A PRELIMENARY DESIGN OF A NEUTRON BEAM AT THE TAJURA RESEARCH REACTOR CORE FOR BORON NEUTRON CAPTURE THERAPY USING THE MONTE CARLO CODE MCNP:

PART II: FILTERING AND OPTIMIZATION OF THE EPITHERMAL NEUTRON BEAM

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الملخص

تم إنجاز التصميم الأولي لحزمة نيترونية فوق حرارية تتدفق عبر القناة الأفقية رقم ستة (VI) في مفاعل الأبحاث بتاجوراء الغرض منها علاج أورام المخ المستعصية بطريقة أسر البورون للنيترونات الحرارية (BNCT) بواسطة البرنامج المتخصص الكود MCNP. تتدفق النيترونات والفوتونات المتولدة في قلب المفاعل من خلال فوهة أنبوبة القناة الأفقية الممتدة عبر عاكس البريليوم إلى خارج القلب لمسافة كافية تسمح لمستخدمي القنوات الأخرى بالحركة قبل أن تصل موضع المريض. أنبوبة القناة مصنوعة من الفولاذ الذي لا يصدأ ومدرعة بالخرسانة التي تعمل على عكس و توهين الإشعاع المتسرب. تمر النيترونات والفوتونات من خلال المهدئات والمرشحات التي تم اختيارها بعد دراسة الخواص النووية لهذه المواد وتحديد سمكها وترتيبها عن طريق حسابات الكود المذكور حيث تعمل الأولى على تهدئة النيترونات السريعة وتعمل الثانية على امتصاص الإشعاع الغير مرغوب فيه والإبقاء ما أمكن على حزمة مسددة من النيترونات الفوق حرارية ، وعليه فقد تم اختيار الألمونيوم-27 كمادة مهدئة والبورون الطبيعي كمرشح للنيترونات الحرارية والبيزموث-209 كمرشح لأشعة جاما ووضعها داخل القناة الأفقية بنفس الترتيب.

ABSTRACT

An epithermal neutron beam at the horizontal channel (HC) number VI of the Tajura research reactor is preliminarily designed for the purpose of brain tumor treatment based on the method of Boron Neutron Capture Therapy using MCNP code. The neutron and photons generated in the reactor core leak through the cavity of the HC in the Beryllium reflector and guided through a tube to patient position. The tube is extended to allow space for other HCs users. It is made of stainless steel surrounded by concrete shield which reflects and attenuates the escaping radiation. Investigation of the nuclear properties of different materials is carried out in order to determine which materials are more suitable as neutron moderators and those as neutron and gamma absorbers and attenuators (filters). Using the mentioned code, the thickness and order of moderators and filters is determined such that producing an optimized collimated beam of epithermal neutrons. Al-27 is selected as a moderator and natural boron as a thermal neutron filter and Bi-209 as a gamma filter. They all have been placed inside the HC VI in the same order.

KEYWORDS: Neutron beam therapy; BNCT; Monte Carlo code; Research reactor; Brain tumor; Attenuation filter; Moderator; Epithermal neutrons; Photons

INTRODUCTION

The most suitable horizontal channel, HC VI, core configuration, and control setting have been determined in part I of this paper. It was found that the epithermal (1eV to 10 keV) neutron flux is acceptable. However, the thermal (below 1eV) neutron flux and fast (above 10 keV) neutron flux in addition to the photon flux still need further reductions. In this part, MCNP code is used to optimize the neutron beam coming out of the channel by introducing different filtering and moderating materials. There is no need to rerun several times the neutron and photon transport problem in the core during the selection process of type, thickness and order of such materials. Instead the so called surface source facility provided by MCNP is used. The neutron and photon data from a core run are recorded at the channel inlet and then used in an independent source problem. The neutron and photon fluxes in an air phantom at the channel outlet before entering the brain are shown in Figure (1). Different filter and moderator materials are studied and the results are compared with the FLUENTAL material.

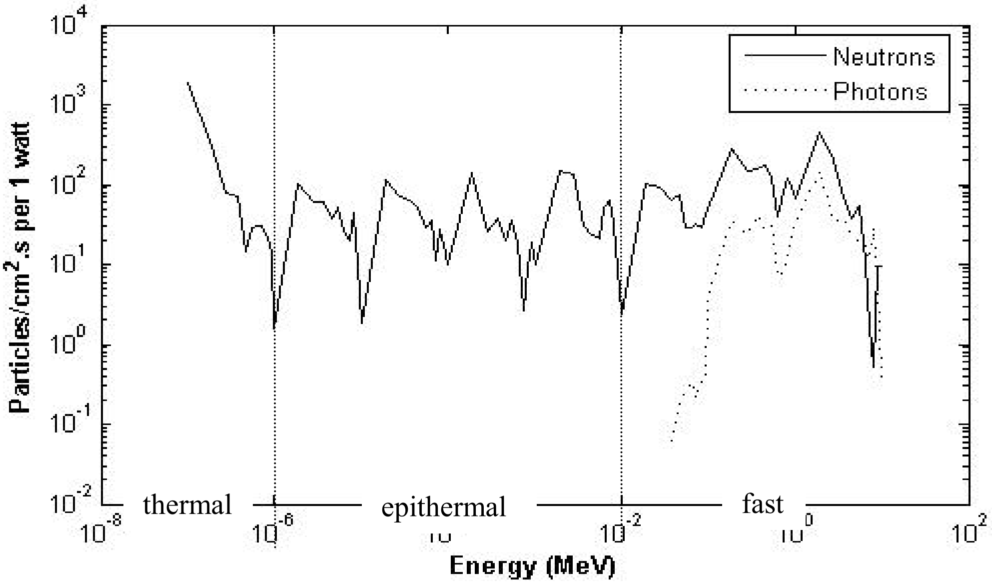

Figure 1: Neutron and Photon fluxes at the outlet port of HC VI

NEUTRON AND PHOTON DOSE RATES

The present channel length of nearly one meter is too short for practical use in BNCT. Therefore, it is extended one meter forward such that it becomes two meters in length; however it has resulted in further attenuation of neutrons and photons by about 30%. Neutron and photon flux at maximum reactor power of 10 MW are converted to absorbed dose rates. They are given in Table (1) in comparison to the recommended values. As can be seen dose rates are still unacceptable for medical purposes and must be reduced below the recommended values.

Table 1: Recommended and calculated beam characteristics

	Required	Calculated
Epithermal neutron flux Φ_{epi}	$\approx 10^9$ n/cm^2.s	$5x10^9$ n/cm^2.s
Fast neutrons dose rate D_f	$\leq$ 0.5 Gy/hr	73.7 Gy/hr
Thermal neutrons dose rate D_{th}	$\leq$ 1.0 Gy/hr	118.3 Gy/hr
Gamma dose rate D_γ	$\leq$ 1.0 Gy/hr	33.9 Gy/hr

MODERATOR AND FILTER MATERIALS

The function of the moderator is to slow down the high energy neutrons to below 10 keV mainly, as a result of elastic scattering reactions. This will serve two objectives: the reduction of the fast neutron dose and increasing the epithermal flux. The best moderators are materials consisting of elements of low mass number with little tendency to capture neutrons and have high elastic scattering cross sections, in addition to abundance and economics. Figure (2) shows the extended horizontal channel with filters and moderators inside.

