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AN ACCELERATOR NEUTRON SOURCE FOR BNCT

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The objectives of the research project are restated here, as they appeared in the abstract of the research proposal:

" The objectives of this proposal are twofold. One objective is to design and test (using the OSU Van de Graaff accelerator) a moderator assembly for a thermal neutron source for the treatment of superficial tumors by Boron Neutron Capture Therapy. We will identify the currrent of 2.5 Mev protons which is necessary to treat a patient in less than one hour. Our second objective is to design and thermally test a target for our thermal and epithermal source of neutrons for BNCT."

Our work to date in fulfilling these project goals is described below.

I. NEUTRONIC DESIGN

I.A. INTRODUCTION

Boron Neutron Capture Therapy is presently being considered as a means for treating two types of tumors: glioblastoma multiforme and malignant melanoma. Compounds are being developed [1], and successes have been reported [2,3] for both tumor types.

The characteristics of the neutron sources for the treatment of glioblastoma multiforme and melanomas may be very different, because glioblastoma multiforme occurs within the brain, while some melanomas spread superficially at the skin level. For glioblastoma multiforme the source neutrons should have energies in the range of 1 eV to 1 keV, in order to penetrate to the tumor in large numbers, without depositing too much energy at the skin's surface. For superficial melanomas, a thermal neutron source is most appropriate; while for deep melanotic lesions, a spectrum which is nearly as energetic as that which is used in the treatment of glioblastoma, may be appropriate.

If BNCT is to be widely used to treat glioblastoma multiforme and melanomas, then due to public concerns about siting reactors in hospitals, accelerator-based sources of neutrons are necessary [4]. We have previously designed a moderator assembly for an accelerator-based epithermal neutron irradiation facility (AENIF) for the treatment of glioblastoma moderator [5]. It was found that the requirements of the accelerator imposed by limits for beam quality and irradiation time are not unreasonable in light of recent advances in radio frequency quadrupole (RFQ) technology at Los Alamos Scientific Laboratory.

A purpose of our research is to design a moderator assembly for an ATNIF for the treatment of superficial melanoma and to integrate this design with the design of a moderator assembly for an accelerator epithermal neutron irradiation facility (AENIF) for the treatment of glioblastomas.

IB. BACKGROUND

The moderator assemblies for the AENIF and ATNIF are based upon 2.5 MeV protons striking a 5 cm diameter ^{7}Li target to produce neutrons. The target total neutron yield is 1.12×10^{-4} n/proton [5]. The target neutrons are emitted with a maximum energy of about 800 keV. The most energetic target neutrons are emitted in the direction of motion of the proton beam, while less energetic target neutrons are emitted at wider angles. About one-fifth of the target neutrons are emitted in backward directions.

The AENIF moderator assembly is designed to transmit to the patient a large fraction of the target neutrons, degraded in energy to between 1 eV and 10 keV. Basically the AENIF moderator assembly consists of a cylinder of BeO, which is 25 cm in diameter and 22.5 cm in height, surrounded by a 30•cm•thick alumina reflector. Also, 0.01 g/cm^{2} of ^{6}Li is placed at the moderator assembly exit window to reduce thermal neutron contamination at the irradiation point [5] (a point on the centerline of the moderator assembly 3 cm from the exit window).

The moderator assembly yields at the irradiation point, an epithermal neutron flux of 3.1 x 10^7 n/cm^2•s per mA of proton current, with a neutron kerma to fluence ratio of 4.9 x 10^{-11} cGy•cm^2/n for a differential element of tissue at the irradiation point. The maximum absorbed dose rate to a tumor, in a 9 cm radius spherical head phantom, occurs at a depth of 3.5 cm, and is 3.4 x 10^{-4} Gy/s per mA of proton current for a ^{10}B concentration of 30 μg/g tumor. Therefore, for a single session irradiation of 20 Gy to the tumor, the treatment time is about 100 min for a 10-mA beam, and about 33 min for a 30 mA beam [5].

In order to determine whether the treatment of glioblastomas or superficial melanomas requires a greater proton current, design calculations similar to those which have been performed for an AENIF for the treatment of glioblastomas are repeated for an ATNIF for the treatment of superficial melanomas. These design calculations are described and evaluated in the following sections.

I.C. ATNIF MODERATOR ASSEMBLY DESIGN

I.C.1. Design Criteria

The design criteria for the ATNIF moderator assembly is that the thermal neutron flux be as large as possible, and that the contamination of the thermal neutron field by fast and epithermal neutrons and gamma rays be as small as possible.

