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Epithermal Neutron Flux Enhancement Using SMA in Designing a Cf-Based Neutron Beam for BNCT

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Abstract

Great interest has prompted Boron Neutron Capture Therapy (BNCT) as a new treatment for brain tumors. The use of ^{252}Cf as a neutron source for BNCT makes the in-hospital treatments of tumors to be possible. Newly proposed subcritical multiplying assemblies (SMA) are explored to improve relatively low neutron fluxes of the source and construct the feasibilities of ^{252}Cf as a neutron source. The MCNP code has been used to evaluate the effective multiplication factor of the entire system and the intensities and percentages of epithermal neutron flux at the patient-end surface of the system. The neutron beam using SMA shows the epithermal neutron flux enhancement of about 13 times as large as the beam without using SMA. It is expected that the neutron beam proposed in this research will be more effective for treatment of tumors due to the increased therapeutic neutron fluxes.

I. Introduction

Boron Neutron Capture Therapy (BNCT)(1,2) has the potential to be a very effective treatment of brain tumors or other inoperable tumors. Conventional treatment of tumors, surgery or other radiation therapy, could be costly or even ineffective for particular types of cancer and the conventional radiation therapy may result in damage in the normal tissue cells by unnecessary irradiation. The goal for epithermal neutron beam design for BNCT is to generate a neutron beam with enough intensity to provide therapy while minimizing patient risk and discomfort.

The use of ^{252}Cf as a neutron source, which has been first proposed by J. K. Kim et al.(3,4), could offer a more practical means for therapy. They have showed new possibilities in using ^{252}Cf and have performed optimal design of the epithermal neutron beam for BNCT. However, ^{252}Cf source requires much longer time needed for effective therapy since the neutron fluxes of the source are admittedly far too low for treatment of tumors compared with other neutron sources, reactor beam(5) or accelerator beam(6). Subcritical multiplying assemblies (SMA) are, therefore, explored to provide a remedy for the drawback and construct the feasibilities of ^{252}Cf as a neutron source for BNCT.

In this study, a new type of the SMA is proposed to increase the effective multiplication factor, k_{eff}, of the entire system, i.e. to enhance the neutron fluxes of the system. All neutron beam design procedures are performed by the MCNP(7) code, Monte Carlo N-Particle Transport Code, simulations. The intensities and percentages of epithermal neutron fluxes at the patient-end surface of the system are evaluated and compared with the results in the beam without using SMA.

II. Boron Neutron Capture Therapy (BNCT)

Boron Neutron Capture Therapy (BNCT) is potentially an important method of treating certain types of tumors that cannot be treated by surgery or other conventional treatment. BNCT consists of the selective loading of a tumor with a substance having a high neutron capture cross section, ^{10}B, and subsequent irradiation with thermal/epithermal neutrons. The neutron capture reaction with boron that allows BNCT is as follows:

$$^{10}B + n \rightarrow {}^{7}Li + \alpha \qquad Q = 2.339\ MeV$$

The boron has a 3837 barns neutron absorption cross section for thermal neutrons. This is much higher than the neutron absorption cross section for other elements in the brain, which are typically much less than a barn. The ranges of the recoiling lithium and the alpha particle are small enough, 5μm and 9μm respectively. These ranges are less than or comparable to the diameter of a red blood cell, and therefore the entire amount of energy can be absorbed in one cell or a cell and its nearest neighbors, depending upon the location of the ^{10}B in the cell. This energy deposition can completely kill the cell.

In order to provide a significant therapeutic effect, the boron must have a high concentration in the tumor and the neutron beam at the tumor position must consist primarily of low energy neutrons that will readily interact with the boron. An acceptable neutron beam design for BNCT must be concerned with three factors. First, the gamma contamination should be as low as possible. Secondly, neutron energy must be favorable for BNCT while at the same time removing the dangerous high energy neutrons and the damaging incident thermal neutrons, which would cause a high surface dose to a patient. Previous works(8) indicates that the best energy range for BNCT is a 4 eV to 40 keV epithermal neutron beam. Finally, the total dose rate delivered at the therapy point must be high enough to allow effective therapy in a reasonable exposure time.