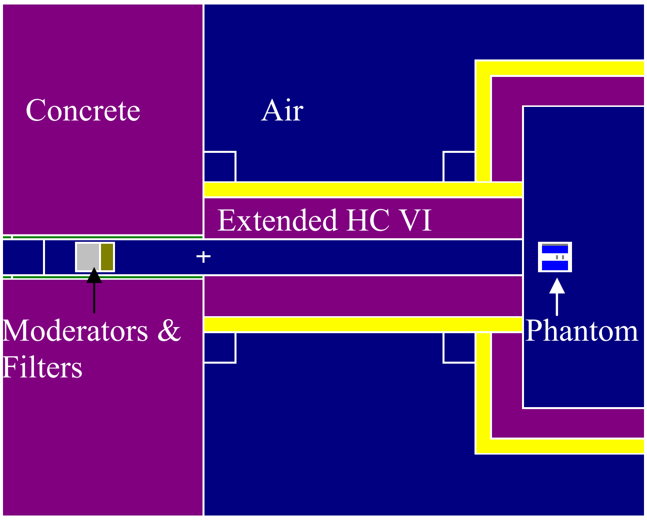

Figure 2: Moderator and filter materials inside horizontal channel VI

Materials such as H_2O, D_2O, Be-9, Al-27, C-12, B, and Cd are famous neutron moderators and filters and materials such as Pb-207 and Bi-209 are used as photon filters. There are several factors to be considered for selection of materials for the neutron filter/moderator and the thermal neutron filters.[1,2,3,4] The neutron filter/moderator should have a high resonance scattering cross section in the fast energy range and low cross section in the epithermal energy range. Light elements are preferable because of the forward-oriented angular distribution of scattered neutrons in the laboratory frame of reference and greater energy loss per collision relative to heavy elements. The thermal neutron filter should absorb thermal neutrons efficiently while transmitting epithermal neutrons with little attenuation. For both types of filters, production of gamma rays has to be minimized and / or controlled. Desirable engineering characteristics for the filter/ moderator materials are that they do not undergo phase changes, decompose or emit toxic substances in the radiation field and potentially elevated temperatures of the service environment. Materials that accumulate high long term radioactivity should be avoided because they may cause difficulty in BNCT system modification and decommissioning and provide an undesirable background radiation component. The effect of impurity and moisture in the materials on beam performance should also be taken into account. Further more the cost of materials and component fabrication is also an important factor in beam design.

Photon filter materials must be characterized with a high mass absorption coefficient for gamma rays, and minimum production of secondary gammas, and a low neutron absorption cross section in the epithermal range. Lead and Bismuth are high Z-material with well known engineering properties often used for photon attenuation.

The neutron cross sections of moderators and filters shown here in figures are retrieved from the ENDF/B cross section library used by MCNP and weighted on the neutron spectrum produced from HC VI channel. The photon cross sections are generated like wise.

Moderator materials

Neutron moderation partly reduces the fast neutron dose and increases the epithermal dose. However, high fast neutron absorption cross section is required in order to reduce the fast neutron dose to an acceptable minimum. Undesirable moderation of epithermal neutrons may take place simultaneously. A high moderator absorption cross-section in the epithermal range is a disadvantage. On the other hand high absorption cross-section in the thermal range is an advantage because it is desirable to reduce the thermal neutron dose. Table (2) summarizes the cross section requirement in the three energy ranges. However, instead of looking at each cross section separately, a combination of the two through their product makes the selection easier.

Table 2: Optimum cross section behavior throughout the energy range

Energy range	Thermal	Epithermal	Fast
Σ_s	high	low	high
Σ_a	high	low	high
$\Sigma_s * \Sigma_a$	high	low	high

The three moderators Aluminum-27 (Al-27), Beryllium-9 (Be-9), and Carbon-12 (C-12) are evaluated through their scattering and absorption cross sections which are shown in Figures (3, 4, and 5). Comparing figures, it is noticed that Al-27 stands as the best candidate among the three. One disadvantage is the high absorption cross section in the epithermal range, however, it is made up by the low scattering cross section in the same range. The photon production cross section (Figure 6) which is defined as the total cross section of all reactions leading to the production of photons is higher than that of other materials but the higher photon absorption attenuation coefficient (Figure 7) reduces the unwanted photon flux. As a matter of fact there is no such an optimum characteristic for a good moderator only in relative respect.

