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

PART I: OPTIMIZING THE CRITICAL CORE CONTROL SETTINGS FOR THE SELECTION OF THE HORIZONTAL CHANNEL

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الملخص

بناءً على نتائج الحسابات النيترونية والفوتونية التي أجريت على مفاعل الأبحاث بتاجوراء بواسطة البرنامج المتخصص (الكود) MCNP-4C وجد أن القناة الأفقية رقم ستة (VI) هي الأنسب من بين القنوات الأخرى لإنتاج حزمة نيترونية فوق حرارية الغرض منها علاج أورام المخ المستعصية بطريقة أسر البورون للنيترونات الحرارية (BNCT). مكّنت الحسابات النيترونية من الوصول إلى ترتيب أمثل لمنظومة التحكم والحصول على بعض النتائج المرضية من خلال دراسةٍ تأثير إدخال أنواع مختلفة من أعمدة التحكم لأعماق متباينة في قلب المفاعل على المفاعلية؛ فمثلا الفيض فوق الحراري في بداية القناة أكبر بكثير من 10^9 n/cm^2.s وهي القيمة المطلوبة في طريقة BNCT عند موضع المريض في نهاية القناة ، ولكن القيم العالية لكل من الفيضين النيترونيين الحراري والسريع وفيض الفوتونات تحتاج إلى تخفيض كبير بواسطة المرشحات والمهدئات قبل وصول الحزمة إلى نهاية القناة لتخفيض الجرعة التي تصل إلي الأنسجة السليمة.

ABSTRACT

The neutron and photon calculations of the Tajura research reactor core carried out using the code MCNP-4C led to the choice of the horizontal channel (HC) number (VI) for the production of an epithermal neutron beam. The beam should be capable of treating brain tumors based on the method of Boron Neutron Capture Therapy (BNCT). The neutronic analysis of the core reactivity and control rod worth and settings are also performed by the same code and revealed satisfactory results such that the epithermal neutron beam at the inlet of the channel is well above the required value of 10^9 n/cm^2.s at the patient position at the outlet. Fast and thermal neutron and photon fluxes are still too high. BNCT requires that they must be as low as possible particularly the photon dose should be lower than 1Gy/hr. Therefore, filtering and moderation are needed for the reduction of the overall dose to normal healthy tissue.

KEYWORDS: Neutron beam therapy; BNCT; Monte Carlo; MCNP code; Research reactor; Brain tumor; Flux; dose; Reactivity control; Attenuation.

INTRODUCTION

Boron Neutron Capture Therapy (BNCT) is a new form of radiation treatment to tumors, which has recently gained world wide interest. Different institutions have started utilizing research reactors and accelerators for this purpose. The treatment aims at the destructions of brain tumor cells with minimum injury to healthy tissue. The procedure is to load sufficient number of B-10 nuclei in the tumor then exposing this tumor to sufficient number of thermal neutrons. The B-10 nuclei become unstable and produce Li-7 and alpha particles, which should destroy the undesirable tumor cells [1-3]. In this paper, the three dimensional continuous energy MCNP-4C code [4] is used in the neutronic modeling of the Tajura Research Reactor (TRR) core fueled with IRT2M type fuel (appendix A) [5,6] for the purpose of finding the most appropriate horizontal channel from which the neutron therapy beam is to be extracted. This requires finding the new criticality settings of the core and finding the 3-D distribution of the flux. This constitutes the first part of an overall project aiming at the refinement and purifying the neutron beam and hence guiding it through a prolonged horizontal channel to the patient position.

RESEARCH REACTORS

In research reactors the neutrons are generated from sustained chain reaction in fissionable materials like U-235. Some of the neutrons will leak out from the core through horizontal channels (HC), which are built inside the reflector, and come out of the reactor pool through the biological shield (concrete). Recently, many research reactors worldwide have been subjected to modifications in order to be used for medical purposes. Meanwhile, they can still be used for many other applications. In BNCT the neutron beam is guided through the horizontal channel to the patient position after undertaking steps to reshape the channel in order to produce a quality therapy beam. The neutron beam intensity from research reactors is more stable and can be controlled with power level of the reactor. Figure (1) is a schematic side view of a research reactor used for treatment [7].

BNCT NEUTRON BEAM REQUIREMENTS [8-12]

The therapy beam should consist only of neutrons in the epithermal range 1eV to 10 keV Penetration through the skull material thermalizes neutrons, hence enabling them to react efficiently with boron nuclei concentrated in the tumor. There are two important beam characteristics:

- Epithermal neutron beam intensity of 10^9 n/cm^2.s is recommended by past experience.
- The fast dose rate to epithermal neutron flux ratio ranges between 2.5×10^{-13} and 13×10^{-13} [Gy/(n/cm^2)]
- The gamma dose rate to epithermal neutron flux ratio ranges between 1×10^{-13} and 13×10^{-13} [Gy/(n/cm^2)].
- The ratio of the thermal flux to the epithermal flux should be less than 0.05. Thermal neutrons in the beam cause some radiation damage to the scalp.
- The ratio of the total neutron current to the total neutron flux should be greater than 0.7. This is a measure of how much the neutrons are guided in the forward direction.
- The size of the neutron beam depends on tumor size. Circular apertures with diameter from 12 to 14 cm are used.

