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DOSE CALCULATION AND TREATMENT PLANNING FOR THE BROOKHAVEN NCT FACILITY

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INTRODUCTION

Consistency of the calculated to measured fluxes and doses in phantoms is important for confidence in treatment planning for Boron Neutron Capture Therapy (BNCT) at the Brookhaven Medical Research Reactor (BMRR)[1]. Two phantoms have been used to measure the thermal and epithermal flux and gamma dose distributions for irradiations at the BMRR and these are compared to MCNP calculations. Since MCNP calculations in phantoms or models would be lengthy if the calculations started each time with fission neutrons from the reactor core, a neutron source plane, which was verified by spectrum and flux measurements at the irradiation port, was designed. Measured doses in phantoms are especially important to verify the simulated neutron source plane. Good agreement between the calculated and measured values has been achieved and this neutron source plane is now used to predict flux and dose information for oncologists to form treatment plans as well as designing collimator and room shielding. In addition, a program using MCNP calculated results as input has been developed to predict reliable flux and dose distributions in the central coronal section of a head model for irradiation by the BMRR beam. Dosimetric comparisons and treatment examples are presented.

PHANTOM CALCULATIONS

The horizontal section of the BMRR epithermal beam is depicted in Figure 1. To speed up the MCNP calculations, a neutron source plane was designed to start neutrons at the Li-poly face. The source plane combines information from both measurements and MCNP calculations, including the neutron spectrum, energy-dependent angular distributions, beam intensity profiles along the Li-poly face, and flux and dose measurements at the irradiation port. MCNP calculations with this source plane include enough backup material of bismuth and Li-poly shield behind the plane to account for scattered neutrons in the backward direction. Calculations were made to determine the flux and dose distributions in phantoms for comparisons with the measurements. Several important features in MCNP, including the thermal neutron scattering of material, hydrogen content, streaming effect, and neutron flux vs. activation relation, were carefully considered in the calculations.

PHANTOM MEASUREMENTS

One of the phantoms is a lucite ellipsoid which is represented by the equation: $(X/9.8)^2 + (Y/7.5)^2 + (Z/7.5)^2 = 1$. The dimensions of X, Y, and Z are in centimeters. Lucite rods with slits and holes to place dosimeters, like bare and Cd-covered gold foils and TLD's, can be

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Figure 1. The Present BMRR Epithermal Beam.

Figure 2. Measured and Calculated Fluxes in the Central Rod of Lucite Phantom.

inserted into the phantom for flux and dose measurement. The phantom can be used to evaluate the fluxes and doses at different depths along the central line and 4 cm off center for irradiation from two orthogonal directions. The other phantom is a cylindrical lucite container which can be filled with water. This phantom is 16.6 cm in diameter and 23 cm in length. Lucite rods with slits and holes to place dosimeters can be inserted along the central axis of the phantom for measurements. Both phantoms have been used to measure the thermal and epithermal fluxes by bare and Cd-covered gold foils and gamma doses by TLD's.

COMPARISONS OF PHANTOM DOSIMETRY

Measurements at the epithermal port taken over a 6 month time spread have shown differences of less than 3%. The comparisons of calculated to measured results are shown in

Figure 2. Up to 8 cm into both phantoms, the differences between calculated and measured thermal and epithermal fluxes at different depths are within 10%. With the simulated neutron source plane, good agreement has been obtained between calculations and measurements for two shapes of phantoms with different compositions. Thus, the neutron source plane used in the MCNP calculations was verified to be appropriate for flux and dose prediction in models.

TREATMENT PLANNING

Based on the consistency of phantom dosimetry, the neutron source plane was used with a head model to calculate the flux and dose distributions. This model has been used to develop treatment planning for BNCT by Zamenhof et al.[2] Besides the two ellipsoids separating the brain and skull areas, a layer of tissue equivalent material with higher hydrogen density is attached to the skull to evaluate the skin dose, especially the fast neutron dose.

The central coronal section of the head model was divided into many cells in the MCNP calculations. In Figure 3 is shown the horizontal section of the head model calculation setup in MCNP simulating a patient who is lying on the treatment table and facing up. The fluxes and doses in each cell were calculated by MCNP. When the BMRR beam comes from the left side of the head, the direction is designated as 0 degree. When the beam comes from the top of the head, it is a 90 degree irradiation. Rotation of the head to the right side for irradiation, makes the beam incident at 180 degrees. Several MCNP runs were completed with statistical error of thermal flux calculation in each cell reduced to less than 3%. Then a program was written to use polynomial equations fitting the flux and dose information in each cell as a function of angle. The program is based on these polynomial equations to calculate the flux and dose distributions in each cell in the central coronal section of the head model. Different combinations of head orientations and irradiation weighting factors can be input to optimize an irradiation setup. The RBE's factors of different dose components can be input to calculate the total RBE dose in each cell, so the irradiation time can be calculated based on tolerance dose limit in critical areas.

