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AN EPITHERMAL NEUTRON BEAM FROM THE MURR AND FROM AN ACCELERATOR SOURCE COMPARED TO THE BEAM AT THE BMRR

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INTRODUCTION

An ideal neutron beam for BNCT is a beam of epithermal neutrons, forward directed, and free of gamma rays and thermal and fast neutrons. There are now two reactor-based epithermal beams[1,2] in service in the USA and one in The Netherlands[3]. Several designs for reactor- and accelerator- based epithermal beams have been proposed. Of these neutron beams, three neutron beams have been selected, evaluated, and compared: (1) the operating Brookhaven Medical Research Reactor (BMRR) epithermal beam[1], (2) the designed Missouri University Research Reactor (MURR) epithermal beam[4], and (3) the accelerator-based epithermal neutron beam designed by Wu[5]. The horizontal sections of these three neutron beams are depicted in Figure 1 to Figure 3. Irradiation points for future reference are labelled as "X" in each figure. These neutron beams are compared with respect to the neutron spectra, neutron and gamma fluxes and doses, and beam directionality.

NEUTRON SPECTRA

In BNCT, for good beam penetration and low skin neutron dose, the beam will have neutrons with energies between 0.4 eV and 10 keV. But, there are always thermal and fast

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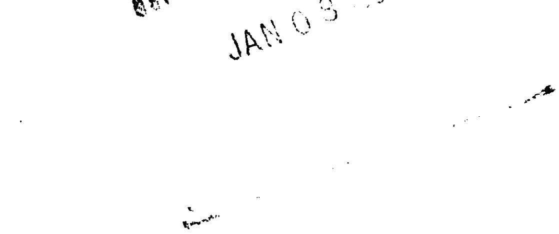

Figure 1. The Present BMRR Epithermal Beam.

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Table 1. Comparisons of Beam Parameters at the Irradiation Point "X".

	Power MW	Φ_{epi} x 10^9 n/cm^2/s	D_n/n_{epi} x 10^{-11}cGy /(n/cm^2)	D_γ/n_{epi} x10^{-11}cGy /(n/cm^2)	J/Φ
BMRR*†	3	1.2	4.8	1.4	0.67
MURR*	10	9.5	2.9	0.4	0.82
Accelerator*	10 mA	0.9	4.3	2.7	0.66

* Calculated by MCNP † Measured

neutrons associated the epithermal neutrons. The spectra at the irradiation port of these three neutron beams are shown in Figure 4. The spectra of the BMRR and MURR are similar in shape. The spectrum of the accelerator-based neutron beam has fewer high energy fast neutrons because the maximum bombarding proton energy is limited to 2.5 MeV to minimize the gamma rays produced by the higher energy protons bombarding the ^{7}Li target[5]. The neutrons coming from the ^{7}Li(p,n)^{7}Be reaction have a maximum energy of 0.79 MeV. However, because the fast neutrons between 10 keV and 100 keV are greater than the MURR and BMRR beams, the neutron dose coming from these fast neutrons compensates for the missing high energy neutrons.

Figure 2. The MURR Epithermal Beam.

Figure 3. The Accelerator-Based Epithermal Beam.

Figure 4. Comparisons of the Neutron Spectra Normalized at the Peaks.

Besides, the spectrum of the accelerator based neutron beam shows higher thermal and low energy epithermal neutrons in the beam which could be very important if the ^{10}B compound concentrates in the scalp as well as the tumor.

Comparisons of the beam parameters for these neutron beams are listed in Table 1. The BMRR has less Al in the moderator and more Al_2O_3. The Al and Al_2O_3 plates were assembled in the A and B regions of the BMRR to produce the epithermal beam. The design for the MURR, as seen in Figure 2, replaces two graphite wedges with Al wedges. Thus, the fission neutrons are directly moderated by the Al moderator. But for the BMRR beam, the fission neutrons from the core have to pass through 14 cm of graphite reflector and 19 cm of bismuth before they reach the moderator tanks, which greatly reduces the beam intensity. For 1 MW power, the BMRR has an epithermal flux 4.0 x 10^8 n/cm^2/s at "X" (177.0 cm from the core), while in contrast the MURR beam has a more intense epithermal flux of 9.5 x 10^8 n/cm^2/s at "X" (310.0 cm from the core).