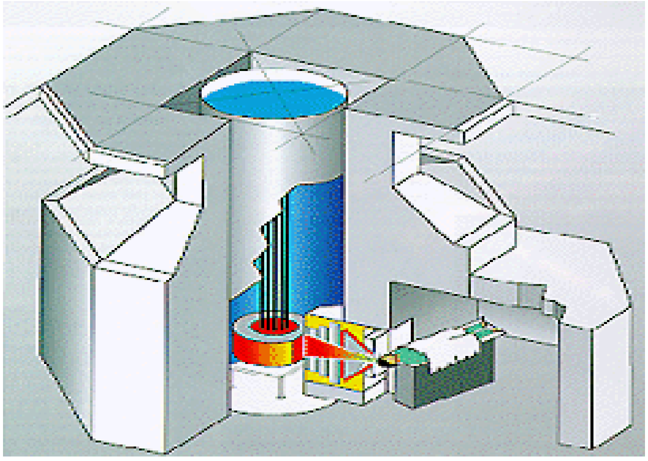

Figure 1: Side view of the research reactor

In this paper the energy distribution and gamma contamination of the neutron beam are calculated. Modifications to the channel and beam purification from fast and thermal neutrons and gamma ray such that only epithermal neutron is produced is the subject of part II. Epithermal neutrons are used to avoid the inherent problem of thermal neutron beam doses. Epithermal neutron beams have dose profiles peaking at 2 to 3 cm depth in skull tissue with effective penetration that can be quite deep i.e. >7 cm, thus treating deep seated brain tumors.

TAJURA RESEARCH REACTOR CORE CALCULATIONS

For any reactor core modeling, a set of system parameters must be determined. These parameters, such as core reactivity, flux and power distributions are continually monitored to ensure safe, reliable and economical reactor operation at the related power level over the core lifetime. The calculations of the core multiplication factor and flux distribution are of course the most common type of analysis performed in nuclear core studies. In this section different core loadings and expected control rods positions to reach criticality are described. The purpose of this analysis is to determine the amount of negative reactivity or control rod movement required to compensate for the excess reactivity contained in the initial fuel loading as well as to allow for flexible and safe reactor operation. The full transport problem is performed using detailed modeling of the reactor core based on reactor data given in appendix B. The objective is to select the best HC for medical applications which must be characterized with a high epithermal neutron beam and low gamma contamination.

The energy range of neurons is classified as follows: the thermal neutron range is between 0 and 1 eV, the epithermal neutrons range is between 1 eV and 10 KeV, and the fast neutron range is above 10 KeV. The photon energies are by one energy bin from 0 eV to 10 MeV.

The Monte Carlo N-Particle (MCNP-4C) code

MCNP is a complete package that simulates neutron, photon and electron transport. MCNP is continually developed by the MC group at Los Alamos Nuclear Laboratory in USA. It is a very huge and complicated program written in FORTRAN language. MCNP is used in nuclear reactor modeling; design of radiation equipment, radiography, radiotherapy treatment planning, radiation shielding calculations, and many other jobs. It is based on the Monte Carlo (MC) method which has the advantage of treating complex geometries, and represent continuously the energy and angular variables. MCNP is used in the calculations throughout this research work.

The reactor core

The TRR serves as the neutron source for the proposed BNCT facility modeling. The reactor core is a pool type reactor. Light water is used as both moderator and coolant. Figure (2) shows a horizontal x-section of the core as viewed by MCNP at a specific height showing some of the eleven H-channels.