I.C.2. ATNIF Moderator Material Selection

The ATNIF moderator assembly is geometrically very much like the AENIF moderator assembly. It consists basically of a cylinder of moderator 30 cm in diameter, of unknown thickness, surrounded by a reflector, with an axial height and radial thickness which must be determined.

D_2O was chosen as the moderator,based on its large moderating power and its small macroscopic cross-section for radiative capture of thermal neutrons.

I.C.3. Reflector Material Selection

The selection of the ATNIF moderator assembly reflector material is based upon a calculation of the albedo (b) of an axially infinite cylindrical reflector. Only low mass number reflectors were considered, because we want the reflector to moderate any fast or epithermal neutrons while reflecting them back into the system. For very thick reflectors, D_2O has the largest albedo. However, for reflectors up to 60 cm thick, the albedo for graphite is larger than the albedo of D_2O . For very thin reflectors, the albedo is largest for BeO and Be. Unfortunately, BeO and Be are very much more expensive than graphite; and so we have chosen graphite as the reflector material since it is not clear, at this point in time, that it is necessary to have a very thin reflector. Since 40 cm of graphite yields a value of the albedo which is within 5% of the albedo for an infinitely thick graphite reflector, we chose 40 cm as the thickness of graphite reflector around which to begin our optimization of the ATNIF moderator assembly.

I.C.4. Calculational Methods

The neutronic calculations consist of two parts: (1) neutron source generation in the lithium target, and (2) coupled neutron and gamma-ray transport in the moderator assembly and phantom. Neutron generation in the lithium target was calculated by simulating the production of neutrons as protons slow down in the target, using the doubly differential cross section [6] for the $^7Li(p,n)^7Be$ reaction, and the stopping power for protons in lithium[7].

The coupled neutron and gamma-ray transport calculations in the ATNIF moderator assembly and phantom were performed using the three-dimensional multigroup Monte

Carlo code MORSE-CG [8]. The neutron energy and direction at the beginning of each history were selected probabilistically on the basis of the calculated neutron generation in the lithium target.

I.D. RESULTS

Figure 1 illustrates our optimized ATNIF moderator assembly and a rectangular parallelepiped phantom. The thermal neutron fluence where the assembly centerline intersects the phantom surface is $(3.5 \pm 0.3) \times 10^{-4}$ neutrons/(cm^2•target neutron). For a 2.5 MeV proton beam producing 7.0×10^{11} target neutrons/(sec•mA), the thermal neutron flux is $(2.5 \pm 0.2) \times 10^8$ neutrons/(cm^2•sec•mA). The absorbed dose rates to tissue at the phantom surface with a ^{10}B concentration of zero are (0.47 ± 0.03) cGy/(min•mA) for neutrons and (2.0 ± 0.4) cGy/(min•mA) for gamma-rays. The boron absorbed dose rate to tumor at the phantom surface is (3.2 ± 0.2) cGy/(min•mA) for a tumor ^{10}B concentration of 24 μg ^{10}B per gram of tumor,which is the ^{10}B concentration which has been reported for human melanoma which have been treated with BNCT [3]. The corresponding total (i.e. neutron plus gamma plus boron) dose equivalent rate to the tumor is 10.1 cSv/(min•mA). At this dose equivalent rate, the time which it takes to deliver 40 Sv to the tumor (the dose equivalent recommended for the cure of the melanoma lesion [3]) is 13.2 minutes for a 30 mA proton beam. For a tumor dose of 40 Sv, the corresponding total dose equivalent to normal tissue with a ^{10}B concentration of 3 μg ^{10}B per gram is 15 Sv. This is less than the 18 Sv normal tissue tolerance dose equivalent recommended in Ref. 3; and is another indicater of the adequacy of our ATNIF thermal neutron field for the treatment of melanoma.

We conclude that from a neutronic standpoint, a 30 mA 2.5 MeV proton accelerator can be used to treat both superficial and deep lesions from melanomas and gliomas. Different moderator assemblies are necessary for the optimal treatment of these tumor types. We have presented in this paper the two extremes; a moderator assembly for superficial tumors and our previously designed moderator assembly for deep tumors. Optimal moderator assemblies for tumors of intermediate depths must yet be designed.

