An evaluation on the design of beam shaping assembly based on the D-T reaction for BNCT

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Abstract. Boron Neutron Capture Therapy (BNCT) can be achieved by using a compact neutron generator such as a compact D-T neutron source, in which neutron energy must be in the epithermal energy range with sufficient flux. For these requirements, a Beam Shaping Assembly (BSA) is needed. In this paper, three BSA designs based on the D-T reaction for BNCT are discussed. It is found that the BSA configuration designed by Rasouli et al. satisfies all of the International Atomic Energy Agency (IAEA) criteria. It consists of 14 cm uranium as multiplier, 23 cm TiF_3 and 36 cm Fluental as moderator, 4 cm Fe as fast neutron filter, 1 mm Li as thermal neutron filter, 2.6 cm Bi as gamma ray filter, and Pb as collimator and reflector. It is also found that use of specific filters is important for removing the fast and thermal neutrons and gamma contamination. Moreover, an appropriate neutron source plays a key role in providing a proper epithermal flux.

1. Introduction

Boron Neutron Capture Therapy (BNCT) is an indirect radiotherapy for destruction of cancer cells. To utilize BCNT, ^{10}B enriched compounds, preferentially concentrated in malignant tissues, must be first introduced into the patient's body. The tissues are then irradiated by a low-energy neutron beam, which can induce $^{10}B(n,^{4}He)^{7}Li$ reactions producing secondary charged particles with high biological effectiveness.

One of the critical parameters in BNCT is the neutron flux of a neutron source. It must be an appropriate rate for a sufficiently long enough time. The neutron source providing the required neutron beam with high neutron flux has previously seen only in a nuclear reactor. However, a suitable nuclear reactor for such purpose is expensive and difficult to be realized in or near urban areas. This leads to the development of other neutron sources for BNCT. For example, Montagnini et al. [1] proposed a compact neutron generator based on the D-T fusion reaction as a suitable neutron source for in-hospital treatments. It has greater safety, lower energy for an incident deuteron beam, lower cost, smaller size, and higher social acceptability.

Owing to the fact that the typical neutron energy emitted from D-T fusion reaction is 14.1 MeV, these neutrons cannot be used directly in BNCT. Therefore, they are moderated to the epithermal energy

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range, between 1 eV and 10 keV. For this purpose, neutrons must be treated within a particular system, called a beam shaping assembly (BSA). By using appropriate geometry configuration and material selection in BSA design, the quality and intensity of neutron beam can be optimized. Further, as the intensity of the beam determines the treatment time, it must be considered in the BSA design as well. According to the International Atomic Energy Agency (IAEA) recommendation, epithermal neutron flux should be on the order of 10^9 n/cm^2 s. It is pivotal to note that since the neutron flux usually decreases greatly when neutrons pass through different components of BSA [1], it is necessary to increase the number of neutrons emitted from the neutron source. In this paper, the main components of BSA are compared and three BSA designs are discussed.

2. BSA Components

As mentioned earlier, a BSA is basically designed to moderate high energy neutrons to lower energies. In addition, it must remove fast and thermal neutrons and gamma contaminations. A BSA consists of the multiplier, moderator, neutron filter, reflector, gamma shielding and collimator as major components. In order to obtain a suitable neutron beam for BNCT, a proper design procedure must be employed.

2.1. Multiplier

A multiplier is used to increase the number of neutrons emitted from a neutron source, due to the fact that the neutron flux is significantly decreased when neutrons pass through different materials of the BSA. Hence, the material of the multiplier should be properly chosen. Uranium is a typical material used as a neutron multiplier to increase the number of neutrons via fission reactions.

Rasouli et al. [3] used an isotropic source of 14.1 MeV neutrons placed at the centre of a sphere made of natural uranium to determine the optimal thickness of uranium, generating the highest flux of neutrons. The number of neutrons per neutron source was found to increase with the uranium's thickness and reached a maximum value with a 14 cm radius. They also compared the geometry of uranium, namely cylindrical and spherical. It was found that the uranium geometry played a minor role on neutron multiplication. Two cylinders containing uranium at the maximum point generate approximately the same number of neutrons as generated by the spherical uranium. Thus, a sphere is certainly preferable due to its lightness.