Figure 4 shows an example of dose calculations for treatment planning. After the tumor area and boron concentration and distribution are determined or approximated, the total RBE dose in each cell is calculated for irradiation by a 60 degree beam. Then the total RBE dose in each cell is normalized to the Minimum Tumor Dose (MTD) which is identified as 100%. By applying the tolerance dose limit, the MTD can be determined. The Maximum Skin Dose (MSD) can be

Figure 3. The Calculation Arrangements for the Head Model in the MCNP Calculation.

determined separately and also the irradiation time. As seen in Figure 4, a 2 x 2 x 2 cm^3 tumor with a uniformly distributed ^{10}B concentration of 30 ppm is assumed and the rest of the head has a ^{10}B level of 10 ppm. The tumor is irradiated by the BMRR beam coming from 60 degrees. Based on 10 RBE-Gy tolerance dose limit in the hypothalamic zone[3], the MTD is calculated as 38 RBE-Gy with a 54-min irradiation at 3 MW power of the BMRR. The MSD is 14.6 RBE-Gy. Here the RBE's were assumed 2.5 for ^{10}B reactions, 4.5 for fast neutron and nitrogen reactions, and 1 for gamma ray reactions.

Figure 4. The Dose Calculations for the Assumed Tumor in the Head Model.

CONCLUSIONS

Two phantoms, an elliptical lucite phantom and a cylindrical water phantom, have been used for dosimetric measurements to verify the MCNP calculated results using a simulated neutron source plane. Repeated measurements have been made with reliable reproducibility. The agreements between the measured and calculated values are good. Thus, based on the consistency of comparisons, the simulated neutron source plane was used with the head model to predict flux and dose distributions in the head model. A program was created to calculate the flux and doses of each component in the central coronal section of the head model for irradiation by the BMRR beam. Different combinations of head orientations and irradiation weighting factors can be combined to better predict the dose distribution. Once the tumor area and ^{10}B concentration and distribution were determined, a simple but reliable treatment planning can be made to predict an preliminary irradiation setup.