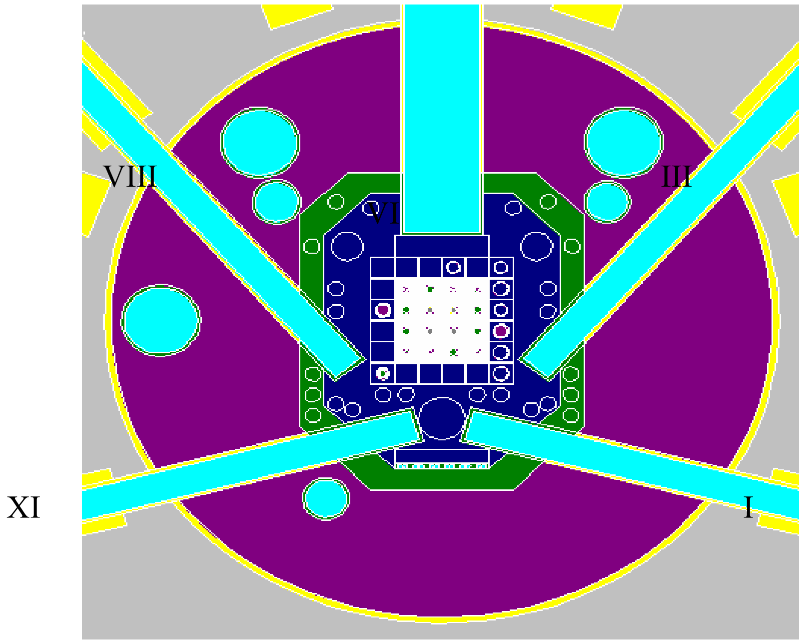

Figure 2: Reactor core layout

The core is 6x6 arrays. In this core two types of fuel assemblies are used, three tube fuel assemblies and four tube fuel assemblies. The three tube fuel assemblies have a central channel for a control rod. Surrounding the fuel, five different types of beryllium blocks can be used. They are as follows: 1. A solid unit. 2. A unit with small central plug. 3. A unit with large central plug. 4. Unit with vertical experimental channel. 5. A unit with control rod channel for regulating rod. These beryllium blocks are surrounded by a stationary beryllium. The stationary beryllium is incased in an aluminum vessel. Both the stationary beryllium and aluminum vessel contain vertical channels with different diameters for irradiation purposes. The reactor contains horizontal channels arranged in radial and tangential orientation with respect to the core center and at two different horizontal levels. There is another irradiation facility known as pneumatic rabbit system in the stationary beryllium.

Neutron and Photon fluxes at the outlet of horizontal channels

Neutron and photon fluxes at exit ports (Figure 3) of all horizontal channels emerging from the reactor core are calculated in order to select the most suitable horizontal channel. The calculation is performed in a phantom cell which should resemble the neutronic characteristics of the brain. The phantom material used here is water. The last column of Table (1) refers to the neutron current to flux ratios. It indicates the forward directionality and hence the degree of beam collimation which should range from 0.5 for a completely isotropic beam to 1.0 for a parallel beam (see appendix B).

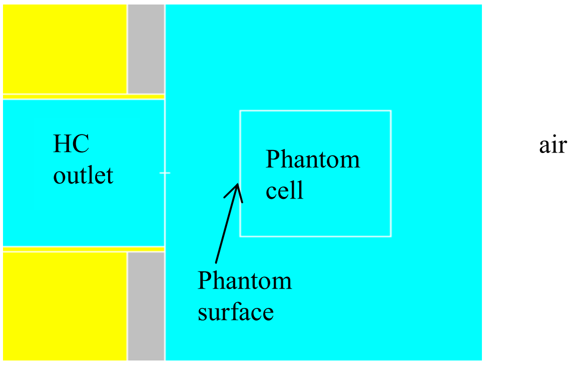

Figure 3: The phantom placed at outlet of HC

Table 1: Neutron and photon Fluxes at the phantom cell placed at the outlet of the different horizontal channels (1/cm^2.s per 1 Watt)

HC #	Φ_{th} x 10^3	Φ_{epi} x 10^3	Φ_f X 10^3	Φ_γ x 10^3	$\frac{\phi_{epi}}{\phi_{th}}$ %	$\frac{\phi_f}{\phi_{th}}$ %	$\frac{\phi_\gamma}{\phi_{epi}}$	$\frac{J}{\phi}$
I	0.17	0.035	0.039	0.058	13.9	16.4	1.67	1.00
II	0.37	0.079	0.051	0.10	15.7	10.2	1.28	0.99
III	0.23	0.11	0.125	0.40	23.8	26.7	3.57	1.00
IV	0.25	0.032	0.041	0.044	9.89	12.8	1.39	1.00
V	0.165	0.033	0.015	0.26	15.3	7.19	8.14	1.00
VI	4.6	1.26	1.94	6.4	16.1	24.8	5.05	0.99
VII	0.13	0.052	0.042	0.39	23.3	19.0	7.50	1.00
VIII	0.20	0.047	0.025	0.075	17.1	9.03	1.62	0.99
IX	0.296	0.078	0.14	0.41	15.0	27.7	5.29	0.99
X	0.40	0.10	0.076	0.10	17.7	13.0	0.97	0.99
XI	0.10	0.040	0.022	0.046	24.1	13.4	1.14	0.99

Channel VI has the highest epithermal neutron flux as compared to other channels. However the photon flux is also high and should be brought to a minimum.

Core loading configurations

Four different cases with different core loading are considered in order to study their effect on neutron and photon leakage into the HC VI. The loading configurations, as viewed by MCNP, are shown in Figure (4).

Case 1: compact loading (4x4) with beryllium (Be) plug in front of the HC VI (reference).

Case 2: rearrangement of fuel assemblies and removable Be units and Be plug is placed in front of the HC VI.

Case 3: the same as case I except that lead (Pb) plug is placed in front of the HC VI.

Case 4: same as case II except that Pb plug is placed in front of the HC VI.

The main objective from shuffling assemblies is to increase neutron leakage from the core to the HC VI with minimum photon contamination. The role of lead plug is to depress gamma flux since lead is a good photon absorber. On the other hand the replacement of Be plug with a Pb plug will decrease neutron multiplication (Table 2).

Table 2: Multiplication factors for different cases

Case	k_{eff}	$\% \Delta k / k$
Case 1	1.15292	13.2
Case 2	1.14669	12.8
Case 3	1.14309	12.5
Case 4	1.13288	11.7

Control rod worth and criticality settings

The worth of different control rods is calculated by MCNP and is listed in Table (3) for the four cases of core loading.

Table 3: Worth of control rods for different cases ($\Delta k / k$ %)

Control rod type	Case 1	Case 2	Case 3	Case 4
Inner shim rods	11	11	11	12
Outer shim rods	8.5	8	8.5	8
Safety rods	4.5	5	4	5
Reg. rod	0.2	0.3	0.3	0.25
Shut down margin	28.6	27	29	30

Two critical control rod settings are considered:

Setting 1: inner shim rods are completely inserted and outer shim rods are partially inserted to reach criticality at different core loadings.

