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Design of a Medical Reactor Generating High Quality Neutron Beams for BNCT

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Abstract

Boron neutron capture therapy (BNCT) is a binary treatment modality that can selectively irradiate tumor tissue. More is known now about the radiation biology of BNCT, which has reemerged as a potentially useful method for preferential irradiation of tumors. We design a square reactor (that can easily be reconfigured into polygonal reactors as the need arises) with four slab type assemblies to produce high quality epithermal neutron beams and thermal neutron beams for use in neutron capture therapy. With a low operating power of 300kW, the heat generated in the core can be removed by natural convection through a pool of light water. The proposed design in this study could be constructed for a dedicated clinical BNCT facility that would operate very safely.

1. Introduction

BNCT is a binary radiation therapy modality that brings together two components that when kept separate have only minor effects on cells[1]. The first component is a stable isotope of boron, ^{10}B that can be concentrated in tumor cells. The second is a beam of low-energy neutrons. ^{10}B in or adjacent to the tumor cells disintegrates after capturing a neutron. This interaction produce high energy, high linear energy transfer, short-range radiation of ^{4}He nuclei (i.e., alpha particles) and recoiling ^{7}Li ions that would be confined to the tumor and destroy its cells.

Currently available epithermal neutron beams are produced directly from the reactor core but they are not sufficiently intense to meet the anticipated demand for BNCT treatments. There is another method of generating an epithermal neutron beam, namely a ^{235}U fission plate set in the thermal column of a low-power reactor[2]. To get a high-intensity, high-quality epithermal neutron beam for BNCT, fission converter-based epithermal neutron beam has been designed for the MIT Research Reactor, the Brookhaven Medical Research Reactor (BMRR) and the Musashi Reactor. Recently, Liu proposed a 300-kW slab reactor having large surface areas as sources for fission neutrons but with a narrow width so that most of the neutrons emerging from the faces and entering the reflector and/or moderator region are fission spectrum neutrons[3].

This paper describes a square core with four slab assemblies and an inner D_2O tank that we designed[4] to provide a high-intensity, high-quality neutron beam. To get the neutron beams as many as required, we could make the core polygonal.

2. Design Goals

Thermal neutrons are attenuated exponentially in tissue with half-value layers of 1.5 to 2.5 cm and could effectively irradiate tumors <3-cm depth. Thermal neutrons are appropriate for use in irradiating skin tumors or tumors in small animals such as rats and mice. Epithermal neutrons have a lower probability of interacting with and damaging the skin as they enter. This probability then gradually decreases with greater depths. These would be used to treat tumors from 2- to 8-cm depth.

Neutron beams used for BNCT are designed to meet the best dosimetric conditions for patients. These conditions include that a beam intensity $>1\times10^9$n/cm^2·s to deliver necessary fluence to a patient within a reasonable period (<1 hour). Besides flux intensities, the neutron beams should be of high quality, i.e., they should deliver low doses of fast neutrons and gamma rays. The design goals in this study are an epithermal neutron flux $>1.0\times10^9$n/cm^2·sec, a thermal neutron flux $>3.0\times10^9$n/cm^2·sec, the dose from fast neutrons $<3\times10^{-13}$Gy·cm^2/n and the dose from gamma rays $<2\times10^{-13}$Gy·cm^2/n. Forward directed beams (ratio of neutron current-to-flux, J/ϕ, close to 1) offer better dosimetry in the target than do isotropic beams.

3. A 300-kW Square Reactor for BNCT

The core designed in this study is moderated and cooled by light water and reflected by D_2O tank or dense graphite, except on epithermal sides where aluminum was used instead, which also serves as a filter to extract epithermal neutrons. Because of the larger surface areas of the slab assembly, neutron leakage is significantly higher than from a cylindrical core. Thus, the criticality of the core becomes harder to achieve and more ^{235}U must be loaded into the core.

On the epithermal side of the core, there is an aluminum cylinder. Aluminum serves as part of the reflector and also as an epithermal neutron filter. In Figure 1, an aluminum fluoride is placed for the second stage of moderation to slow neutrons leaking throughout the aluminum filter. A cadmium film is attached to the face of the aluminum fluoride on the irradiation port side to eliminate thermal neutrons in the beam. A nickel shell covering the Al, the AlF_3, and the Cd film was used to inelastically scatter fast neutrons from the reactor core. Next to the Cd film is a neutron beam shutter. The shutter can move up and down to control beam delivery. When the shutter is down or closed, a section in the shutter of B_4C-poly encased by steel (pure iron used in the calculations) on both side blocks the beam between the core and the irradiation port; when the shutter is raised, a moderator section of the shutter lies between the core and the irradiation port, thus producing an epithermal neutron beam or a thermal neutron beam. We design two moderator sections in the beam shutter for comparison of neutron beam intensity and directionality(Fig. 2). Steel was used in the shutter to inelastically scatter fast neutrons in the mega-electron-volt range; then, the hydrogen in polyethylene and boron in B_4C are used to effectively moderate resonant neutrons and remove thermal neutrons. A bismuth shield for absorbing gamma rays from the core and also those induced by construction materials is placed in the beam shutter.