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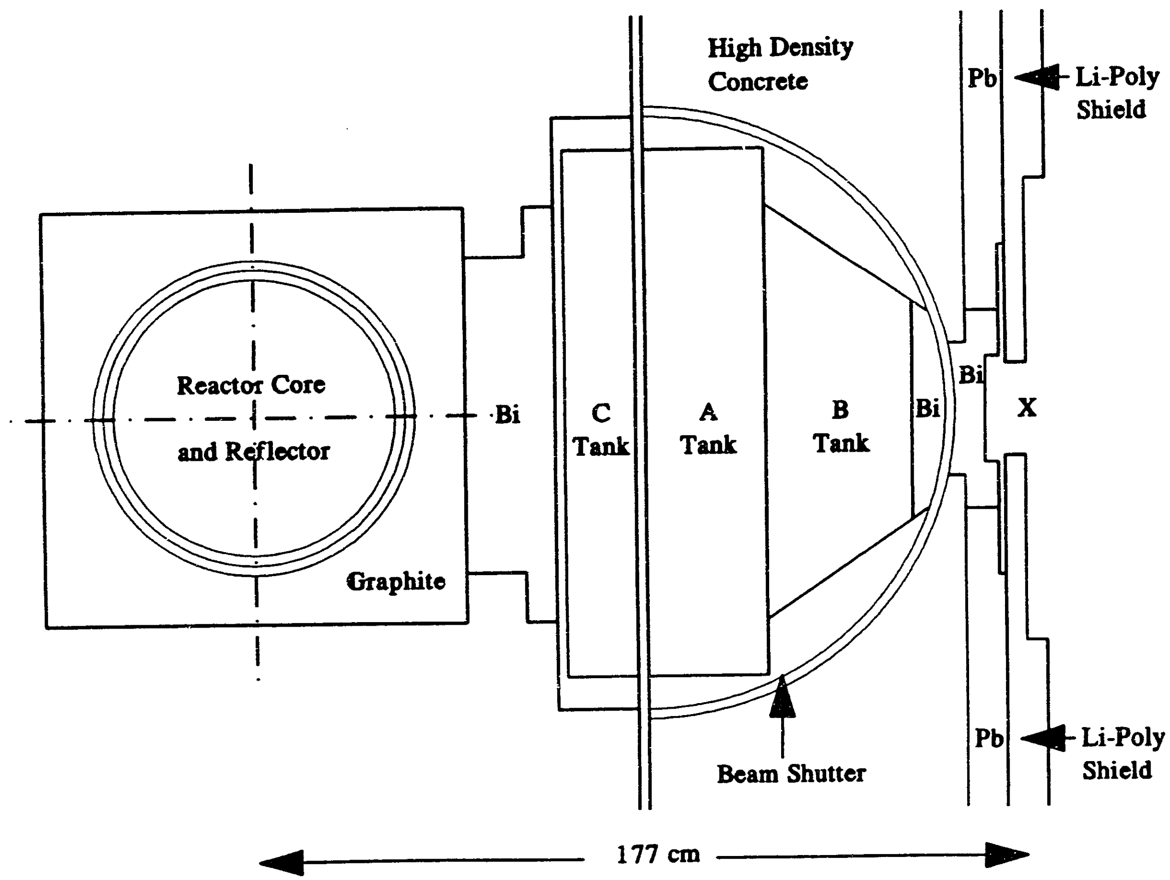
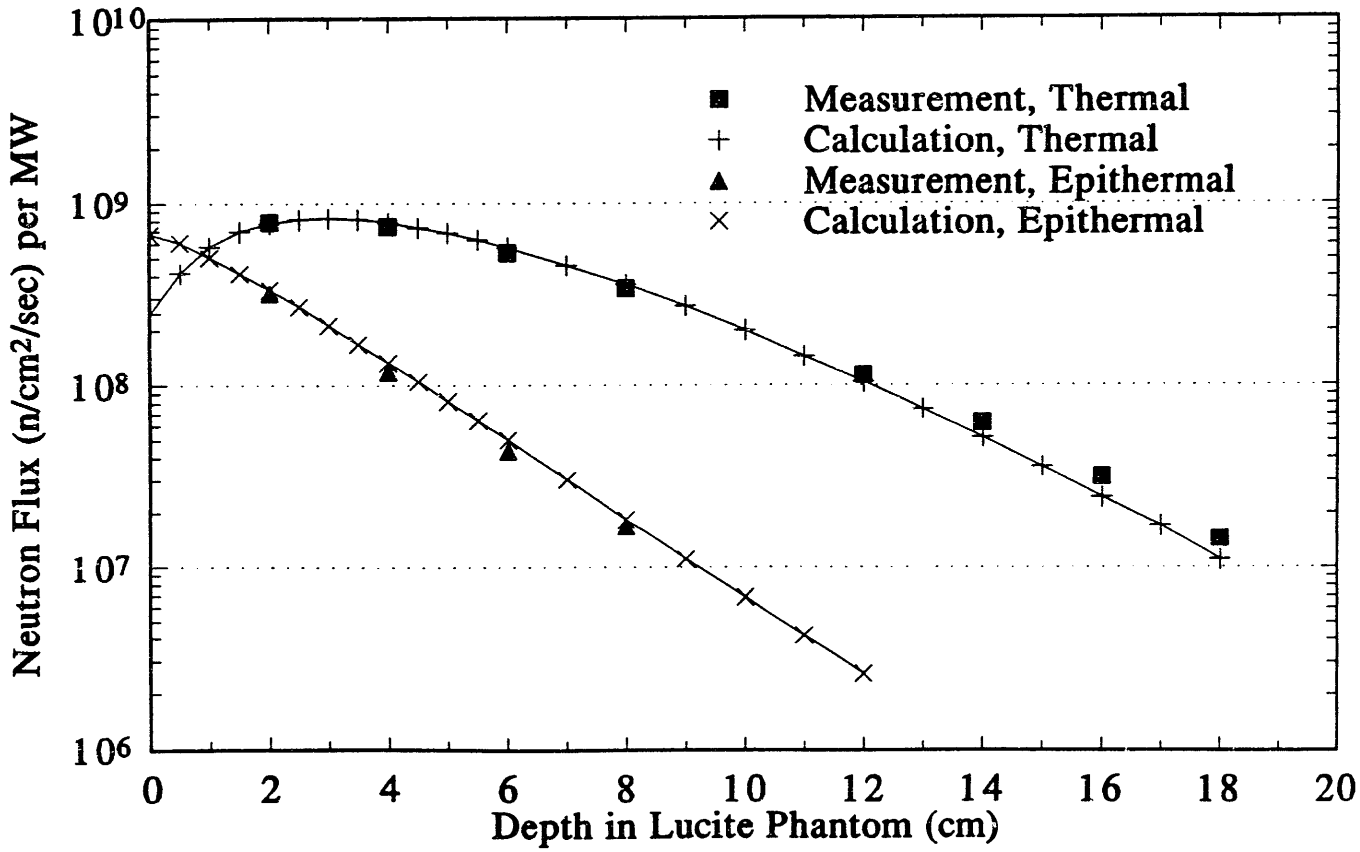
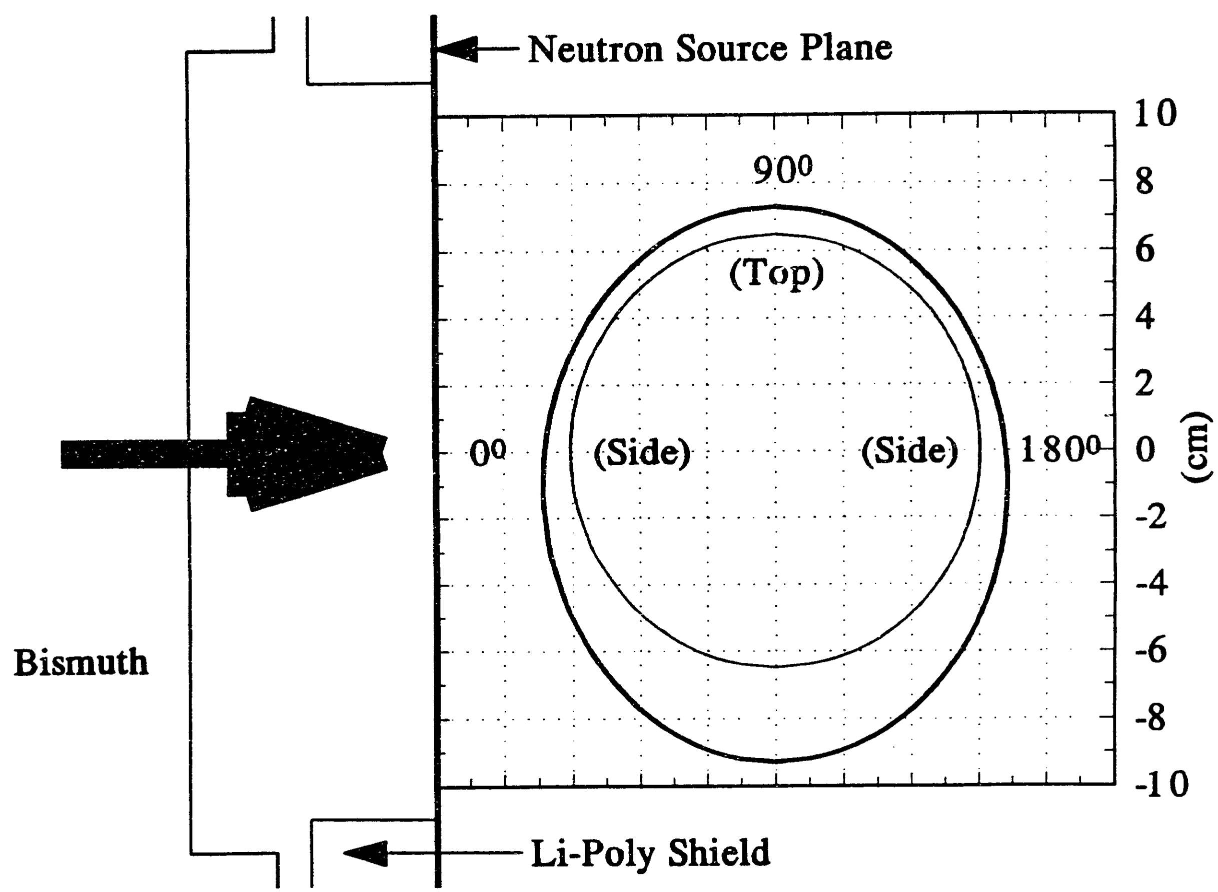
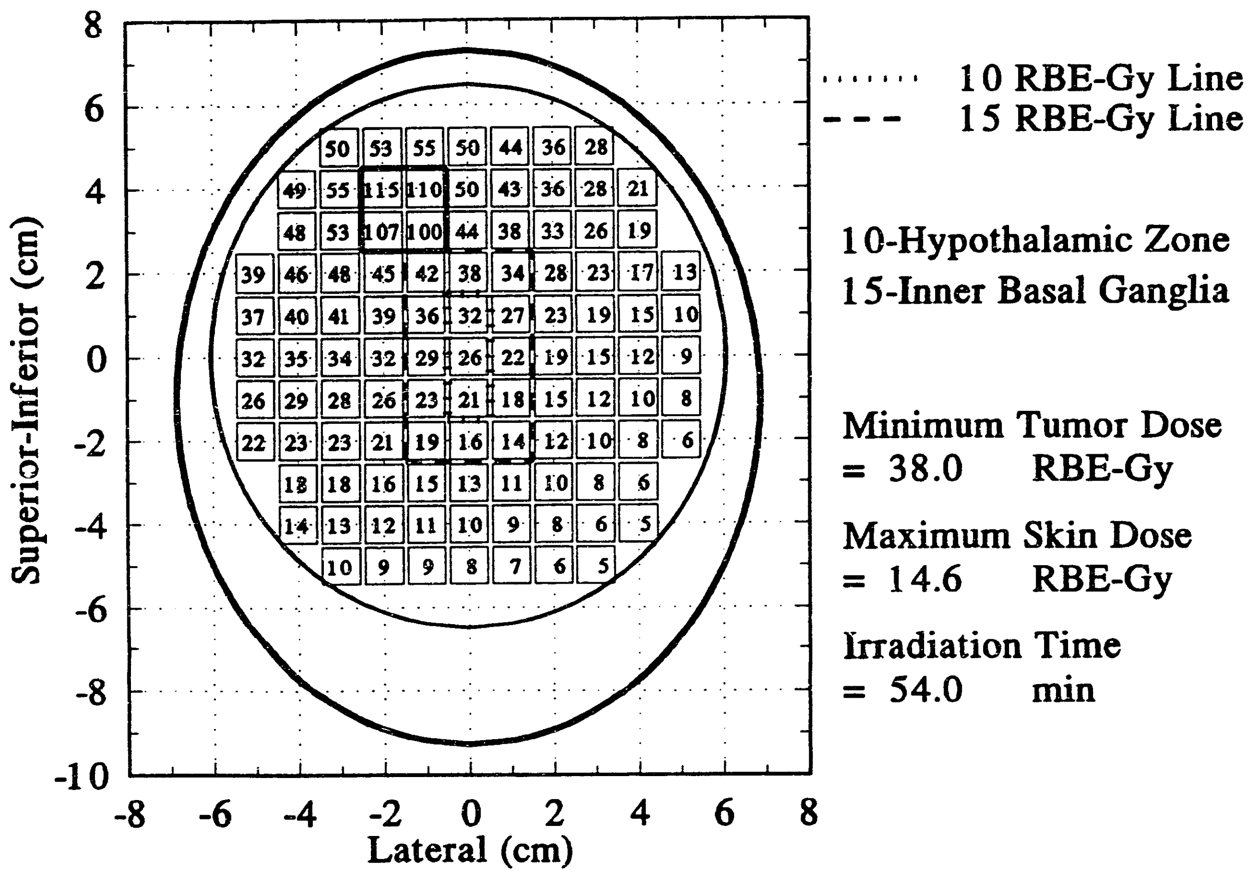


High Density
Concrete
Pb
Li-Poly
Shield
Reactor Core
and Reflector
Bi
C
Tank
A
Tank
B
Tank
Bi
Bi
X
Graphite
Beam Shutter
Pb
Li-Poly
Shield
177 cm


Measurement, Thermal
Calculation, Thermal
Measurement, Epithermal
Calculation, Epithermal
Neutron Flux (n/cm2/sec) per MW
Depth in Lucite Phantom (cm)
10^10
10^9
10^8
10^7
10^6
0
2
4
6
8
10
12
14
16
18
20


Neutron Source Plane
10
8
6
4
2
0
-2
-4
-6
-8
-10
(cm)
90⁰
(Top)
0⁰
(Side)
(Side)
180⁰
Bismuth
Li-Poly Shield



Superior-Inferior (cm)
Lateral (cm)
10 RBE-Gy Line
15 RBE-Gy Line
10-Hypothalamic Zone
15-Inner Basal Ganglia
Minimum Tumor Dose
= 38.0 RBE-Gy
Maximum Skin Dose
= 14.6 RBE-Gy
Irradiation Time
= 54.0 min

Fig 4

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