Setting 2: inner and outer shim rods are inserted at the same level to reach criticality at different core loadings.

Table (4) shows the depth percent of inner and outer shim rods for the two settings. They are then used alternately with the four cases of core loadings to calculate the neutron and photon fluxes at the outlet of the HC VI (Table 5). Referring to tables 4 and 5, case number 3 in both settings is preferred mainly because of less gamma and high epithermal neutron flux. By changing the Be-9 plug with Pb-207 plug it was possible to reduce gamma flux. However, setting number one is chosen because of the preferable less insertion of outer shim rods. The full insertion at the center will push the neutron level toward the periphery raising the flux at the channel.

Figure 4: Reactor core configuration for the four cases

Table 4: critical control rod settings

Setting No.	Case No.	Insertion %	k_{eff}	$\Delta k / k$ %
Setting 1 (outer SR only)	Case 1	39.6	1.00308	0.31
	Case 2	37.9	1.00164	0.16
	Case 3	10.8	1.00313	0.31
	Case 4	30.4	1.00193	0.19
Setting 2 (inner & outer SRs)	Case 1	68.3	1.00068	0.07
	Case 2	67.5	1.00482	0.48
	Case 3	65.0	1.00360	0.36
	Case 4	62.5	1.00241	0.24

Table 5: Neutron and photon fluxes of the phantom cell placed at the outlet of horizontal channel VI (1/cm^2.s per 1 Watt)

Setting #	Case #	Φ_{th} x 10^3	Φ_{epi} x 10^3	Φ_f x 10^3	Φ_γ x 10^3	$\frac{\phi_{epi}}{\phi_{th}}$ %	$\frac{\phi_f}{\phi_{th}}$ %	$\frac{\phi_\gamma}{\phi_{epi}}$	$\frac{J}{\phi}$
I	1	4.65	1.4	1.7	6.7	17.8	22.1	4.85	0.98
	2	4.7	2.3	4.9	9.0	19.2	40.9	3.95	0.99
	3	2.4	1.8	2.8	0.66	25.9	40.3	0.37	0.98
	4	2.5	1.8	3.6	0.86	22.8	45.6	0.48	0.98
II	1	4.4	1.5	1.3	5.7	21.3	21.0	3.68	0.99
	2	3.7	2.4	4.2	8.5	23.3	38.5	3.54	0.97
	3	2.2	1.8	2.6	0.60	28.1	39.0	0.09	0.99
	4	2.0	2.6	3.0	0.63	34.2	39.6	0.25	0.98

Flux profile over the whole core

The thermal, epithermal and fast neutron fluxes over the core in two dimensions (x,y) for the selected case number three and for setting number one are shown in Figures (6, 7 and 8) respectively. In Figure (7) the thermal flux is depressed in the center of the core and increases in the Be-9 reflector due to the effect of fuel assembly and the full insertion of inner control rods. But in Figure (8 and 9) the fast and epithermal neutron fluxes are flat in the center of the core and decrease in the Be-9 reflector. Figure (5) shows the core layout as it comes out from the MCNP-4C code.