On the thermal side of the core, dense graphite is used as a moderator to diffuse thermal neutrons to the irradiation port instead of the Al, AlF_3, and Cd film on the epithermal side.

4. Results of Numerical Experiments

To carry out the neutron and photon transport computations needed for this study, the MCNP code was used. In this study, MCNP, Version 4A, running on an HP C-180 workstation was used[5]. Continuous nuclear cross-section data of the code ENDF/B-V and Group T-2 recommended cross-section data for Fe, ^{11}B, ^{7}Li, and ^{2}H were used in the computations, including the appropriate thermal neutron scattering functions $S(\alpha, \beta)$ for H_2O, graphite, D_2O. The $S(\alpha, \beta)$ data at 300 K were used. MCNP was run in neutron/photon mode in all cases and track-length estimators were used to tally neutron and photon fluxes in interest regions. In a criticality calculation the fission neutrons and prompt gamma rays produced from fission during each cycle are written to the surface source file. These particles can be transported in a subsequent fixed-source calculation.

We obtained the neutron and gamma fluxes and doses in areas of interest, particularly at each irradiation port in the subsequent fixed-source calculations. To reduce the computational time required to obtain flux values with acceptable errors (fractional uncertainty $<10\%$), the variance reduction technique, splitting, was used in the MCNP analysis. Neutrons in the Ni tube were split $\sim$1.5 to 1 as they crossed planes perpendicular to the beam centerline.

Table 1 and 2 compare the proposed epithermal and thermal neutron beams to several of the existing neutron beams used for BNCT. It indicates that for the proposed epithermal neutron beam, the flux intensity per unit reactor power is 12 to 1450 times higher than the three existing ones in use for BNCT. Furthermore, the beam is more forward-directed with lesser contamination from fast neutrons and gamma rays than the existing beams. For the proposed thermal neutron beam, the flux intensity per unit reactor power is 1.7 to 3.7 times higher than the ones at BMRR and Musashi, and the beam is well confined and forward-directed with low contamination from fast neutrons and gamma rays. Delayed gammas are ignored in MCNP criticality calculation. The gamma dose might be increased when delayed gamma rays from the core are included. The value could be still less than the value of the design goal when the delayed gamma rays are included as the intensity is 3/4 times of the prompt gamma rays[6].

Beam analysis for BNCT applications is based on the resulting depth-dose distributions of neutrons and photons in a head or head phantom. Dose rates as a function of depth can be calculated by tallying neutron and gamma-ray fluxes as a function of energy, then modifying those fluxes with energy dependent KERMA factors.

An uptake of 43.05 ppm ^{10}B is assumed in tumor volumes and 12.3 ppm in normal tissues. An RBE of 3.2 is used for the neutron dose and a compound factor (including RBE) of 3.8 is used for the boron dose in tumor cells and a compound factor of 1.3 is used for the boron dose in the normal brain tissues. The radiation tolerance threshold for average normal tissue is 11 Gy-Eq. Figure 3 provides the resulting curves for total tumor dose during the irradiation period (D_{Tumor}) versus depth.

5. Conclusions

A nuclear reactor consisting of slab assemblies was designed to produce neutron beams for use in BNCT: it is a square reactor with two epithermal neutron beams and two thermal neutron beams. (A hexagonal type was also designed.) The proposed facility, based on this square reactor core with a maximum operating power of 300kW, provides an epithermal neutron beam of $3.2\times10^{9}\mathrm{n_{epi}/cm^{2}\cdot s}$ intensity with low contamination by fast neutrons ($<1.6\times10^{-13}\mathrm{Gy\cdot cm^{2}/n_{epi}}$) and gamma rays ($<1.0\times10^{-13}\ \mathrm{Gy\cdot cm^{2}/n_{epi}}$) and a thermal neutron beam of $8.9\times10^{9}\mathrm{n_{th}}\ \mathrm{/cm^{2}\cdot s}$ intensity with low contamination by fast neutrons ($<1.1\times10^{-13}\mathrm{Gy\cdot cm^{2}/n_{th}}$) and gamma rays ($<1.2\times10^{-13}\mathrm{Gy\cdot cm^{2}/n_{th}}$). Both neutron beams are highly forward-directed with low contamination by fast neutrons and gamma rays.

With a maximum operating power of 300 kW, the proposed epithermal neutron beams could provide therapeutic fluences in 14 min. The heat generated in the core can be removed by natural convection through a pool of light water.

The proposed design in this study could be constructed for a dedicated clinical BNCT facility that would operate very safely.