II. NEUTRONIC TESTING

As a first step towards developing a predictive capability for the thermal neutron distributions inside a head phantom, we have made thermal neutron dose measurements inside three rectangular parrallelapiped water phantoms using the OSU Van de Graaff accelerator and an existing simple moderator assembly for an epithermal neutron source. The purpose of these measurements is to assure ourselves of the accuracy of our Monte Carlo neutron transport calculations for predicting the thermal neutron fluence. A BF3 detector with a small active volume was used along with a scanning system to scan the phantoms. A representative set of Depth Dose curves and Dose Profiles are shown in Figs 2 and 3. Work is currently in progress to use Monte Carlo codes to calculate these dose distributions to see how well they conform with the measured distribution. Since the thermal neutron distributions are of ultimate interest in tumor treatment using BNCT, developing a predictive capability for the different neutron beams designed by us is very important .

III. NEUTRONIC CALCULATIONS IN SUPPORT OF TARGET THERMAL-HYDRAULIC DESIGN

As part of the target thermal-hydraulic design study, Monte Carlo studies to determine neutronically acceptable target areas must be performed (the calculations which are presented above are based on a 5 cm diameter target); since the beam heat flux, and hence the thermal design challenge, decreases inversely with the target area. Adopting a standard engineering approach, we have de-coupled the problems of moderator assembly design from target design.

The neutron fluence is plotted versus the Li target radius in Fig. 4. From the figure we can see that the epithermal and thermal neutron fluences reach their maxima for a target radius of about 4 cm. For target radii greater than about 4 cm the epithermal and thermal neutron fluences decrease with increasing target radius. For example the epithermal neutron fluence decreases by about 38% as the target radius increases from 2.5 cm to 10.16 cm (8" diameter). Such a decrease in the epithermal neutron flux would cause the irradiation time to increase by about a factor of 1.6, and a one-half hour irradiation would increase in length to about 50 minutes.

Examining Fig 4. more closely one sees that the ratio of the thermal to the epithermal neutron flux increases for target radii greater than 4 cm. This is not good, because it means that the neutron field is more contaminated with thermal neutrons. These thermal neutrons can be filtered out by increasing the thickness of lithium-6 at the moderator assembly irradiation port; but such filtering of thermal neutrons unavoidably decreases the epithermal neutron flux. Instead we must see if reducing the thickness of moderator material in the moderator assembly can compensate, in part, for the decrease in the epithermal neutron flux and the increase in the thermal neutron flux, which is a consequence of increasing the target radius. Our estimate of an increase in the treatment time by a factor of about 1.6 is preliminary. A true comparison of the increase of the treatment time with an increase in the target radius must be based on comparing targets of different radii and their corresponding moderator assemblies, where the thickness of the moderator material in the moderator assembly is adjusted, for each target radii, to yield approximately equivalent neutron fields.

From the above discussion it is clear that the design of a moderator assembly is coupled with the design of a target heat rejection system, since larger targets are easier to cool but are inferior from neutronic considerations. Besides this unavoidable coupling of the designs, we envision coupling these two designs by having D_2O moderator serve as the working fluid in the primary of a target heat rejection system. We describe below our preliminary target assembly designs.

IV. TARGET DESIGN AND THERMAL-HYDRAULIC ANALYSIS

Table 1 is a summary of high power deposition accelerator targets and their operating parameters. The Canutron target is designed to be liquid Li with a Be substrate. It is designed to dissipate 25kw, which is 1/3 of the power which our target must dissipate. As part of a report on the Canutron [9], an accelerator neutron source for industrial thermal neutron irradiation application, Ref. 9 describes a thermal-hydraulic analysis for a 10 mA average current of 2.5 MeV protons distributed over a 80cm non-flowing liquid lithium target . The range of a 2.5 MeV proton in liquid lithium is approximately 250 mm [7]. The lithium thickness of the target is greater than this (~1mm), although only the first 90 mm contribute to neutron production, since the threshold for the $^7Li(n,p)^7Be$ reaction is 1.88 MeV [6]. Although the liquid lithium temperature significantly exceeds the lithium melting temperature of 180 °C in the CANUTRON design, it is not so large that the evaporation rate of lithium atoms from the target surface is unacceptably high. The CANUTRON target design provides a starting point for the design of an ATNIF target.

The FMIT target was designed to be a liquid lithium jet[10] for use with a 20~35 Mev 100 mA beam depositing 2~3.5 MW in the target. The beam power deposition is approximately 50 times larger for the FMIT target than for our target. We conclude that it is unnecessarily complex for our application, and perhaps even not appropriate since our power is deposited much more superficially. Finally, the RTNS target was designed and operated as a rotating titanium tritide target on a copper alloy substrate [11]. The target successfully dissipated 52 kW of beam heat which was deposited more superficially than for our beam . We conclude that a rotating solid lithium target would probably successfully dissipate 75 kw of beam heat. However because of the mechanical complexity of rotating targets we have chosen to first examine the potential of non-rotating targets.

