. Interactions between neutrons and Al material produce epithermal neutrons, particularly through ^{27}Al(n,2n)^{26}Al reactions [23]. Containing fluorine (F), it is the second moderator that contributes. F is also an element that has high scattering cross section to fast neutron and contributes as well in increasing the number of epithermal neutrons [24].

Increase in epithermal neutron flux at every variation of generation is also contributed to by the reflector. Combinations of reflector Pb with Pb or Ni are appropriate to increase the number of epithermal neutrons. Pb as the main material for the reflector has high elastic scattering cross section and low absorption cross-section to epithermal neutrons [25]. Such characteristics of Pb cause fast neutrons leaking out from moderators to be directed back into the moderator for re-moderation. Fast neutron having been moderated will increase the number of epithermal neutrons. The presence of the second reflector will also contribute to increasing epithermal neutrons in addition to the role of Pb as the main reflector [26].

Epithermal neutrons generated by a combination of best moderator and reflector enter the collimator. Collimators made of Ni and C and FeC materials can maintain high epithermal neutron flux. This is due to Ni material having high reflectivity against epithermal neutrons [25].

The ratio of thermal to epithermal neutron flux until the 21^{st} generation has reached a value between 169 – 1869. This value agrees with the recommendation of the IAEA, which is > 100. Such a ratio can be achieved by Cadmium (Cd) filter placed at the end of the collimator. A Cd filter has high absorption characteristics to thermal neutrons ensued by such low gamma radiation release as to make it widely used as thermal neutron filter [25,12].

The ratio of fast to epithermal neutron flux reaches a value within 10-53. It suggests that some configurations do not satisfy the recommended standard > 20. The existence of fast neutron flux in high values affects the ratio of fast neutron dose rate to epithermal neutron flux, which becomes high as well. The presence of some configurations having a ratio of fast neutron to epithermal neutron flux below 20 can be accounted for by fast neutron filter being unable to effectively filter fast neutron beams that penetrate the moderator material [27].The ratio of fast to epithermal neutron flux at the end of the optimization is within 1.32 x 10^{-13} - 9.32 x 10^{-13} Gy·cm^2 and only four (4) configurations that satisfy the IAEA standard of < 2.0 x 10^{-13} Gy·cm^2.

Moderation process transforming fast neutron into epithermal neutron also produces gamma. The ratio of gamma dose rate to epithermal neutron flux at the end of the optimization is found within 9.57 x 10^{-15} – 4.86 x 10^{-14} Gy·cm^2/n. Such a value has met the IAEA standard of < 2.0 x 10^{-13} Gy·cm^2/n. Gamma particles in the double-layered BSA predominantly results from interactions of protons with beryllium target through ${}^{9}_{4}Be(p,\alpha){}^{6}_{3}Li^{*}(\gamma){}^{6}_{3}Li$ reactions. A few numbers of gamma rays also results from capture reaction through ${}^{9}_{4}Be(p,\gamma){}^{10}_{4}Be$ reaction and inelastic collisions in forms of ${}^{9}_{4}Be(n,n'\gamma)$ reactions [28]. Gamma particles are also produced by the reaction between neutron and aluminum through ^{27}Al(n,γ)^{28}Al reactions [23]. The gamma particles can be reduced by Pb material placed at the end of double-layered BSA, sincePb is very good in absorbing gamma particles [12].

Summary

A double-layered BSA has been successfully optimized using the genetic algorithm method. The optimization is aimed to obtain a maximum solution of double-layered BSA configuration such that the resulting radiation beams satisfy the requirement for BNCT. The optimization of double-layered BSA using the genetic algorithm method results in four (4) individuals that can produce optimal radiation beams. The most desirable configuration is obtained by combining: (1) Al with either one of CaF_2 or PbF_2 material as moderator, (2)Pb with one of Ni or Pb as reflector, (3) Ni with FeC, or C material as collimator, (4) using FeC+LiF and Cd as the filter for fast and thermal neutron and Pb as gamma filter. The parameters of radiation beams resulted by those four configurations of double-layered BSA has satisfied the IAEA standard.

Acknowledgment

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