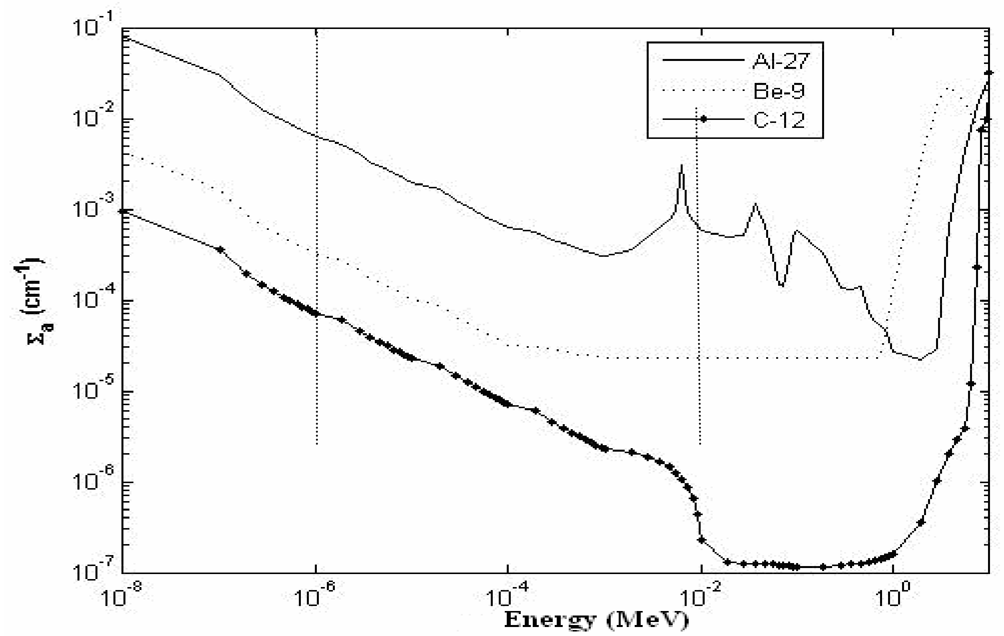

Figure 3: The absorption cross section for some moderator materials

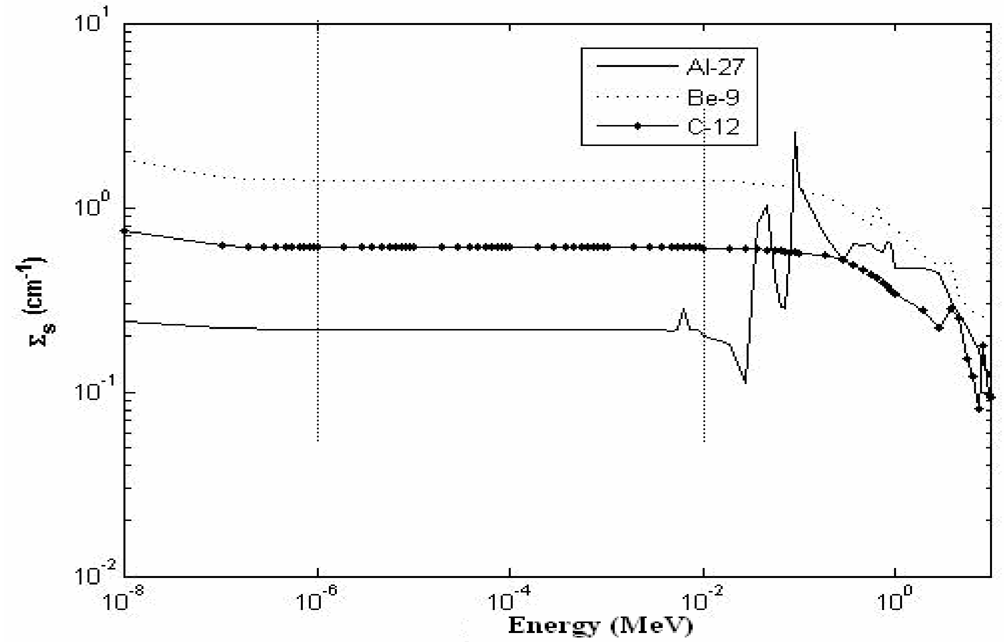

Figure 4: The elastic scattering cross section for some moderator materials

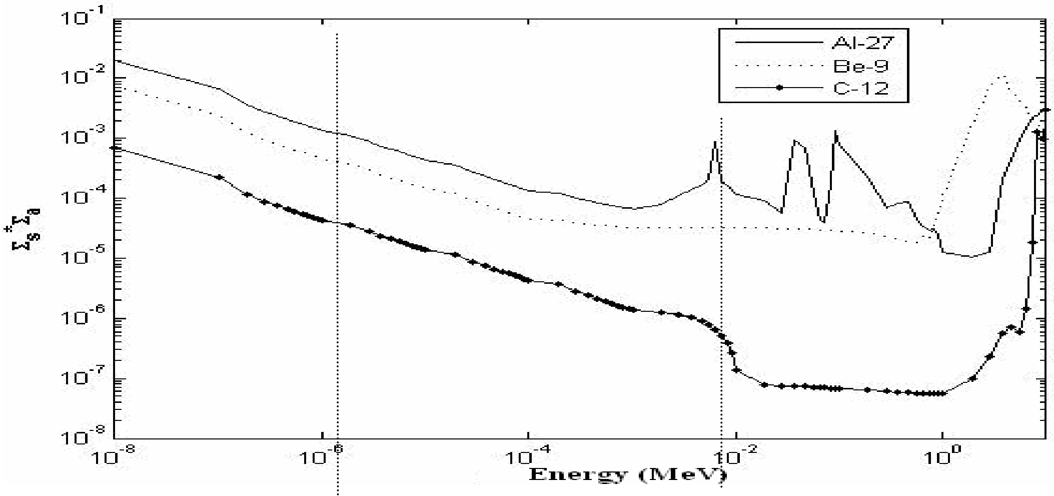

Figure 5: $\Sigma_s \times \Sigma_a$ **for some moderator materials**

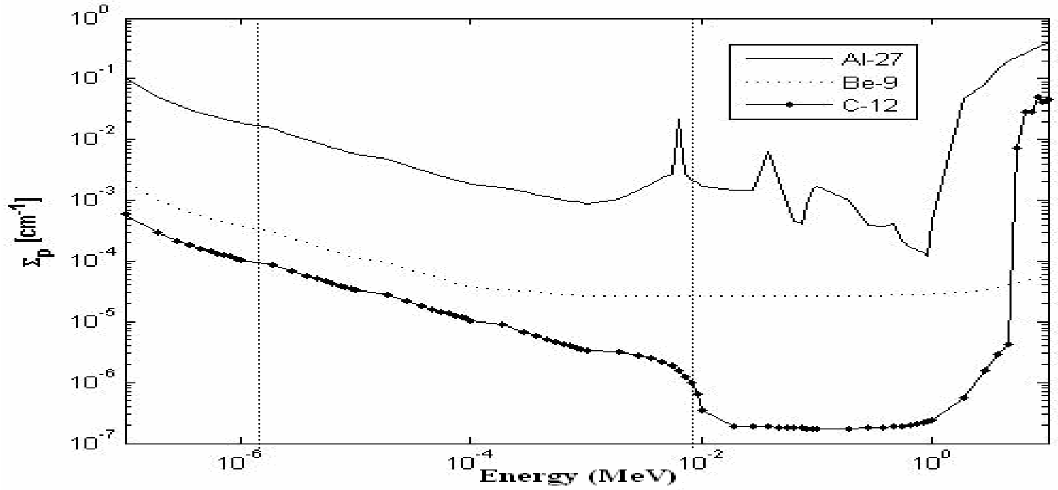

Figure 6: The production cross section for some moderator materials

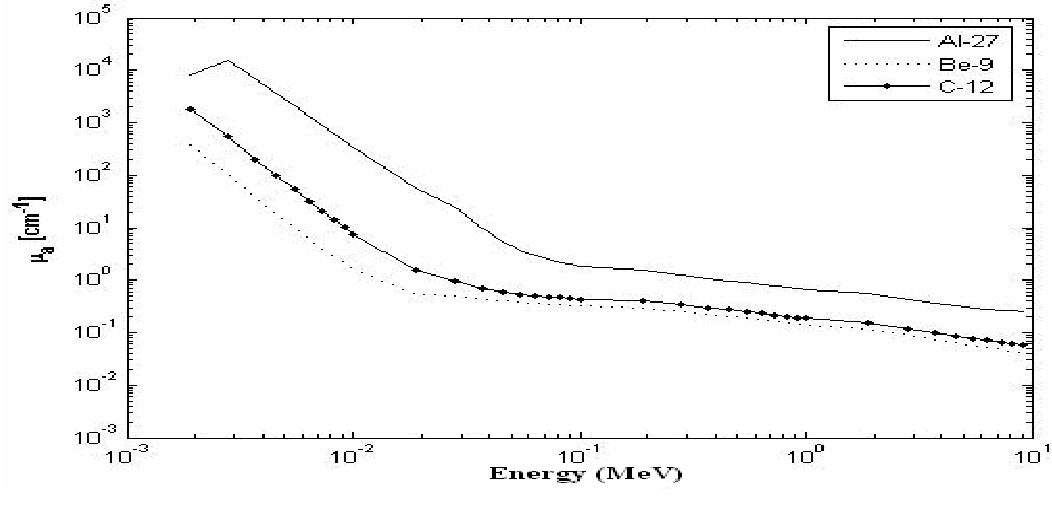

Figure 7: The absorption attenuation coefficient for some moderator materials

When Al-27 moderator is placed in the horizontal channel it attenuates all kinds of fluxes including the epithermal flux. Figure (8) illustrates this effect. The optimum thickness search will be done later after thermal neutron and photon filters are selected.

Thermal neutron filters

The natural elements Cadmium (Cd), Boron (B), and Lithium (Li) are chosen for comparison as thermal neutron filters aiming at the elimination of thermal neutrons from the beam. A glance at Figure (8) showing the absorption cross sections of the three elements, Cadmium has a sharp cutoff at 0.5 eV and seems to be the best candidate. Even though it is more able to attenuate gamma photons (Figure 10), it generates energetic photons upon neutron capture (Figure 11) which makes it prohibitable. Boron comes second in rank to cadmium in terms of the ability to absorb thermal neutrons. It is more favorable because it generates lower energy photons. Lithium is dismissed because it has the lowest absorption cross section for thermal neutrons even though it generates almost no photons. However, all of these elements attenuate some of the desirable epithermal neutrons (Figure 9). Figure (13) shows the effect of varying boron filter thickness on the epithermal neutron flux and thermal neutron dose rate.

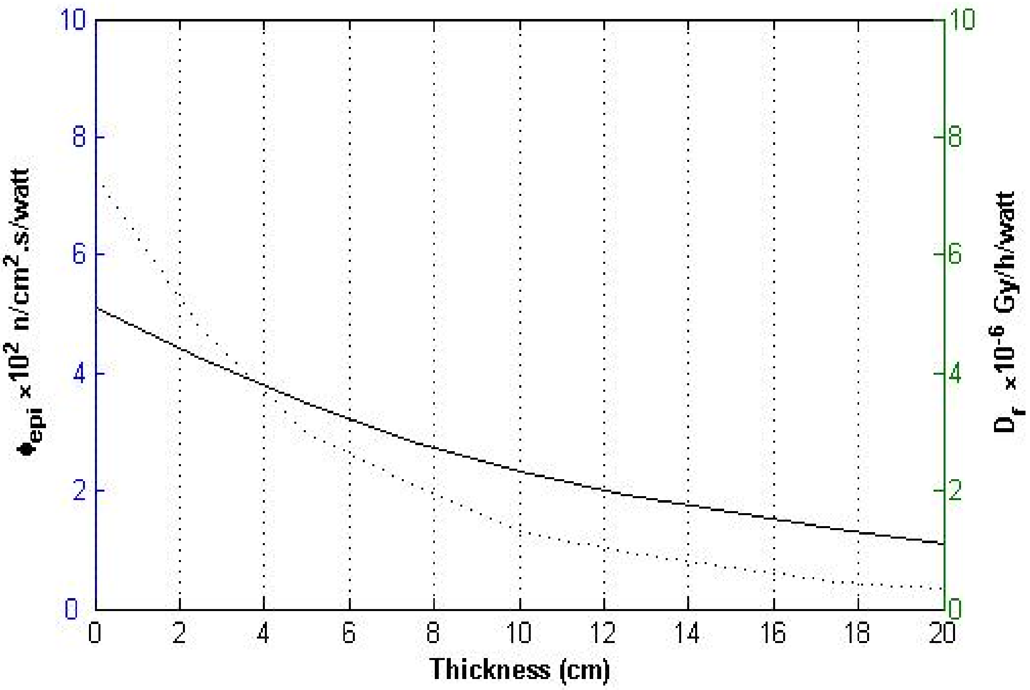

Figure 8: the attenuation of epithermal neutron flux and fast and thermal neutron dose rates in aluminum-27 moderator