III. Method

The primary computational design tool in this study is a three dimensional, pointwise-continuous energy cross section Monte Carlo code, MCNP 4A, capable of performing neutron, photon, or coupled neutron/photon transport. The neutron energy spectrum for the ^{252}Cf source is modelled as a Watt fission spectrum using coefficients provided with the MCNP code.

The purpose of the subcritical multiplying assemblies (SMA) is to enhance the neutron fluxes at the patient-end surface of the beam assembly. Incorporation of the SMA into the design involves using fissionable material, ^{235}U, to provide a secondary source of neutrons. For subcriticality, the assembly is designed with an effective multiplication factor, k_{eff}, less than 1.0 (which avoids most of the safety, environmental, siting, and operational problems inherent in fission reactors). For an SMA, the neutron population is multiplied by a factor of $1/(1-k_{eff})$. Neutron source multiplications of up to 90 have been shown to satisfy the non-reactor criterion. Bare uranium dioxide fuel (UO_2) having 20% enriched U-235 is adopted for the SMA. The geometrical model of the SMA is a hexagonal array of 168 UO_2 fuel rods with a 2.5 cm pitch and a 0.5 cm surface separation between cylinders as shown in Figure 1. The k_{eff} was calculated to be 0.9561 for the SMA described above. This implies that the neutron population is multiplied by a factor of 22.8.

The design work for optimization is increasing the intensities and percentages of the neutron flux in the epithermal therapy range at the patient-end surface of the beam assembly while reducing the fast neutron flux at the same location. The optimum dimensions of only D_2O moderators were determined in an iterative MCNP runs(3) and the optimum dimensions of other parameters are currently underway to calculate. In addition, the chopped cone-shaped Al filter is newly proposed to follow the aperture of irradiation port having been optimized previously(3), 11 cm in radius.

All MCNP tallies are normalized to per starting particle. For most of the study, enough source particles were used, when possible, so that the overall error for each case was less than 5% and the individual error for each energy bin was less than 10%.

IV. Results and Conclusions

Design parameters, having been determined above, were configured into a neutron beam assembly. A diagram of the proposed Cf-based epithermal neutron beam system for BNCT using subcritical multiplying assemblies (SMA) is presented in Figure 2. This design does not take into account the additional shielding materials and the fission heat calculations of the SMA core.

Table 1 shows the comparison of neutron fluxes and its percentages at the patient-end surface for a beam without using SMA, a beam proposed initially, a beam optimized for D_2O moderator dimensions only, and a beam with a chopped cone-shaped Al filter. The neutron beam using SMA shows the epithermal neutron flux enhancement of about 13.22 times as large as the beam without using SMA. It is expected that this enhancement will cause an astonishing gain in dose rate in the head phantom. With this approach, the use of ^{252}Cf becomes feasible as a source of epithermal neutrons for BNCT.

All design parameters must be optimized to complete the design work and the dosimetric properties of this design must be acceptable for BNCT. These calculations are currently underway to acquire the optimized beam configuration for an epithermal neutron beam for BNCT. The prospect of using a ^{252}Cf source and SMA in designing a beam for BNCT is an exciting proposition that should be continued in future work.