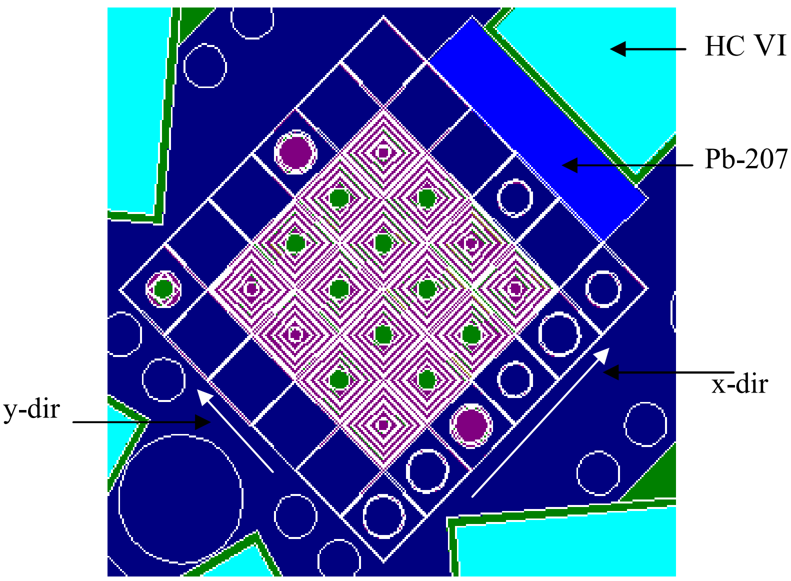

Figure 5: Core layout

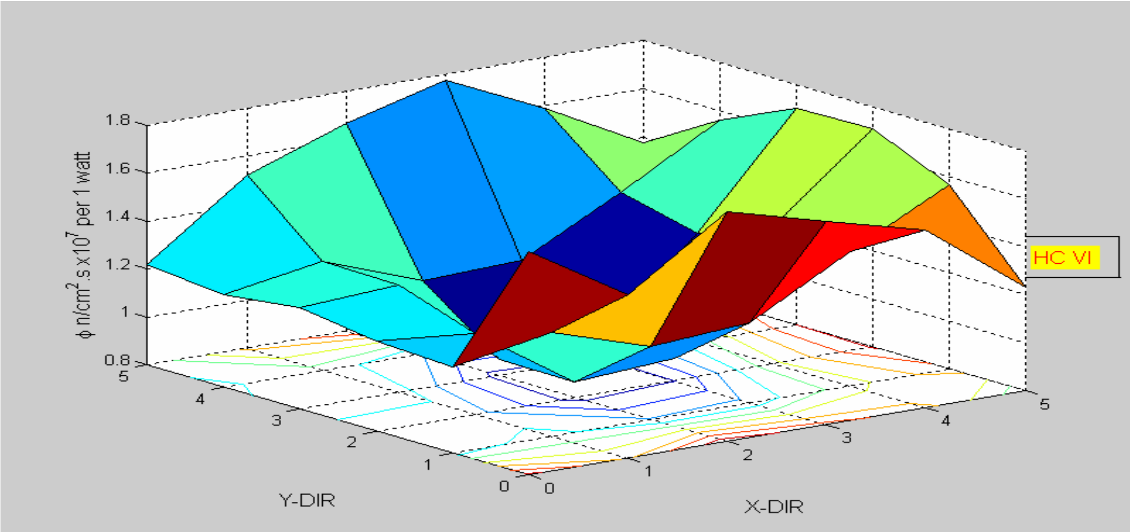

Figure 6: Thermal neutron flux profile over the whole core in the x-y plan

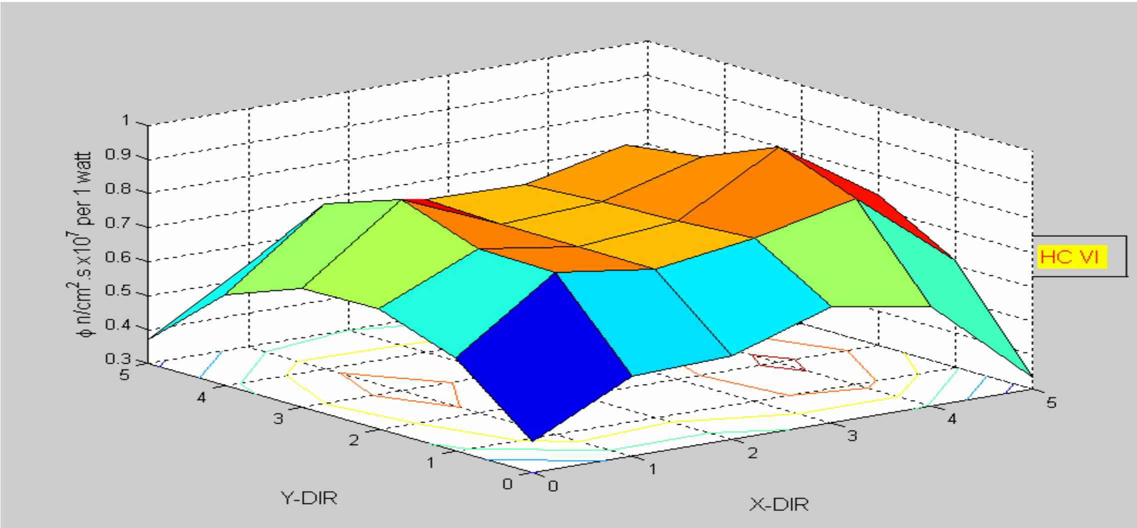

Figure 7: Epithermal neutron flux profile over the whole core in the x-y plane

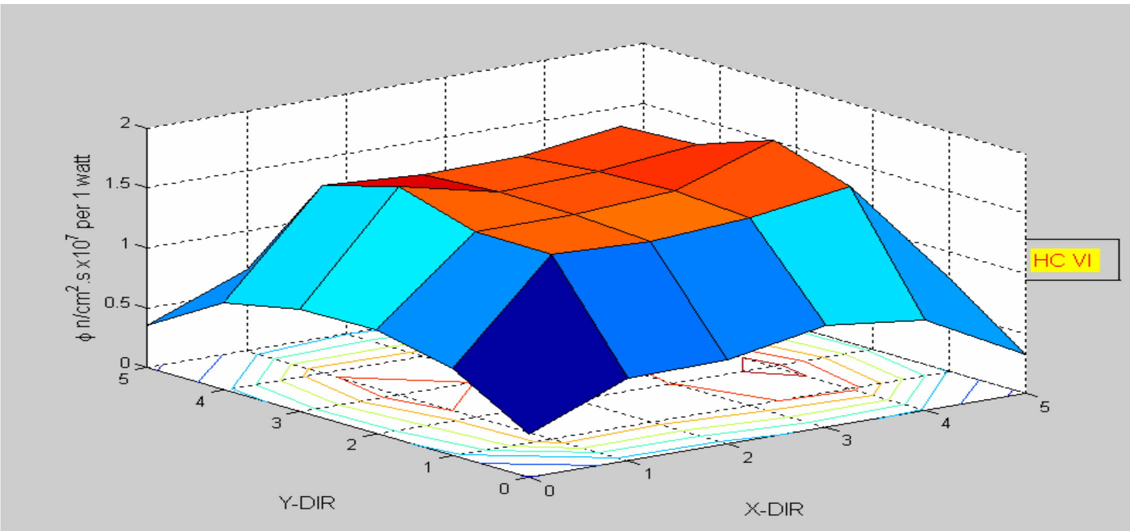

Figure 8: Fast neutron flux profile over the whole core in the x-y plan

The thermal, epithermal and fast neutron fluxes in the z-direction in cell (3-2) in front of horizontal channel VI for the selected case number three and for setting one for control rod position are shown in Figure (10). Figure (9) shows cell (3-2) in which the neutron fluxes distribution in axial direction is calculated.