References

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Table 1: Epithermal Neutron Beams for Neutron Capture Therapy

Reactor	Power (MW)	ϕ_{epi} $\times 10^{9}$ $/\mathrm{cm}^2 \cdot \mathrm{s}$	D_n/n_{epi} $\times 10^{-13}$ $\mathrm{Gy} \cdot \mathrm{cm}^2/\mathrm{n}$	D_γ/n_{epi} $\times 10^{-13}$ $\mathrm{Gy} \cdot \mathrm{cm}^2/\mathrm{n}$	J/ϕ	ϕ /Power
BMRR[7]	3	2.7	4.3	1.0	0.67	0.9
MITR[8]	5	0.2	13	14	0.55	0.04
Petten[8]	45	0.33	10.4	8.4	> 0.8	0.0073
Beam Shutter Type A (X1)	0.3	1.8[a]	1.53[b]	< 1.0[c]	0.81	6
Beam Shutter Type B (X2)	0.3	3.2[d]	1.57[e]	< 1.0[f]	0.74	10.6

[a] Statistical error estimate 0.8%

[b] Statistical error estimate 7%

[c] $D_{\gamma_{prompt}}/n_{epi} = 0.29$ with statistical error estimate 8%

[d] Statistical error estimate 0.7%

[e] Statistical error estimate 6%

[f] $D_{\gamma_{prompt}}/n_{epi} = 0.29$ with statistical error estimate 10%

Table 2: Thermal Neutron Beams for Neutron Capture Therapy

Reactor	Power (MW)	ϕ_{th} $\times 10^{9}$ $/\mathrm{cm}^2 \cdot \mathrm{s}$	D_n/n_{th} $\times 10^{-13}$ $\mathrm{Gy} \cdot \mathrm{cm}^2/\mathrm{n}$	D_γ/n_{th} $\times 10^{-13}$ $\times \mathrm{Gy} \cdot \mathrm{cm}^2/\mathrm{n}$	J/ϕ	ϕ /Power
BMRR[3]	3	51	3.0	0.8	0.55	17
Musashi[6]	0.1	0.8	0.87	2.08	–	8
Beam Shutter Type A (Y1)	0.3	4.8[a]	1.27[b]	< 1.5[c]	0.86	16
Beam Shutter Type B (Y2)	0.3	8.9[d]	1.12[e]	< 1.5[f]	0.77	29.6

[a] Statistical error estimate 0.75%

[b] Statistical error estimate 8%

[c] $D_{\gamma_{prompt}}/n_{epi} = 0.62$ with statistical error estimate 8%

[d] Statistical error estimate 0.72%

[e] Statistical error estimate 7%

[f] $D_{\gamma_{prompt}}/n_{epi} = 0.65$ with statistical error estimate 10%

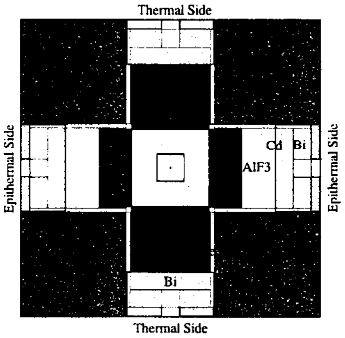

Figure 1: The midplane horizontal section of the geometrical design in MCNP when the beam shutter is open

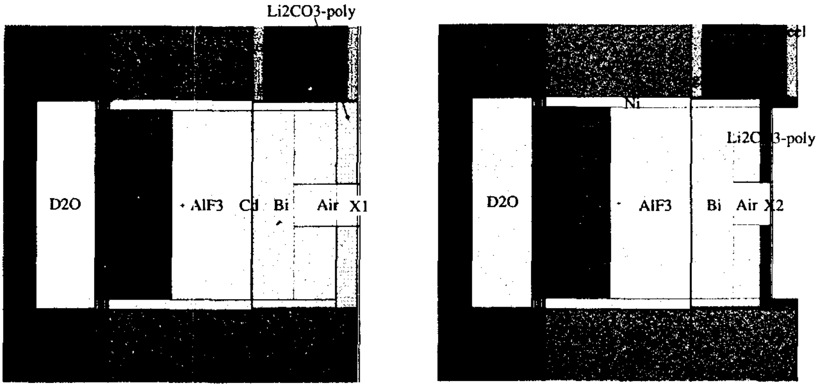

Figure 2: The midplane vertical sections of the proposed epithermal neutron beam tubes

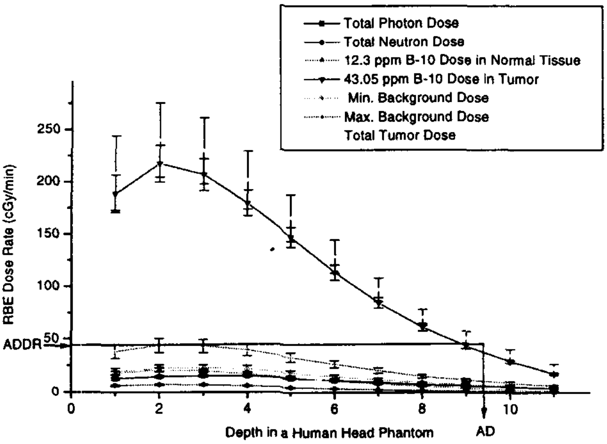

Figure 3: Depth-dose profile in a human head phantom