FLUXES AND DOSES

The BMRR is operating at 3 MW power while the MURR is operating at 10 MW power. The accelerator-based neutron beam might be operated at 10 mA current. Under the condition of 10 ppm ^{10}B uniformly distributed through a head model, it takes about 54 minutes to deliver 2.5 x 10^{12} n/cm^2 thermal neutron fluence to the center of the head model[6], about 7 cm deep. It takes only 5 minutes for the MURR beam to reach this amount of thermal neutron fluence. For an accelerator-based neutron beam, it becomes 84 minutes to reach the goal. The irradiation time can be important but not critical, but a higher flux beam is preferred to reduce the irradiation time.

Another important comparison of the neutron beams is the neutron and gamma doses associated the beam. As seen in Table 1, the MURR beam has the lowest neutron and beam gamma doses per epithermal neutron. The neutron dose is the major dose delivered to the skin, especially due to high RBE of the epithermal and fast neutrons. The BMRR beam has the highest neutron dose per epithermal neutron of the three neutron beams, but still is a satisfactory beam for patient trials at this time. It appears that the dose to the normal brain reach the tolerance dose limit first using the BMRR beam for irradiation, so the skin dose becomes tolerable, or less than the dose limit[6]. In other words, the skin dose can be controlled under the tolerable limit.

Compared to the neutron dose, the beam gamma dose is insignificant. Taking the BMRR beam as an example, the ratio of the gamma dose per epithermal neutron to the neutron dose per epithermal neutron is 1 to 3.4. In addition, the ratio of the RBE is 1 to 3.7, so the RBE gamma dose per epithermal neutron is about 1/12 of the RBE neutron dose per epithermal neutron.

BEAM DIRECTIONALITY

The design for the MURR beam includes a long air indentation so the beam is directed. A neutron current to flux ratio of 0.82 was calculated for the MURR beam as compared to 0.67 calculated for the BMRR beam at "X". To evaluate the effects of beam directionality when the head model was irradiated by the BMRR beam from the temple side, MCNP calculations were made by using different neutron current to flux (J/Φ) ratios with the same spectrum.

The forward beam ($J/\Phi=1$) delivers a peak thermal flux 30% higher than a beam with J/Φ equal to 0.6. In the center of the brain, the difference is about 20%. Also, the forward beam gives a deeper penetration. Another way of comparison is the "neutron flux gain", which is defined as the ratio of the peak thermal flux in the head to the incident epithermal flux in air. This neutron flux gain is directly related to the beam directionality. The forward beam is expected to have a gain of about 3. The MURR beam has a gain of 2.4 while the BMRR beam has a gain of 1.8 and the accelerator-based neutron beam has a gain of 1.7. In addition, the forward beam delivers 34% less neutron dose in the skin compared to a beam of J/Φ equal to 0.6. Because of high RBE associated epithermal and fast neutrons, this reduction of neutron dose becomes another significant benefit of a forward beam.

CONCLUSIONS

Three epithermal neutron beams based on the BMRR, MURR, and an accelerator were inter-compared for different beam parameters in air at the irradiation point. The BMRR beam has the highest neutron plus gamma doses per epithermal neutron among these neutron beams but is satisfactory for patient trials by BNCT at the present time. The RBE dose delivered to the normal brain reaches the tolerance dose limit before the skin RBE dose reaches its limit, so the skin dose can be controlled under the limit. Generally speaking, a treatment can be completed in 54 minutes using the BMRR beam for irradiation at a full-power operation of the reactor.

The MURR beam has better beam parameters, including lower neutron and gamma doses per epithermal neutron, higher in intensity, and also directed. The irradiation time could be 5 minutes to complete a treatment. The accelerator-based neutron beam which has shown promising beam parameters similar to the BMRR beam could be a choice in hospitals. However, a complete systen at the required power has not yet been demonstrated.