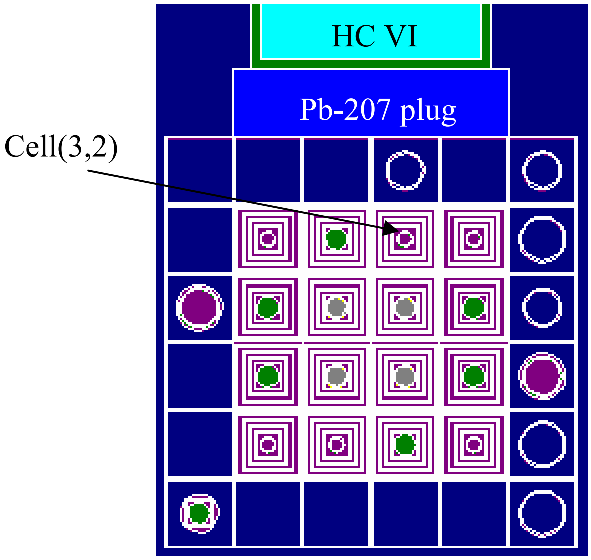

Figure 9: Core layout to indicate cell (3, 2)

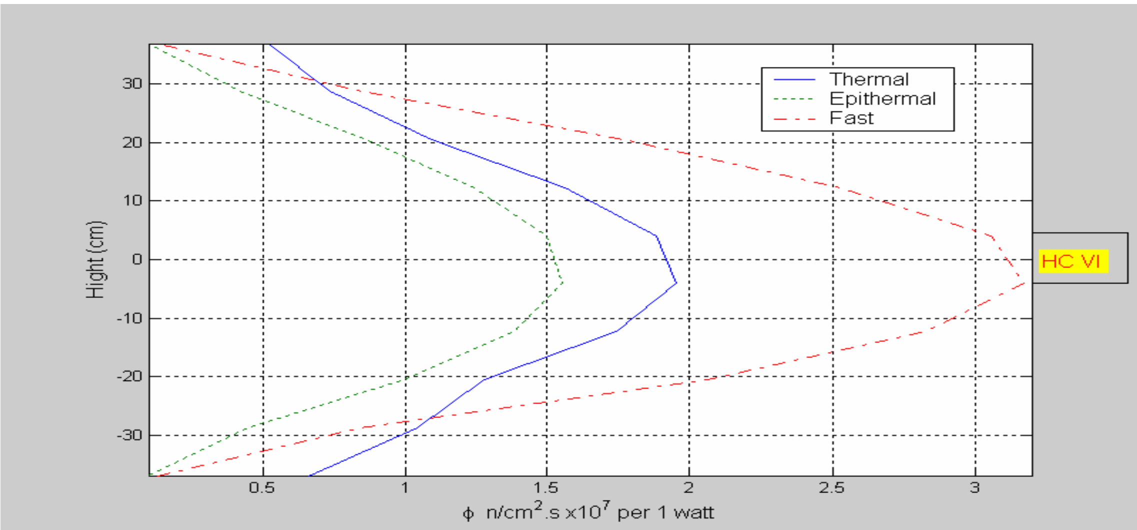

Figure 10: Axial neutron flux profile in cell (3-2)

In Figure (10) the epithermal neutron flux is small at core center while the fast neutron flux is high. Fast neutron flux leaks through the HC VI.

Horizontal channel VI

From section 5 Tables (4 and 5), it is clear that horizontal channel VI has the best neutron beam characteristics for core loading number 3 and control rod setting number 1. In this section the neutron and photon behavior through the horizontal channel tube is studied. Figure (11) shows the side view of H.C. VI as output of the code.