Eskandaria and Kashian [4], employed Pb and ^{238}U as multiplier materials. The large cross section of Pb for (n, 2n) reaction compensate for the neutron losses by leakage and absorption during moderation. Moreover, the neutron flux was maximized by the use of ^{238}U as a neutron multiplier. In this design, Pb was modelled with 1, 2, 3, 4, 5, 6, 8, 10, and 12 cm thicknesses. The suitable thickness for Pb was found to be 3 cm. Further, the layer with ^{238}U was modelled with 0.5, 1, 1.5, 2, 2.5, 4, and 5 cm thicknesses, and the suitable thickness was found to be 2 cm.

Bi, U, and Pb containing acceptable (n, 2n) cross sections for 14 MeV neutrons were examined by Faghihi using MCNP5 code [5, 6]. Results showed that 5 cm Bi was considered as a suitable multiplier. Pb was also another good choice of a multiplier. However, due to gamma emissions, U was not recommended as a multiplier.

2.2. Moderator

As mentioned previously, the multiplied generated neutrons must be moderated to the epithermal range using proper moderator materials. These materials must have low scattering cross sections at desirable epithermal energies, but high scattering cross sections at higher energies. It should be noted that moderator materials with high absorption cross section absorb many neutrons before they have reached the patient, leading to high gamma ray contamination.

For the moderator, Fluental and Fe are considered to be suitable materials [7]. Fluental is a neutron moderator material developed at VTT in Finland [8] and composed of 69% AlF_3, 30% Al and 1% LiF. Fe is however preferred due to its lower cost and higher abundance. Magnesium fluorine (MgF_2) is also proven useful for producing neutrons in the epithermal energy range [9]. Although U is still used as a moderator as well, it was recently considered an improper material owing to its harmful gamma emissions [5].

Verbeke et al. [9] proposed medium materials such as Fluental, Fe, Al, Ni, AlF_3, Al+AlF_3, and LiF as moderators for BNCT. These materials were proven to approximately fulfil IAEA criteria. In fact, because of their low cost compared to Fluental, Al and AlF_3 are commonly used as moderator materials in BSA for BNCT. However, the low density of Al and AlF_3 compared to Fluental is one of their main drawbacks. Relatively thick Al and AlF_3 are required for the same neutron attenuation as achieved with Fluental.

De Boer [10] evaluated Al followed by Al_2O_3 or AlF_3 near the beam exit as a moderator. These combinations exhibited efficient performance since the O and F cross sections fill in the valleys between the energy resonances peaks of Al. Results also showed that AlF_3 was a suitable moderator for neutrons with energies less than 10 keV, whereas Al_2O_3 was a better moderator for fast neutrons with energies which are higher than 10 keV.

Miyamaru and Murata [11] evaluated D_2O, Fluental, carbon, and beryllium as moderator materials. Results showed that D_2O was suitable for epithermal neutron production with the highest flux and most decreased number of fast neutrons. D_2O, H_2O, Li/D_2O, and Fe were also evaluated as moderator materials by Mofakham [12] and D_2O was found to be a suitable material in terms of both absolute and relative thermal-epithermal fluency in the emergent neutron beam.

For finding proper moderators, Rasouli et al. [3] investigated 16 different materials, namely TiF_3, Fluental, AlF_3, Al_2O_3, MgF_2, BeO, Fe, Al, H_2O, CF_2, Mn, PbF_2, LiF, Co, Cu and PbF_4. In their work, the geometry of the moderator and reflector are cylindrical. The epithermal flux and the ratio of epithermal neutron flux over fast neutron flux ($\varphi_{\mathrm{epi}}/\varphi_{\mathrm{Fast}}$) associated with these materials were calculated using the MCNP4C code [3, 13]. Results showed that TiF_3 with 23 cm thickness was suitable material for a moderator. However, although the epithermal flux for TiF_3 reached its maximum value, the resulting $\varphi_{epi}/\varphi_{Fast}$ did not satisfy the IAEA's recommended value, which might be due to the use of uranium as a multiplier that can intensify the fast neutron flux. For increasing $\varphi_{\mathrm{epi}}/\varphi_{\mathrm{Fast}}$, a second moderator was used to reduce the number of fast neutrons. When 23 cm thick TiF_3 was selected as the first moderator, the value of $\varphi_{\mathrm{epi}}/\varphi_{\mathrm{Fast}}$ of 40 cm Fluental as the second moderator was shown to be larger than the critical value recommended by IAEA. Thus, it is suitable to use Fluental as the second moderator in this case.