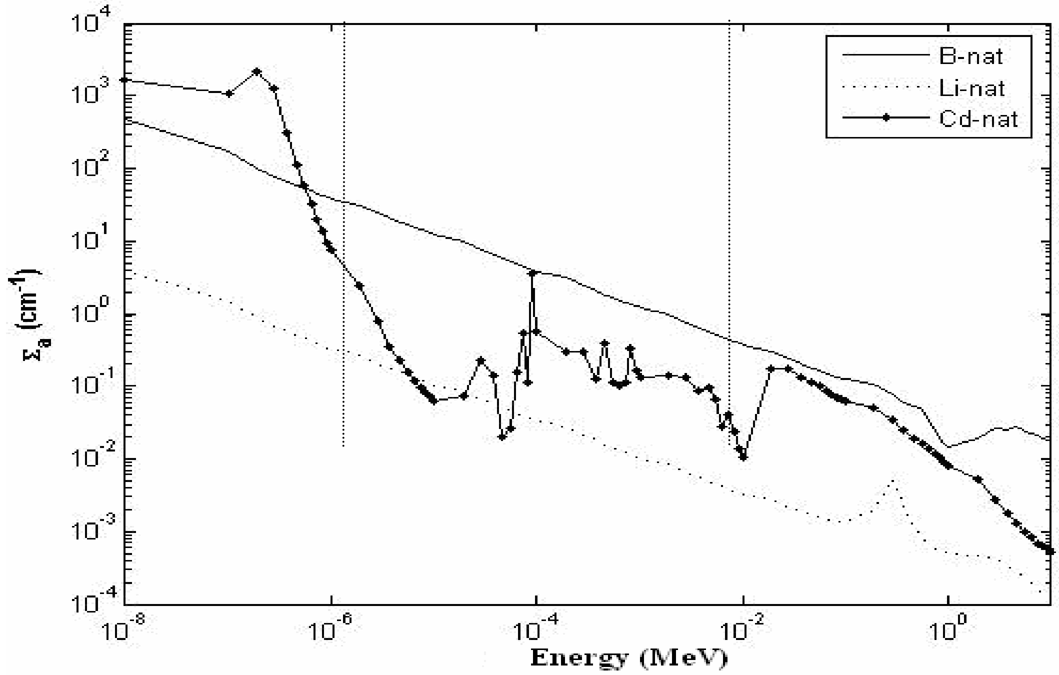

Figure 9: The absorption cross-section for some thermal neutron filters

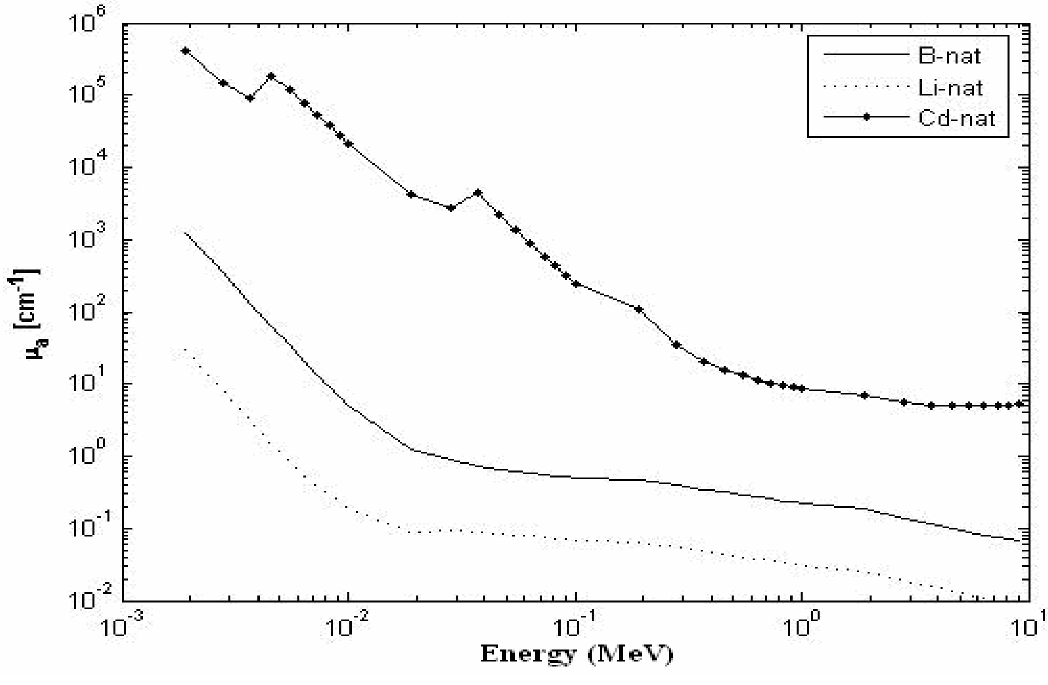

Figure 10: The absorption attenuation coefficient for some filter materials

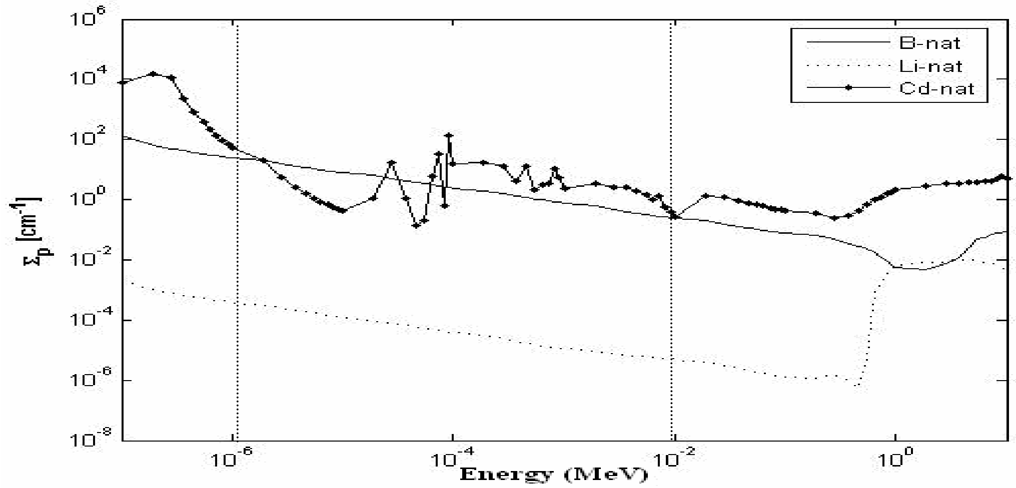

Figure 11: The photon production cross sections for some thermal neutron filters

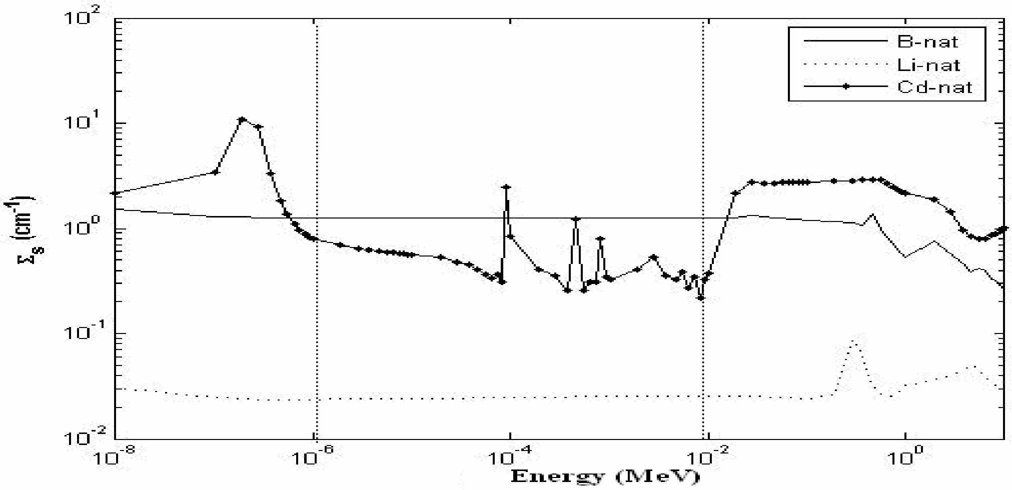

Figure 12: The elastic scattering cross-section for some thermal neutron filters

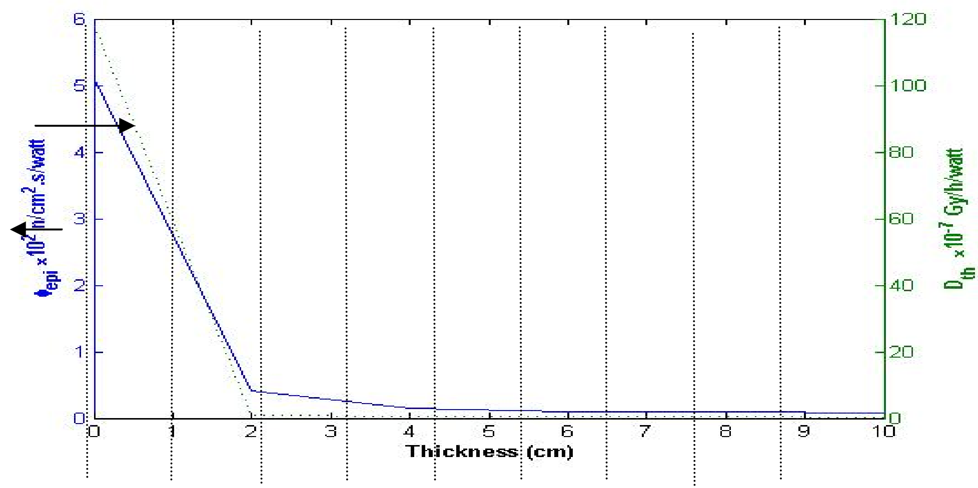

Figure 13: Attenuation of epithermal neutrons and the thermal neutron dose rate in the boron filter

Photon filter

Lead and bismuth are high Z-materials with well known properties often used for photon attenuation. Both exhibit almost the same absorption attenuation coefficient as shown in figure 14. However, the photon production cross section (Figure 15) is lower for Bi-209 and likewise the scattering and absorption cross sections for epithermal neutrons (Figures 16 and 17). These advantages add together to make bismuth preferable to lead. Figure 18 shows the effect of varying the thickness of Bi-209 on the epithermal neutron flux and photon dose rate when used as photon filter material.