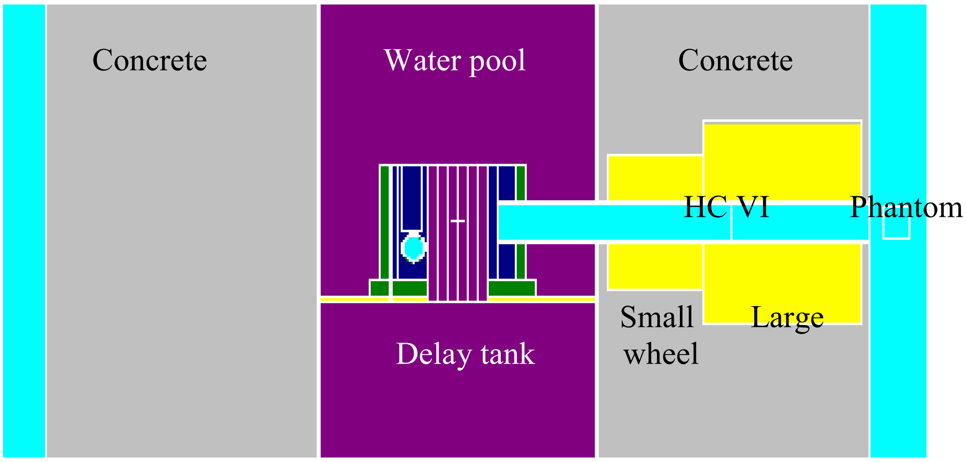

Figure 11: Side view of horizontal channel VI

Figure (12) shows the behavior of neutrons and photons through the horizontal channel with respect to the center of the reactor core. Table (6) shows the neutron and photon fluxes at the entrance and at the outlet of horizontal channel VI.

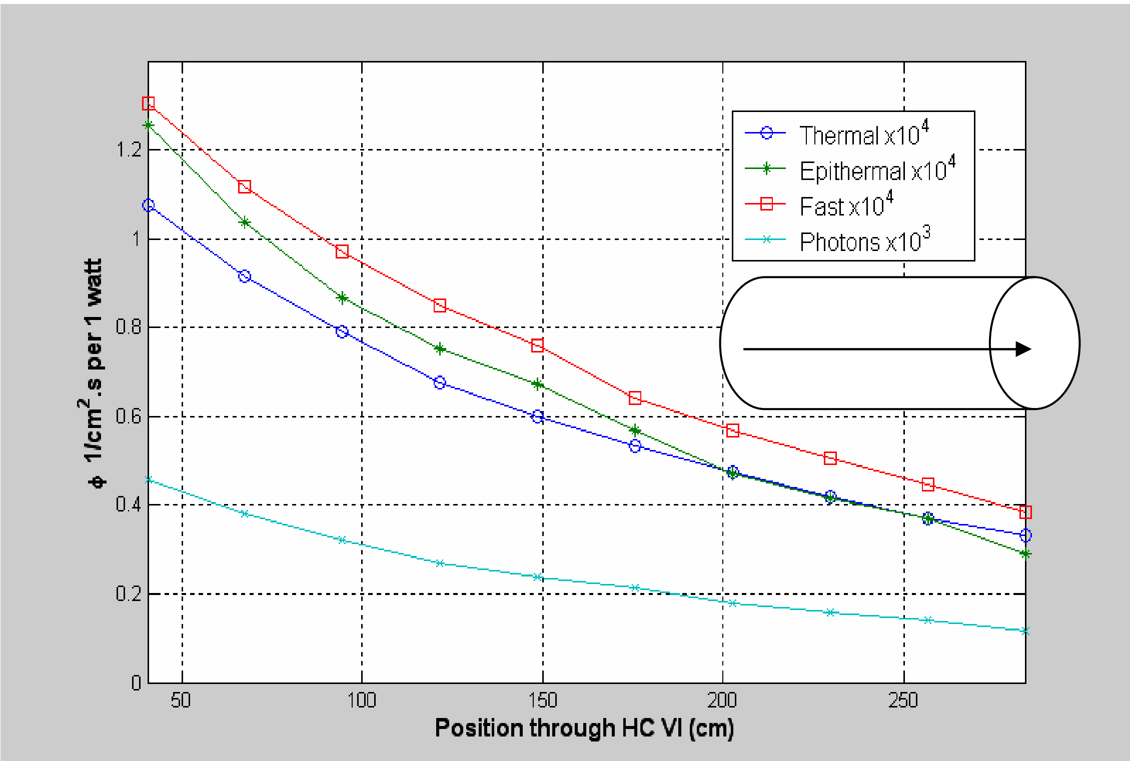

Figure 12: Neutron and photon fluxes verses HC VI depth

Table 6: Neutron and Photon fluxes at inlet and outlet of HC VI

	Inlet of HC		Outlet of HC	
	$x10^4$ per 1W	% SD	$x10^3$ per 1W	% SD
Φ_{th} $n/cm^2.s$	1.07485	1.44	3.3096	2.71
Φ_{epi} $n/cm^2.s$	1.25601	2.21	2.9081	3.34
Φ_{fast} $n/cm^2.s$	1.30476	1.79	3.8316	2.37
Φ_{γ} $\gamma/cm^2.s$	0.45814	2.11	0.1118	4.41

The epithermal neutron flux at the outlet of the channel is 2.9×10^9 $n/cm^2.s$ when the reactor is operated at maximum power of ten mega Watts which is well above the optimum value of 10^9 $n/cm^2.s$ required for the beam. The other fluxes for neutrons and gamma are still high and require filtering and moderation which is the subject of the next part of the paper.

CONCLUSIONS

The Monte Carlo method has proven its usefulness and suitability for the representation of reactor components in three dimensional geometry and the simulation of neutron and photon transport and attenuation throughout the reactor core and the horizontal channel. The basic core calculations are very much consistent with experimental results. In particular:

- Determining the excess reactivity and worth of control rods.
- Predicting the criticality positions to ensure safe and reliable reactor operation.
- Selecting the best horizontal channel, core configuration and control rod setting to reach criticality.
- Predicting the neutron flux profile over whole core and in cell (3-2) vertically
- Studying the neutron attenuation as a function of distance from exit port of HC VI.