References

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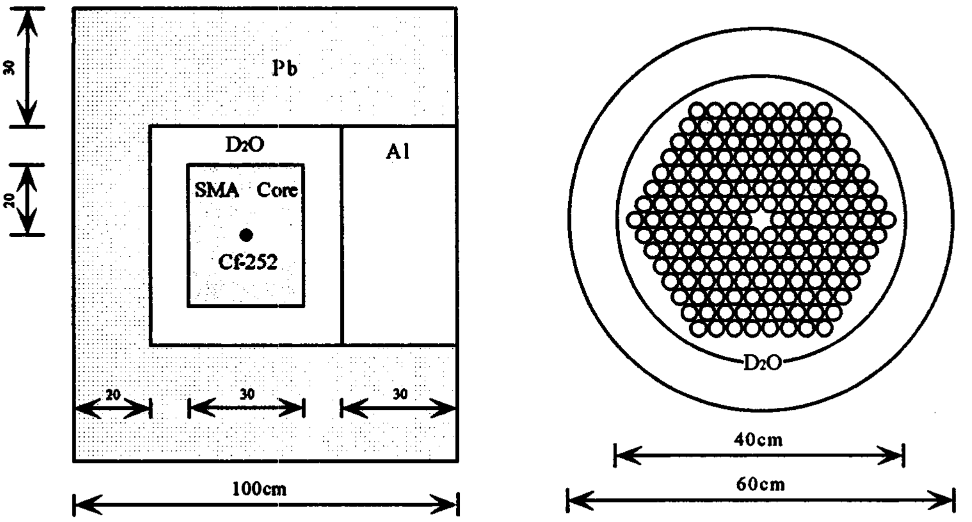
Table 1. Comparison of Neutron Fluxes and Its Percentages at the Patient-end Surface for Each Beam

Neutron Energy, MeV	Thermal (0~4E-6)	Epithermal (4E-6~4E-2)	Fast (4E-2~20)	Total	Epithermal Neutron Enhancement*
No SMA	4.18206E-5 (37.83%)	5.78821E-5 (52.35%)	1.08559E-5 (9.82%)	1.10559E-4	1.00
Proposed Initially	1.85978E-4 (30.93%)	3.64771E-4 (60.67%)	5.04614E-5 (8.39%)	6.01210E-4	6.30
Optimized for D_2O	1.18569E-4 (18.89%)	4.23608E-4 (67.48%)	8.55334E-5 (13.63%)	6.27710E-4	7.32
Cone-Shaped Al Filter	1.85580E-4 (16.76%)	7.65460E-4 (69.11%)	1.56543E-4 (14.13%)	1.10758E-3	13.22

* The ratio of the epithermal neutron fluxes for each beam assembly to the epithermal neutron flux for a beam without using SMA



(a) The midplane horizontal view of the assembly (b) The midplane vertical view of the SMA core (Lattice pitch=2.5cm, Rod diameter=2.0cm)

Figure 1. The Geomctrical Model of the Beam Assembly Initially Proposed

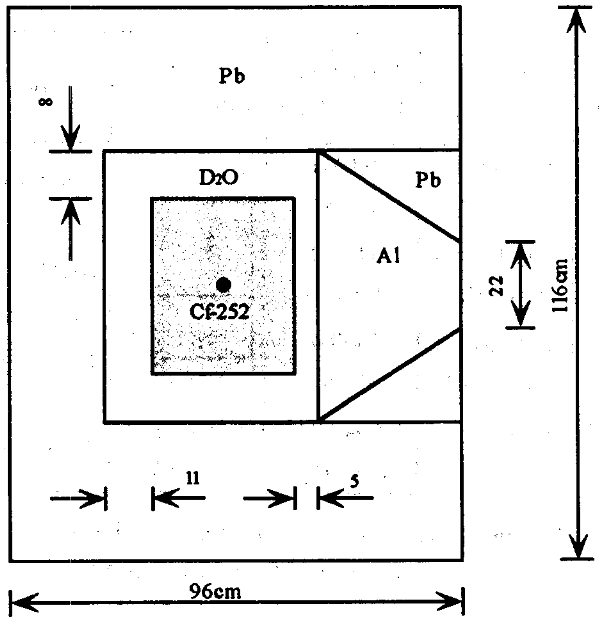


Figure 2. The Geometrical Setup of the Beam Assembly