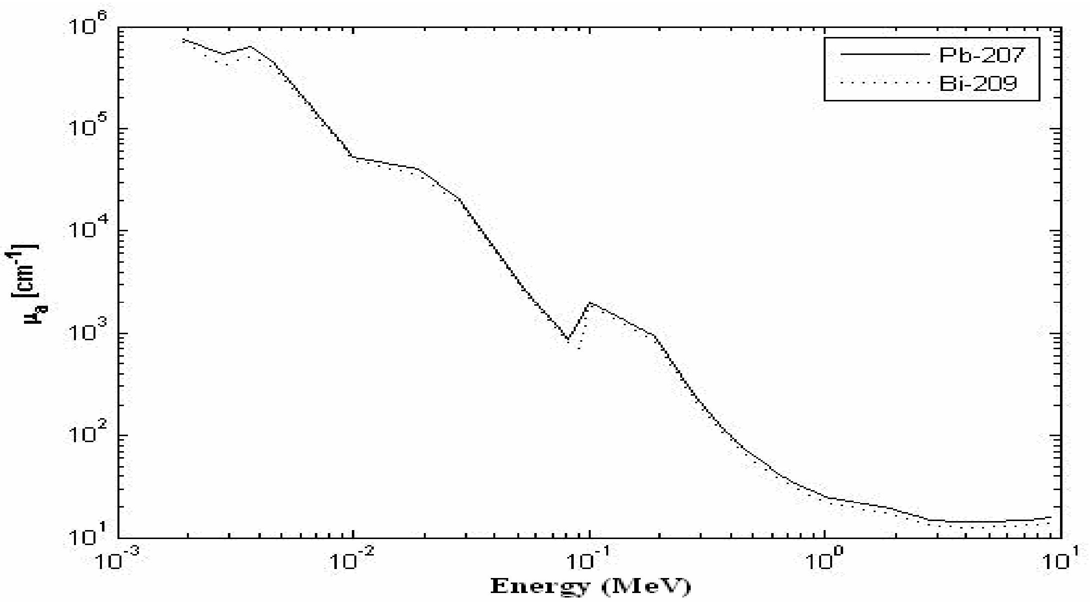

Figure 14: The absorption attenuation coefficient of lead and Bismuth

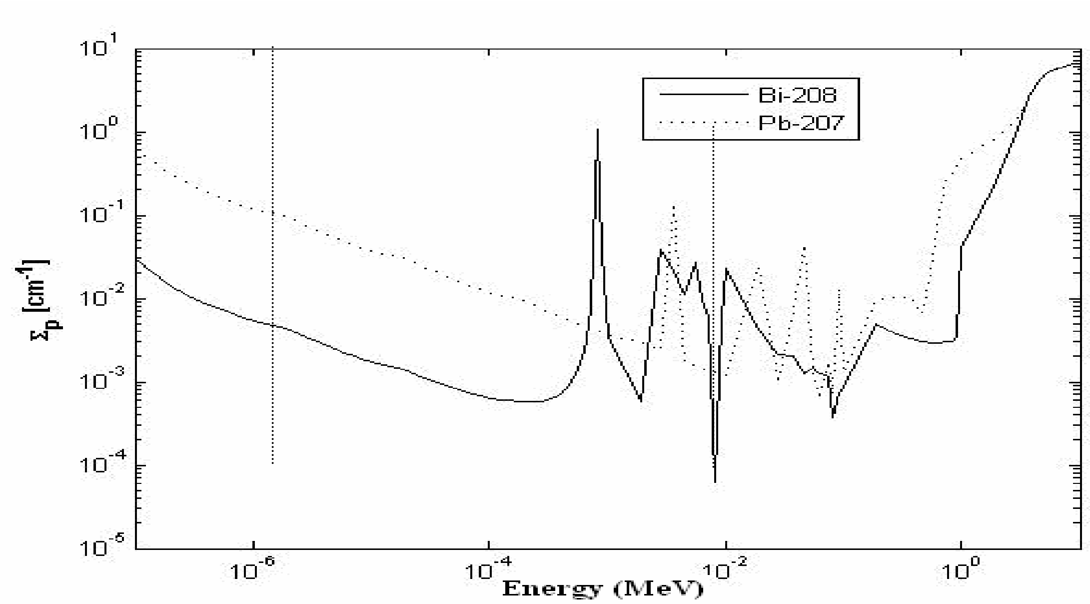

Figure 15: The photon production cross section of Pb-207 and Bi-209

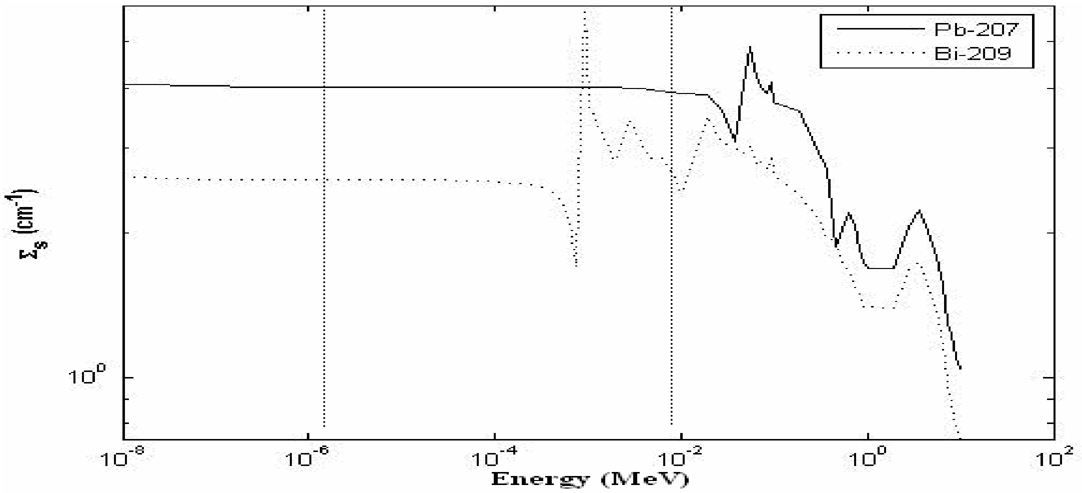

Figure 16: Neutron elastic scattering cross-section for photon filters

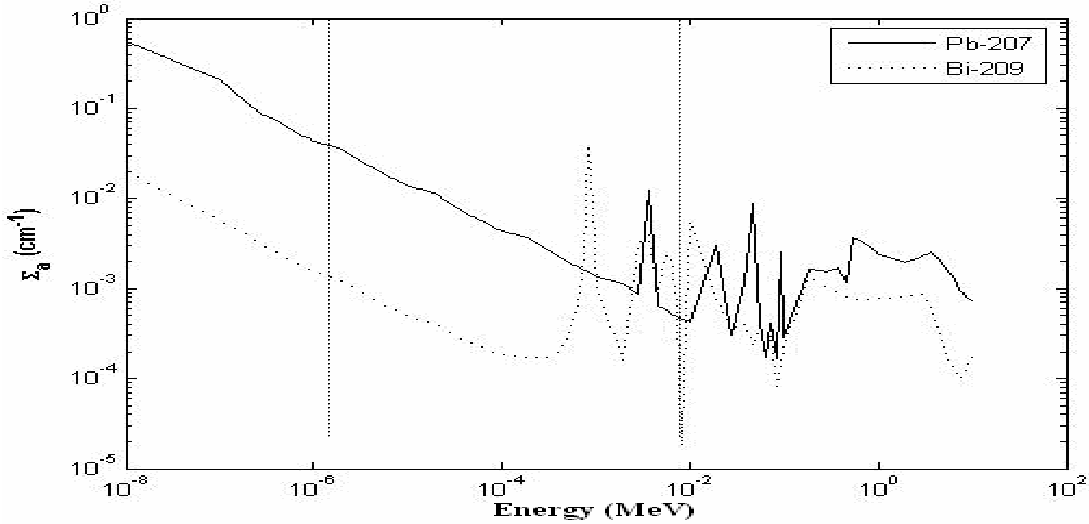

Figure 17: Neutron absorption cross-section for photon filters

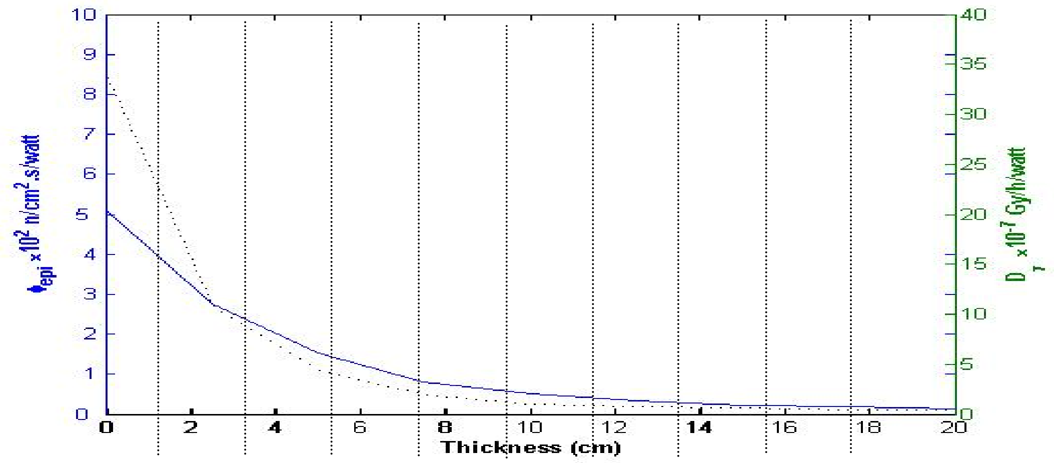

Figure 18: Attenuation of epithermal neutron flux and photon dose rate in Bi-209 photon filter

Combination of moderator and filter materials

Al-27 as a moderator and B-nat as a thermal neutron filter and Bi-209 as a gamma filter have been selected and placed together inside the horizontal channel in the order shown in figure 19. The moderator is placed first to reduce fast neutron energy by elastic scattering. Some neutrons are thermalized increasing the thermal dose rate. Therefore a thermal neutron filter is placed following the moderator. The photon filter is placed last in order to capture photons resulting from neutron captures in the moderator and the thermal filter in addition to photons coming directly from neutron captures in the core.

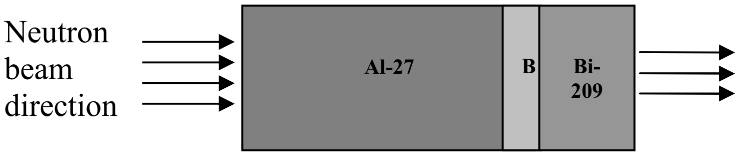

Figure 19: Placement of the moderator and filters inside the HC VI

The attenuation of neutrons and photons when the three materials are placed together is different from that when they are separate. The thickness of the three materials is varied searching for an optimum thickness which may produce acceptable values for safe BNCT. Table (3) gives the epithermal neutron flux and dose rates of fast neutrons, thermal neutrons and photons