The high value of the epithermal neutron flux obtained at the inlet and outlet of the channel VI are promising for further processing in order to obtain quality beam for BNCT.

REFERENCES

[1] R.J. Moss, O. Aizawa, D. Beynon, R. Brugger, G. Constantine, O. Harling, H. B. Liu and P. Watkins, The requirements and development of neutron beams for neutron capture therapy of brain cancer, Journal of Neuro-Oncology, vol. 33, p27-40, 1997.

[2] C.P.J. Raaijmakers, I.A.D. Bruinvis, E.L. Nottelman and B.J. Mijnheer, A fast and accurate treatment planning method for BNCT, Radiotherapy and Oncology, 46, p 321-332, 1998. Birmingham University Home page web site.

[3] O. Aizawa, K. Kanda, T. Nozaki, T. Nozaki and T. Matsumoto, Remodeling and dosimetry on the neutron irradiation facility of the Musashi institute of technology reactor for boron capture, Nuclear Technology, vol. 48, p150-163, Apr. 1980.

[4] J.F. Briesmeister,Ed. "MCNP- Ageneral Monte Carlo N-Particle Transport Code Version4C", LA-13709-M (April 2000)

[5] J.R. Liaw, N.A. Hanan, and J.E. Matos. Feasibility study for LEU conversion of the10Mw IRT-1 Research Reactor at Tajoura Nuclear Research Center in Libya, ANL report, USA, 2004.
[6] A.V. Vatulin, Y.A. Stetskiy, V.A. Mishunin, V.B. Suprun, and I.V. Dobrikova. Development of new-type fuel elements for Russian-built Research Reactors, 2001.private communications, TNRC.
[7] VTT chemical Technology web site.
[8] Y. Oka, I. Yanagisawa and S. An, A design study of neutron irradiation facility for boron neutron capture therapy, Nuclear technology, vol. 55, p642-655, Dec. 1981.
[9] W.A. Neuman and J.L. Jones, Conceptual design of a medical reactor for neutron capture therapy, Nuclear Technology, vol. 92, p77-92, Oct. 1990.
[10] J. A. Bernard, Boron neutron capture therapy and other radionuclide therapies parts I and II, p66-82.
[11] R. F. barth, A. H. Soloway and R. G. Fairchild, BNCT for cancer, Scientific American, p68-73, Oct. 1990.
[12] D. N. Slatkin, A history of BNCT of brain tumors, Postulation of a brain radiation dose tolerance limit, Brain 114, p 1609-1629, 1991.

APPENDIX A

Table A.1: Reactor materials composition in weight percent

No.	Material name	Material Composition	Weight %	Material density (g/cm^3)
1	Fuel U-Al alloy	U-235 U-238 Al-27	29.6 7.4 63.0	3.2
2	Fuel clad	AL-27	100.	2.7
3	Moderator Light water H_2O	H-1 O-16	11.11 88.89	1.0
4	Control rod Absorber Boron carbide B_4C	B-10 B-11 C-12	13.68 62.32 24.00	1.6
5	Control rod clad (absorber clad) S.S-304	Fe-56 Ni-58 Cr-52 C-12	71.92 9.00 19.00 0.08	7.9
6	Reflector	Be-9	100.	1.85
7	Concrete	H-1 O-16 Si-28 Ca-40	1. 50. 35. 14.	2.35
8	Air	O-16 N-14	19.9926 80.0074	0.00125

APPENDIX B

It can be shown from the definition of the partial positive current (J^+) in the forward half space of spherical coordinates and assuming an isotropic flux $\varphi(\underline{r},E,\underline{\Omega}) = \dfrac{\phi(\underline{r},E)}{4\pi}$.

Minimum collimation (isotropic beam)

$$J^+ = \int_{\underline{n}\cdot\underline{\Omega}>0} d\underline{\Omega}(\underline{n}\cdot\underline{\Omega})\varphi(\underline{r},E,\underline{\Omega}) = \frac{1}{4\pi}\int_0^{2\pi} d\psi \int_0^{\pi/2} d\theta \cos\theta \sin\theta \phi(\underline{r},E) = \frac{\phi(\underline{r},E)}{4\pi}\int_0^{2\pi} d\psi \int_0^{\pi/2} d\theta \cos\theta \sin\theta = \frac{\phi}{4}$$

where, the solid angle $d\underline{\Omega} = \sin\theta d\theta d\psi$ and $\underline{n}\cdot\underline{\Omega} = \cos\theta$. The neutron flux is

$\phi = \int d\underline{\Omega}\varphi(\underline{r},E,\underline{\Omega}) = \dfrac{\phi(\underline{r},E)}{4\pi}\displaystyle\int_0^{2\pi} d\psi \int_0^{\pi/2} d\theta \sin\theta = \dfrac{\phi}{2}$, and hence the current to flux ratio is given by $\dfrac{J}{\phi} = \dfrac{\phi/4}{\phi/2} = 0.5$

Maximum collimation (parallel beam)

$\underline{J} = \underline{i}\phi$ and $|\underline{J}| = J = |\underline{i}\phi| = \phi$ hence $J/\phi = 1.0$