According to Yani [14], materials containing F or Mg have a maximum value of fast to epithermal over macroscopic absorption cross sections ($\sum s_{f/epi}/\sum\gamma$). In terms of neutron accumulation in epithermal energy range during the slowing down from source energies, these materials are claimed to be better than other moderator materials. Due to this reason, Eskandari and Kashian [4] also used AlF_3 as a moderator. It has a large ratio of $\sum s_{f/epi}/\sum\gamma$. Based on their work, the ratio of fast neutrons to total neutron flux between 60 and 70 cm of AlF_3 was constant and therefore 60 cm AlF_3 was selected as a moderator.

In another study by Koivunoro et al. [7], the best results for moderator materials were achieved with Fe and Fluental. The material combination of Fluental is ideal to decrease the neutron flux to the desired energy range of ~10 keV without over-moderation. In this system, a 28 cm D–T layer of iron was first used to decrease the fast neutron energy in the range of 1–14.1 MeV. Then, a 34 cm D–T layer of Fluental was used to decrease the neutron flux in the range of >100 keV.

Due to the fact that a good moderator for BNCT should not induce high gamma ray contamination, a material inducing less gamma dose rate must be selected as a moderator material. Based on these criteria, Faghihi [5] selected Fe with 50 cm length and 80 cm thickness as the moderator material.

Furthermore, in order to reduce cost, successive stacks of Al, polytetrafluoroethylene (PTFE) and LiF (Al/PTFE/LiF) were used as a moderator [15]. The reason is that the neutron interaction cross section in Al and PTFE can effectively moderate fast neutrons. Results showed an acceptable behaviour of the proposed moderator and the advantage of irradiating the target with near-resonance-energy protons (2.3 MeV) because of the high-neutron yield at this energy. This leads to production of less fast neutrons and ultimately the lowest treatment times. The 34 cm Al/PTFE/LiF moderator was found to be the suitable option.

2.3. Fast and thermal neutron filter
One of the key considerations in designing a BNCT beam is reducing the fast neutron component of the incident beam. In many cases, the fast neutron flux cannot be properly decreased by the moderator due to a surplus of the fast and thermal neutrons. Because of this, a fast neutron filter material that can reduce the fast component of the flux, resulting in an increased epithermal one, is required. The material commonly used is Al or its compounds [16]. According to the recommendations of IAEA, the desirable minimum beam intensity would be 10^9 epithermal neutrons $cm^{-2}s^{-1}$. In addition, in order to increase the ratio of epithermal neutron flux over thermal neutron flux ($\varphi_{epi}/\varphi_{thermal}$), the thermal neutron flux should be reduced as much as possible. Thermal neutrons cause too high a radiation dose to the skin and soft tissue. In order to reduce these undesired doses, a material functioning as the thermal neutron filter must be used. Elements with good thermal neutron absorbers are ^3He, ^{10}B, ^6Li, ^{14}N, and Cl. Since ^3He is very rare and has a high potential as an energy source, it is not very useful as a thermal neutron absorber [10].

^6Li was considered a suitable thermal neutron filter due to smaller the release of gamma rays in the process. Its high thermal absorption cross section helps to remove thermal neutrons from clinical neutron beams. Thus, lower thermal contamination and lower gamma contamination due to thermal neutron absorption is the result. Gao [17] used ^6Li as a filter for BNCT. The filter was able to increase the average energy of the epithermal neutrons in the epithermal neutron beam. Venhuizen [18] also examined the performance of gadolinium (Gd) as the thermal neutron filter using MCNP calculations [19]. Results, however, showed that Gd is not suitable for this application owing to gamma contamination issue.

Because of its high inelastic scattering cross section, Fe was used as neutron filter material [3]. It decreased the fast neutron flux with energy up to 14.1 MeV. Fe with a thickness of 4 cm was found to satisfy the IAEA's criteria because D_{fn}/φ_{epi} was less than 2×10^{-13} Gy cm^2. Further, due to filter addition, the fast and thermal neutron contaminations was capable of being removed even though epithermal flux is unavoidably reduced.

Faghihi [5] also studied many materials as the filter and recommended Al(40%) + AlF_3(60%) as the suggested filter since it has low epithermal neutron absorption cross sections, high thermal absorption cross section and smaller radiation capture cross section.

2.4. Reflector
A reflector is used for directing the neutrons to the beam port. A proper reflector must have high elastic scattering cross section and low absorption cross section for entering the neutrons to the moderator again. For finding a cheaper alternative reflector, Uhlar et al. [20] tested a two-layer reflector; tungsten (W) as the inner part and Mo as the outer part. Approximate with the same performance, the mass of the W/Mo reflector is five times smaller than to the single component reflector made of W.