for different moderator and filters thickness. Both fast and epithermal fluxes are reduced tremendously by the moderating effect of aluminum, while boron with a small thickness reduces the thermal neutron flux by absorption and bismuth attenuates the photon flux. Further alterations lead to the final thicknesses given in the last row.

Table 3: the effect of moderator and filters thickness on the epithermal neutron flux and dose rates (per 1 Watt)

Thickness (cm)			Φ_{epi}	D_f	D_{th}	D_γ
Al	B	Bi	$n/cm^2.s$	Gy/hr $x10^{-8}$	Gy/hr $x10^{-8}$	Gy/hr $x10^{-8}$
0	0	0	511.211	736.865	1183.37	338.749
10	1	10	2.76059	16.8052	0.45993	1.65164
15	1	10	11.5338	10.1327	3.33971	5.82074
20	0.25	6	11.4601	8.76659	0.52994	7.81961
25	0.25	6	7.30882	6.31816	0.36779	4.30944
30	0.05	3	15.7497	5.23032	2.14567	9.48087

The required and the calculated characteristics of the neutron beam at the patient position are given in Table (4).

Table 4: required and calculated neutron beam characteristics (values at 10 MW thermal power)

	required	calculated
Epithermal neutron flux Φ_{epi}	$\approx 10^9$ $n/cm^2.s$	$2x10^8$ $n/cm^2.s$
Fast neutrons dose rate D_f	≤ 0.5 Gy/hr	0.5 Gy/hr
Thermal neutrons dose rate D_{th}	≤ 1.0 Gy/hr	0.2 Gy/hr
Gamma dose rate D_γ	≤ 1.0 Gy/hr	1.0 Gy/hr

THE BNCT TECHNIQUE [5-7]

The BNCT technique for treating brain tumors depends on the selective loading of tumor cells with B-10 and the subsequent irradiation of these cells with low-energy neutrons. The treatment of Glioblastoma multiform (GBM) is the main field of activity for BNCT. There are two common boronated compounds have proved their prospective effectiveness against GBM. These are borocaptate sodium (BSH), and p-boronophenylalanine (BPA).