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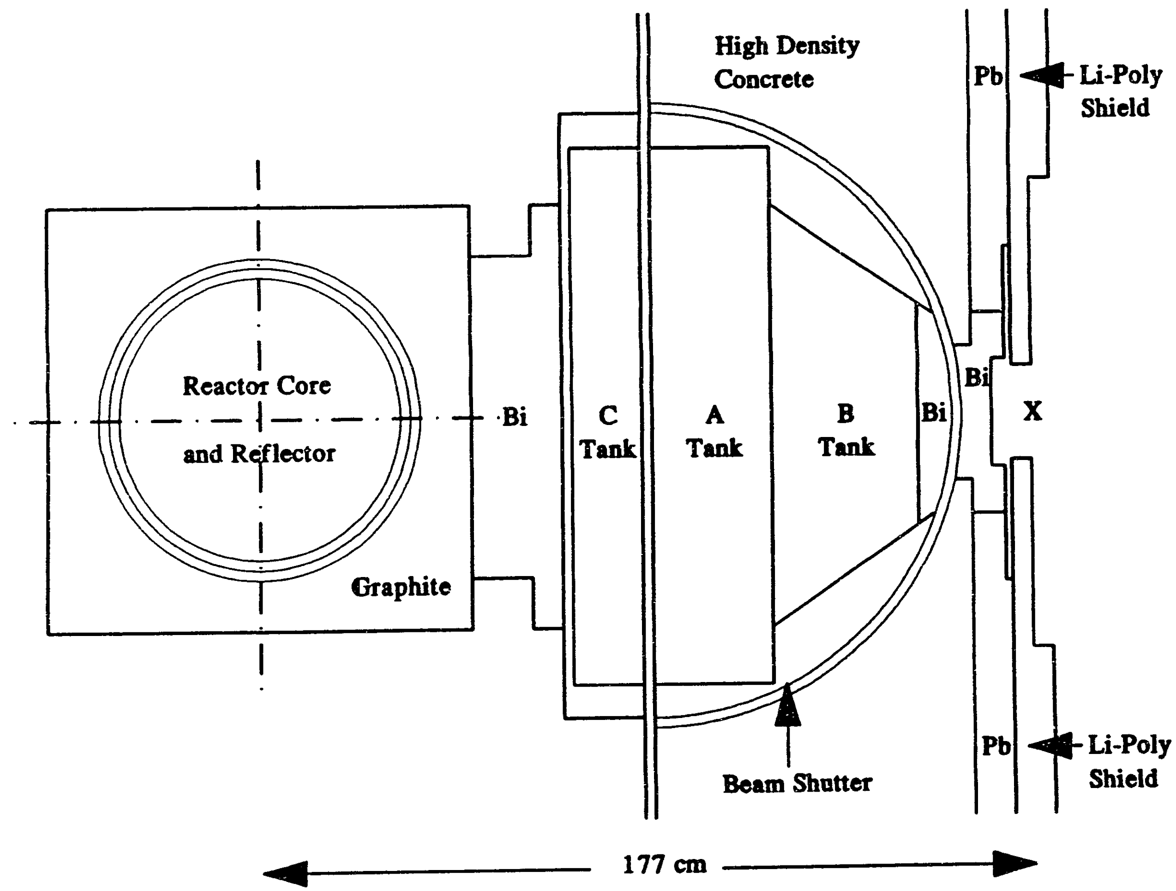
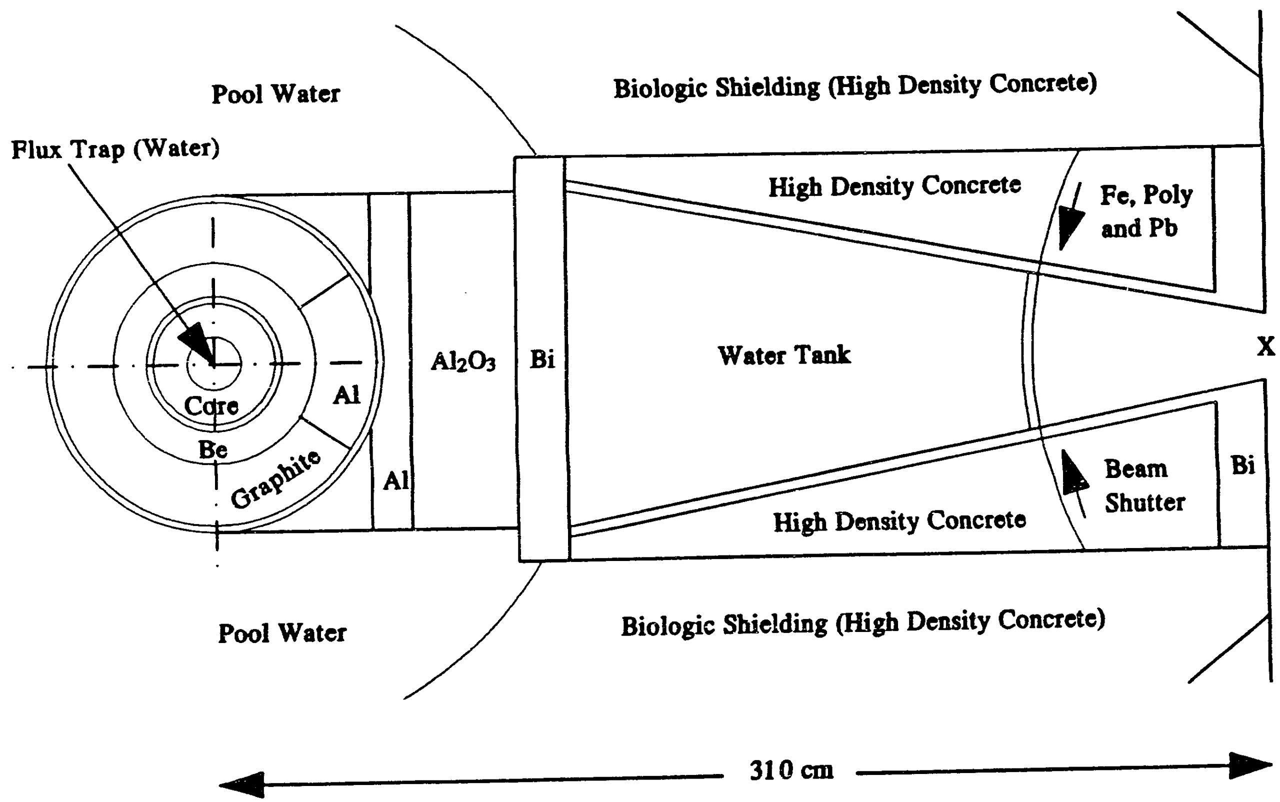
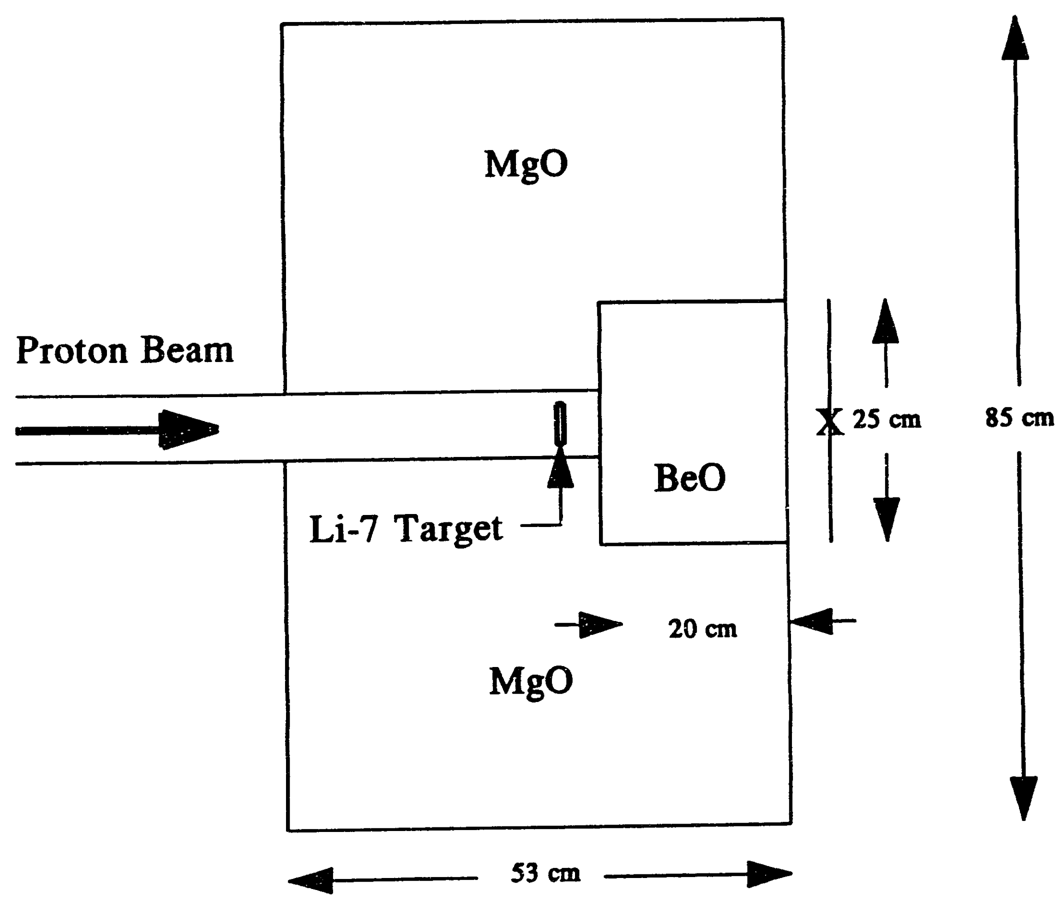
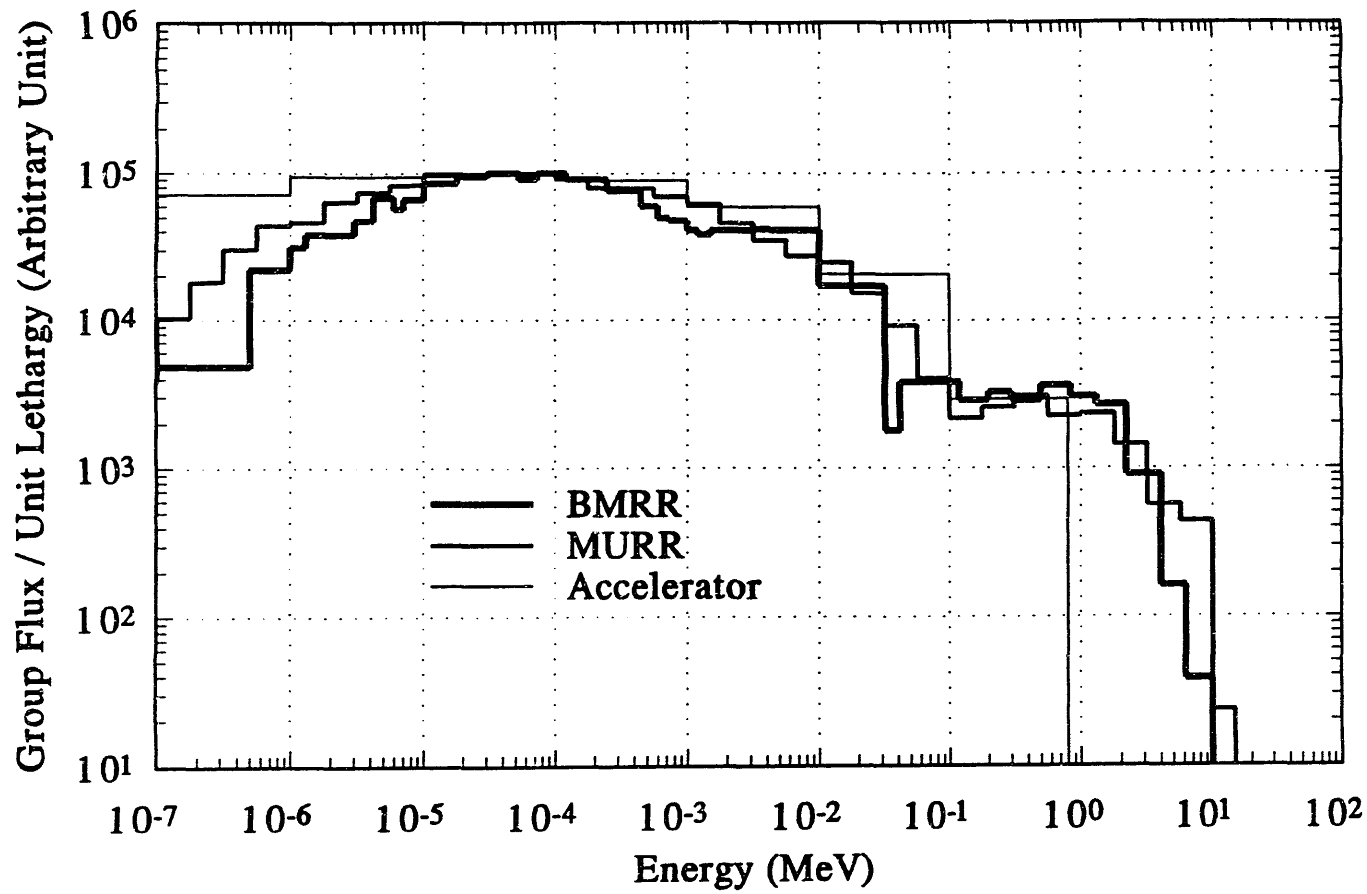


High Density
Concrete
Pb
Li-Poly
Shield
Reactor Core
and Reflector
Bi
C
Tank
A
Tank
B
Tank
Bi
Bi
X
Graphite
Beam Shutter
Pb
Li-Poly
Shield
177 cm


Pool Water
Biologic Shielding (High Density Concrete)
Flux Trap (Water)
High Density Concrete
Fe, Poly and Pb
Core
Be
Graphite
Al
Al
Al2O3
Bi
Water Tank
X
Beam Shutter
Bi
High Density Concrete
Pool Water
Biologic Shielding (High Density Concrete)
310 cm


MgO
Proton Beam
BeO
X 25 cm
85 cm
Li-7 Target
20 cm
MgO
53 cm



Group Flux / Unit Lethargy (Arbitrary Unit)
10^6
10^5
10^4
10^3
10^2
10^1
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
Energy (MeV)
BMRR
MURR
Accelerator

END

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