A research work by Burlon et al. [21] confirmed that Pb is a suitable choice as reflector. Pb has also shown better performance than graphite [15]. Rasouli et al. [3] also evaluated the possibility of using Pb and BeO as the reflector. Their different thicknesses were assessed to determine their reflective capabilities. It was concluded that lead was a suitable reflector to decrease the beam port size to a flat circular surface with a radius of 6 cm. Pb was also used as a reflector material for D–T neutrons [7], even though with a Bi collimator, spectra calculations gave similar results.

Mofakham et al. [12] investigated the use of graphite and boranyloxyboron (B_2O) reflectors to increase both relative and absolute thermal-epithermal neutron fluency. The best results in terms of thermal-epithermal fluency were obtained using a B_2O reflector. For a reflector thickness of 10 cm the relative thermal-epithermal fluency reaches a maximum value of 85%.

2.5. Collimator
A collimator is used to focus output neutron beam to the head phantom. Bi is a commonly used material for a collimator [7]. Reflector material such as Lithium Polyethylene in a trapezoidal shape is also occasionally used to collimate output neutron beam [5].

Uhlar et al. [22] utilized Pb supplemented with a Ni part as a collimator. In a further study, they also employed molybdenum (Mo) supplemented with a nickel part [20]. This is because at low neutron energies, nickel elastic cross section is higher than that of Mo and the Ni absorption cross section is lower than the Mo absorption cross section for a broad energy interval of moderated neutrons.

2.6. Gamma shielding

Gamma shielding is used to reduce gamma rays originated from the nuclear reactions and neutron capture in different BSA materials. Bi is normally used for this purpose. For instance, Rasouli et al. [3] employed Bi for gamma shielding. Results showed that using 2.6 cm Bi, D_{γ}/φ_{epi} was able to be decreased to lower than 2×10^{-13} Gy cm^2. Thus, it is suitable for BNCT.

3. BSA Models

In this section, three BSA models for BNCT are discussed. The first one is a BSA model proposed by Rasouli and Masoudi (figure 1) [23]. They used natural uranium as a neutron multiplier and thick layers of TiF_3 and Al_2O_3 as moderators. These materials were surrounded by a thick Pb reflector. Ni and Li-Poly were used as shield and collimator, respectively. This configuration showed low contamination of the fast and thermal neutrons and gamma at the beam port, which satisfies almost all IAEA criteria.

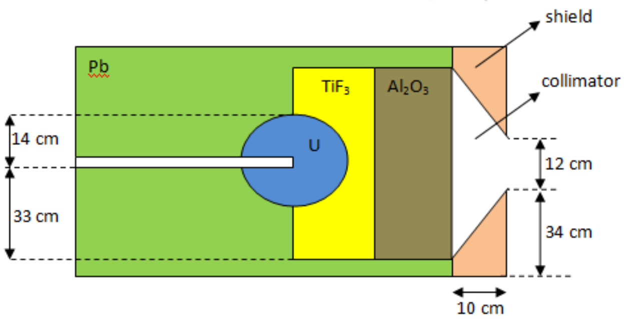

Figure 1. The BSA model proposed by Rasouli and Masoudi [23].

Rasouli et al. [3] also designed BSA for BNCT based on the use of 14 cm in radius metallic uranium as multiplier system for D–T neutron source and moderator/filter/reflector arrangement. TiF_3 with 23 cm in thickness and Fluental with 36 cm in thickness are used for the moderator to achieve a proper epithermal neutron flux. A configuration of 4 cm Fe, 1 mm Li, and 2.6 cm Bi are used for fast neutron, thermal neutron, and gamma ray filters, respectively, as illustrated in figure 2.

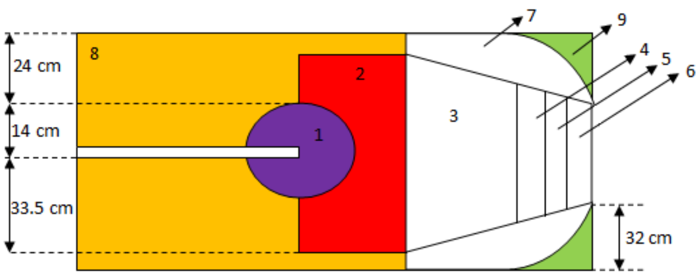

Figure 2. The BSA model proposed by Rasouli et al. [3]. Remarks: 1 is 14 cm uranium, 2 is 23 cm TiF_3, 3 is 36 cm Fluental, 4 is 4 cm Fe, 5 is 1 mm Li, 6 is 2.6 cm Bi, 7 is Pb as collimator, 8 is Pb as reflector, 9 is shield.