There are several nuclides which have high microscopic cross section for thermal neutrons but Boron-10 is the only one that is ideally suited for BNCT because of its high natural abundance (19.6%), relatively high capture microscopic cross-section for thermal neutron (3838 barn), and both physically and chemically stable. B-10 is relatively non-toxic to cells, but its combination with thermal neutrons generates a highly lethal effect. The interaction of B-10 with thermal neutrons produces Li-7 and alpha particles as follows:

$$^{10}B + {}^{1}n \longrightarrow {}^{7}Li + \alpha + 2.79\ \text{MeV} \qquad 6.3\ \%$$

$$\phantom{^{10}B + {}^{1}n} \longrightarrow {}^{7}Li^{*} + \alpha + 2.31\ \text{MeV} \qquad 93.7\ \%$$

$$\phantom{^{10}B + {}^{1}n \longrightarrow} {}^{7}Li^{*} \longrightarrow {}^{7}Li + \gamma + 0.48\ \text{MeV}$$

The charged particles ^{7}Li and α have high Linear Energy Transfer (LET) of 150 keV/µm and 175keV/µm respectively and have short range of (9 µm and 6µm respectively). Therefore they deposit most of their energy within the tumor cell diameter (the diameter of the tumor cell is about 10µm). In about 94% of B-10 capture reactions, excited Li-7 nuclei are produced, which become stable after emitting a 0.48 MeV prompt gamma ray. This gamma radiation is not desirable but can be used to measure the boron content in irradiation area at the time of neutron activation using prompt γ-ray spectroscopy technique.

The alpha particles can attack all parts of the tumor cells equally, also they can kill dividing and non-dividing tumor cells as shown in Figure (20). Alpha particle causes breakage of DNA (nuclear acid) molecules, which results in the subsequent death of the tumor cell.

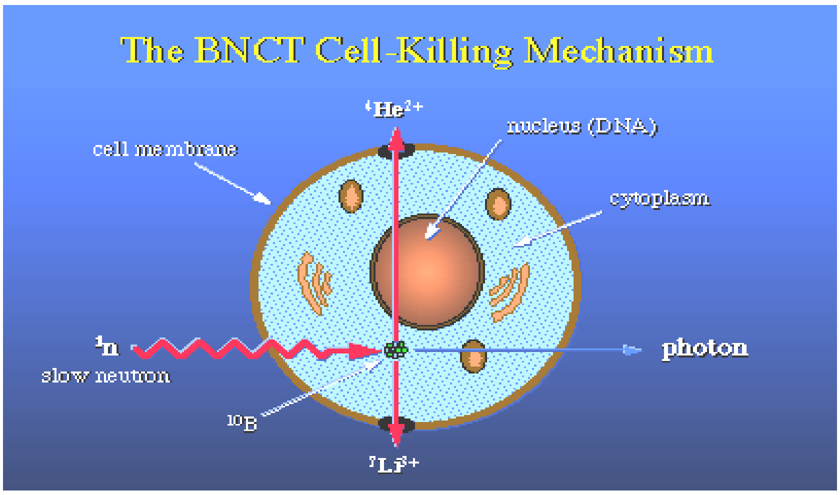

Figure 20: Killing mechanism of the tumor cell

PHANTOM MATERIALS

Once the beam satisfies the conditions set for BNCT it is now ready to hit the brain preferably targeted toward the tumor. Experimentally the brain is replaced by materials called phantoms having a composition of nearly the same nuclear properties as the brain. The major tissue elements of the brain are H-1, C-12, O-16, and N-14. The minor elements include phosphorous, sodium, chlorine, potassium and sulfur with percentage by mass lower than 1%. The elemental composition of brain tissue is summarized in the first row of Table (5). Phantoms given in Table 5 are studied for use as equivalent to brain tissue. They exhibit very close scattering and absorption cross section behavior which can be easily observed in Figures 21 and 22 except for the H_2O scattering cross section at energies above 0.1 MeV.

Table 5: Elemental composition of the phantom materials studied

Material	Density g/cm^3	Weight %				
		H-1	C-14	O-16	N-14	Others
Brain	1.04	10.7	14.5	71.2	2.2	Na (0.2), P (0.4) S (0.2), Cl (0.3), K (0.3)
Polymer gel	1.036	10.6	6.31	81.24	1.85	---
Water	1.0	11.2	---	88.8	---	---
PMMA	1.19	8.0	60	---	32.0	---
A-150	1.12	10.1	77.7	3.5	5.2	F (1.7), Ca (1.8)

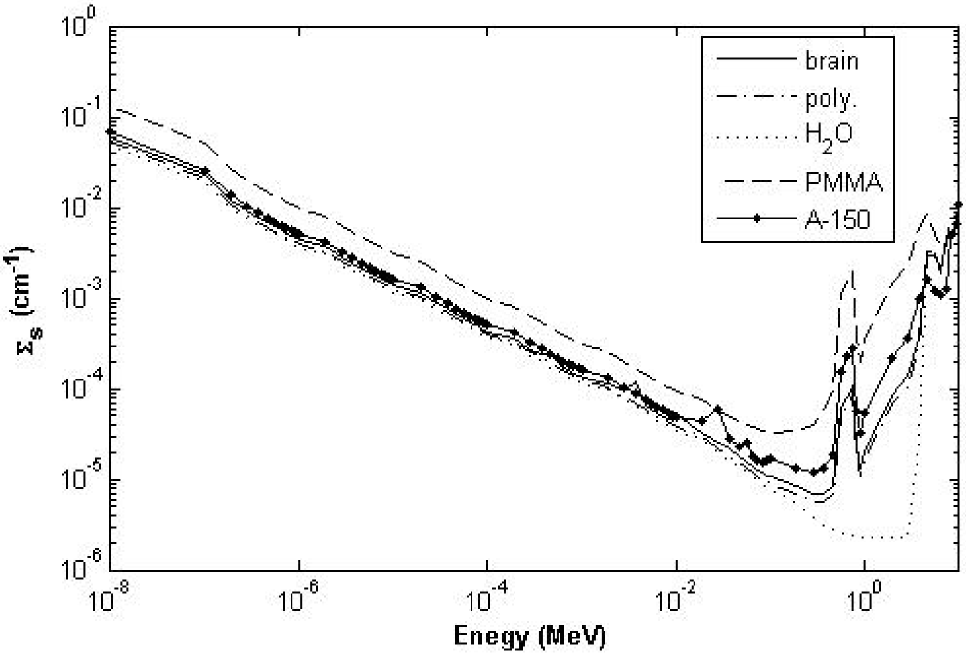

Figure 21: Neutron elastic scattering cross-section for different phantom materials verses energy

Figures (23 and 24) show the neutron and photon spectra in different phantom materials at the exit port of the horizontal channel VI (Figure 2). The behavior of such materials is almost the same. Therefore, it is concluded that phantom materials can be used with confidence as a substitute to brain tissue in experimental work leading to a final design of a BNCT unit.

PHANTOM GEOMETRICAL DESIGN

It is important to model as closely as possible the size and shape of the human head. Simple and approximate designs are studied to simulate the neutron and photon

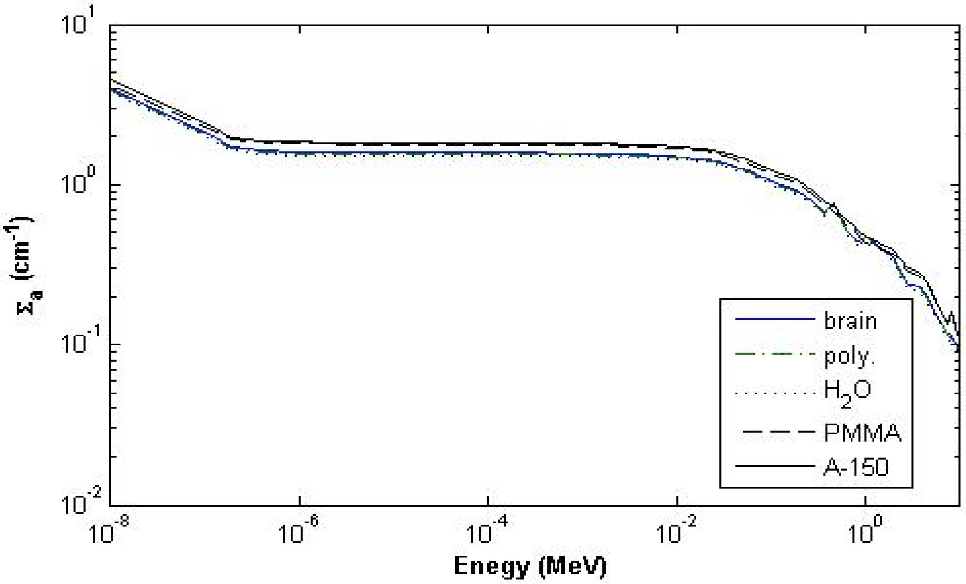

Figure 22: Neutron absorption cross-sections for different phantom materials verses energy

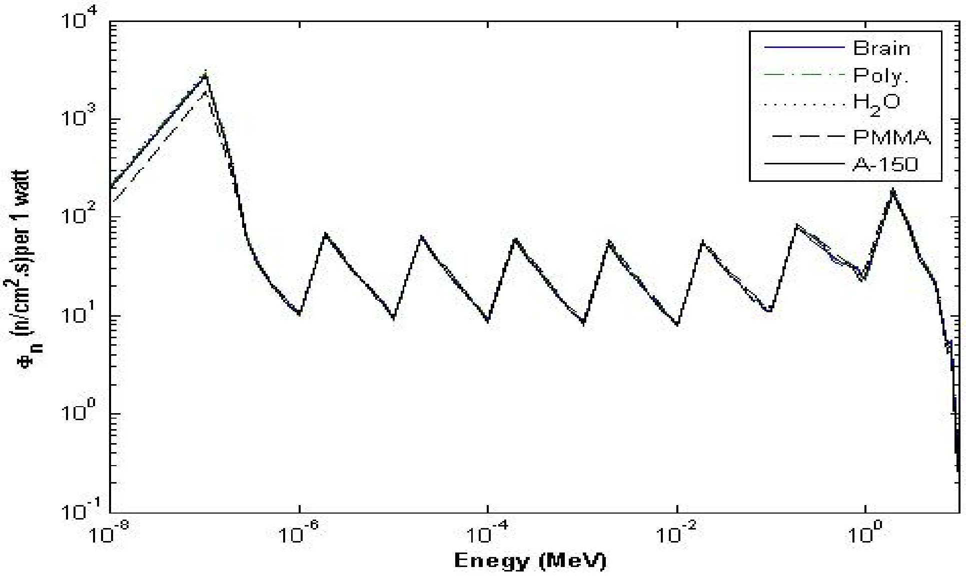

Figure 23: Neutron spectra for different phantom materials

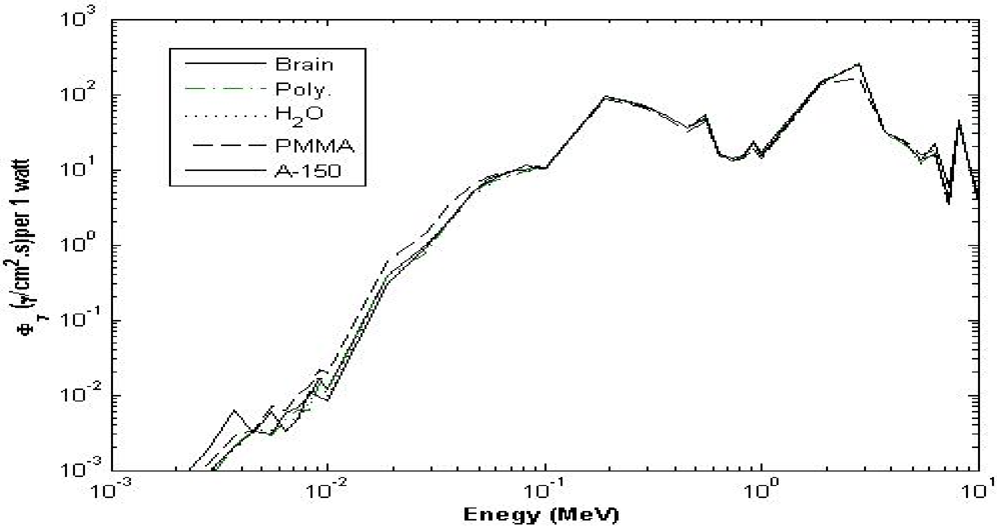

Figure 24: Photon spectra for different phantom materials

radiation transport in the head model. The shape of phantom representing the brain is a right circular cylinder consisting of several materials. The MCNP-4C code is used for simulating the transport of the neutron beam emerging from the horizontal channel VI and incident on the phantom and the resulting neutron and photon dose rates are calculated and listed in Table (6).

Table 6: Neutron and photon dose rates in different phantom materials (per 1 Watt)

Material	Φ_{epi} n/cm^2.s	D_f x10^{-8} Gy/hr	D_{th} x10^{-8} Gy/hr	D_γ x10^{-8} Gy/hr
Air	15.7497	5.23032	2.14567	9.48087
Brain	4.56093	13.7657	0.51089	11.9246
Poly.	4.77475	14.1523	0.46434	11.0455
Water	4.81656	15.0479	0.01608	11.7878
PMMA	5.77293	11.1725	8.06556	11.3688
A-150	4.93870	11.35895	1.21849	11.3105

From the above table the PMMA material gives higher epithermal neutron flux and thermal neutron dose rate than brain tissue results, but for fast neutron and photon dose rates gives lower than brain tissue. Among all phantom materials, Polymer Gel is the best representative to the brain. The neutron beam characteristics are summarized in Table (7) for air and different phantom materials. The air phantom gives lower ratio when compared with all other phantom materials with high hydrogen content causing moderation of high energy neutrons. This has lead to a decrease of epithermal neutron flux and consequently to higher ratios of fast and photon dose rates.

Table 7: Neutron beam characteristic for different phantom materials in air

Material	Φ_{th}/Φ_{epi}	D_f/Φ_{epi} 10^{-13} Gy/(n/cm^2)	D_γ/Φ_{epi} 10^{-13} Gy/(n/cm^2)
Air	0.15	9.0	16.7
Brain	2.17	84.0	72.6
Poly.	2.24	82.0	64.3
Water	2.41	87.0	68.0
PMMA	1.92	39.0	54.7
A-150	2.06	76.4	63.6

This information helps in the experimental work which suggested in future work. Table (8) provides a comparison between the calculated neutron beam characteristics and required neutron beam characteristics in air.

Table 8: Required and calculated neutron beam characteristics in air

	required	MCNP-4C
Φ_{th}/Φ_{epi}	< 0.05	0.15
D_f/Φ_{epi} x 10^{-13} Gy/(n/cm^2)	< 13.0	9.0
D_γ/Φ_{epi} x 10^{-13} Gy/(n/cm^2)	< 13.0	16.7

Form the above table the air phantom gives nearly the same results when compared with the optimum BNCT requirements for the beam. It is clear that a Φ_{th}/Φ_{epi} and D_γ/Φ_{epi} ratio gives higher than the required values. That means that further work is needed to improve this result.

CONCLUSIONS

In part I of this study, the horizontal channel (HC) number VI is selected for BNCT. However, the neutron fluxes and dose rates are too high as compared to the BNCT requirements. In part II different moderators and filters for neutrons and photons have been investigated arriving at the following conclusions:

A Pb-207 plug screen between the core and the cavity of HC VI is placed to reduce photon intensity to about 10 %.

- The extension of the HC about 1 m causes a decrease in the neutron flux to about 47 %. Due to the variance limitation in MCNP calculations at far distances, the neutron and photon fluxes out side the treatment room should be calculated by other discrete ordinates codes like ANSIN or DOT.
- Results show that the required values of neutron beam characteristics can be nearly reached. In particular the Al-27 with thickness 25 cm used as moderator, the B-nat with thickness 0.05 cm used as thermal neutron filter and Bi-209 with thickness 3 cm used as photon filter.
- Modeling of phantom geometry and materials shows good agreement to equivalent brain tissue. Polymer Gel is the best representative to the brain allowing for experimental work to be carried out using this material.

The Tajura research reactor has recently undergone change of fuel. The new low enrichment IRT4M fuel has replaced the old high enrichment IRT2M fuel the maximum reactor power with the new fuel loading may not reach the same power of 10MW when the reactor was loaded with the old fuel. Therefore, further work is needed to refine and update the results by applying the same methodology and hence finalizing the beam design.

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