Rahmani and Shahriari [24] proposed a BSA model containing layers of Mg, Al, Fe, Pb, Bi, C, and Ni joined with their oxide and fluoride compounds as illustrated in figure 3. Collimators, neutron and gamma shields with various materials and sizes were also added to BSA configurations. The suitable thickness of these materials in cylindrical geometry was chosen to satisfy gamma and neutron dose requirements in the treatment position. In this model, 10 cm of Ni was selected as a collimator material in conical shape. Pb with 25 cm in thickness, 5% borated polyethylene, and 1 mm Cd were used as a reflector, neutron shield, and thermal neutron filter, respectively.

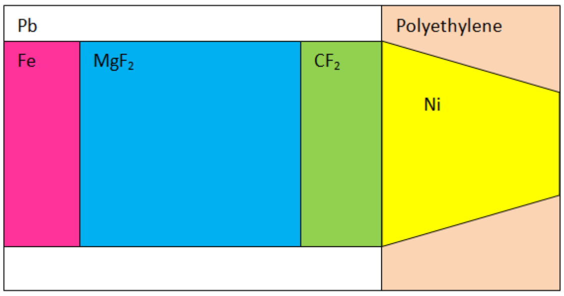

Figure 3. The BSA model proposed by Rahmani and Shahriari, [24].

It should be noted that as the suitable option for the treatment of deep-seated tumors, the epithermal neutrons should possess a minimum intensity of 5×10^8 n/cm^2 s for a reasonable time treatment. Therefore, selecting an appropriate neutron source able to provide this epithermal flux is pivotal before undertaking BSA design. The neutron yield of the available neutron sources capable of satisfying such criteria is in the range of $6.6 \times 10^{11} - 4.4 \times 10^{14}$ n/s [23].

The BNCT parameters of three configurations are presented in table 1. Based on the BNCT free beam parameters of those three BSA configurations, it was found that only the BSA designed by Rasouli et al. [3] satisfies all IAEA criteria. Although the BSA proposed by Rasouli and Masoudi [23] cannot satisfy all IAEA criteria, its neutron beam is effective for deep-seated brain tumor treatments even with D–T neutron generator yielding as low as 2.4×10^{12} n/s. It was found in this configuration that with increase in the neutron source yield, the treatment time decreases. Also, a shorter treatment time can be achieved with the cost of high neutron source intensity. Thus, considering the trade-off between reduction of treatment time and neutron source intensity is vital. In those three configurations, use of specific filters is very important for removing the fast and thermal neutrons and gamma contamination from neutron beam. The free beam parameters recommended for BNCT would be fulfilled by the use of filter. However, the epithermal neutron flux is decreased.

Table 1. BNCT parameters of the three BSA configurations .

BSA model	$\varphi_{epi} \times 10^9$ (n/cm^2 s)	$\varphi_{epi}/\varphi_{thermal}$	$\varphi_{epi}/\varphi_{Fast}$	$D\gamma/\varphi_{epi} \times 10^{-13}$ (Gy cm^2)	$D_{fn}/\varphi_{epi} \times 10^{-13}$ (Gy cm^2)
Rahmani and Shahriari, [24]	8.19	383	17.20	1.18	7.98
Rasouli et al. [3]	4.43	121.2	23.75	1.98	0.59
Rasouli and Masoudi [23]	1.04	20.21	-	5.79	0.67
IAEA criteria [2, 3, 23, 24]	>0.5	>100	>20	<2	<2

4. Conclusion

Progress has been made towards the development of BSA design for moderating primary neutrons into the epithermal energy range. It is found that the BSA configuration designed by Rasouli et al. meets all of the IAEA criteria. It consists of 14 cm uranium as multiplier, 23 cm TiF_3 and 36 cm Fluental as moderator, 4 cm Fe as fast neutron filter, 1 mm Li as thermal neutron filter, 2.6 cm Bi as gamma ray filter, and Pb as collimator and reflector. Use of specific filters for removing the fast and thermal neutrons and gamma contamination from neutron beam and use of a neutron source providing a proper epithermal flux are vital to obtain a BSA configuration satisfying the IAEA criteria.

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