TABLE 1. SUMMARY OF TARGETS

TARGET	CURRENT	ENERGY	POWER	RANGE PROTON	TARGET AREA
Liquid Li Be Backing Canutron 1983	10 mA	2.5 MeV proton	25 kW	~ 250 mm	80 cm^2
FMIT Liquid Li jet	100 mA	20 ~ 35 MeV proton	2000 kW ~ 3500 kW	few cm	~ 6 cm
RTNS Titnanium Tritide on Copper Alloy	130 mA	0.4 MeV deuteron	52 kW	like 0.2 MeV proton ~15 mm	beam area ~ 1 cm^2

Dr. Richard Christensen is examining non-rotating solid lithium targets and Dr. Kambiz Vafai is examining non-rotating liquid lithium targets. Dr. Vafai's preliminary target design and assessment are included in this proposal as Appendix A., below.

Our publications associated with this contract are included as Appendix B.

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PUBLICATIONS

1. "A Neutronic Study of an Accelerator-Based Neutron Irradiation Facility for the Treatment of Superficial Melanoma by Boron Neutron Capture Therapy" B. Qu, T.E. Blue, C.K. Wang, and R.A. Gahbauer, Nucl. Tech., 1990

2. "A Study of a Proton Accelerator System as a Source of Epithermal and Thermal Neutrons at Fluence Rates Characteristic of Neutron Reactor Beams" T.E. Blue, J.W. Blue, C.K. Wang, and T.X. Qu, Proc. Severth ASTM - EURATOM Symposium on Reactor Dosimetry, Strasbourg, France, August 27 - 31, 1990

3. "A Neutron Spectrometer for Neutrons with Energies between 1eV and 10 keV" C.K. Wang, and T.E. Blue, Nucl. Instr. and Meth. A.(in press)

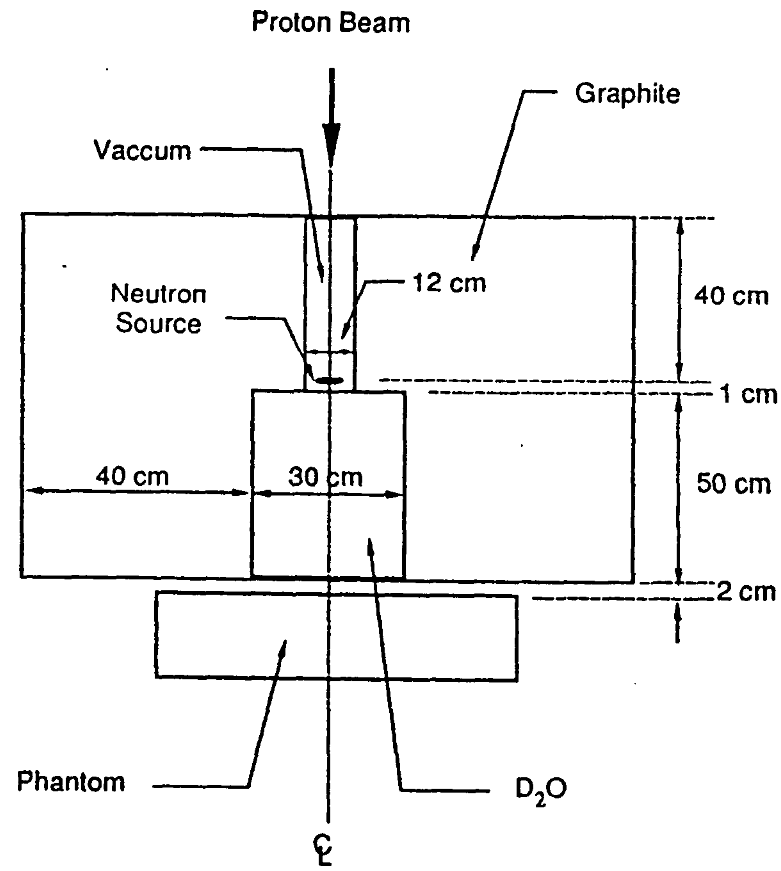

FIG. 1. The optimized ATNIF moderator assembly with a 40 cm x 20 cm x 80 cm rectangular parallelepiped phantom composed of $(C_5H_{40}O_{18}N)n$ on the moderator assembly's centerline, 5 cm from the surface of the moderator.

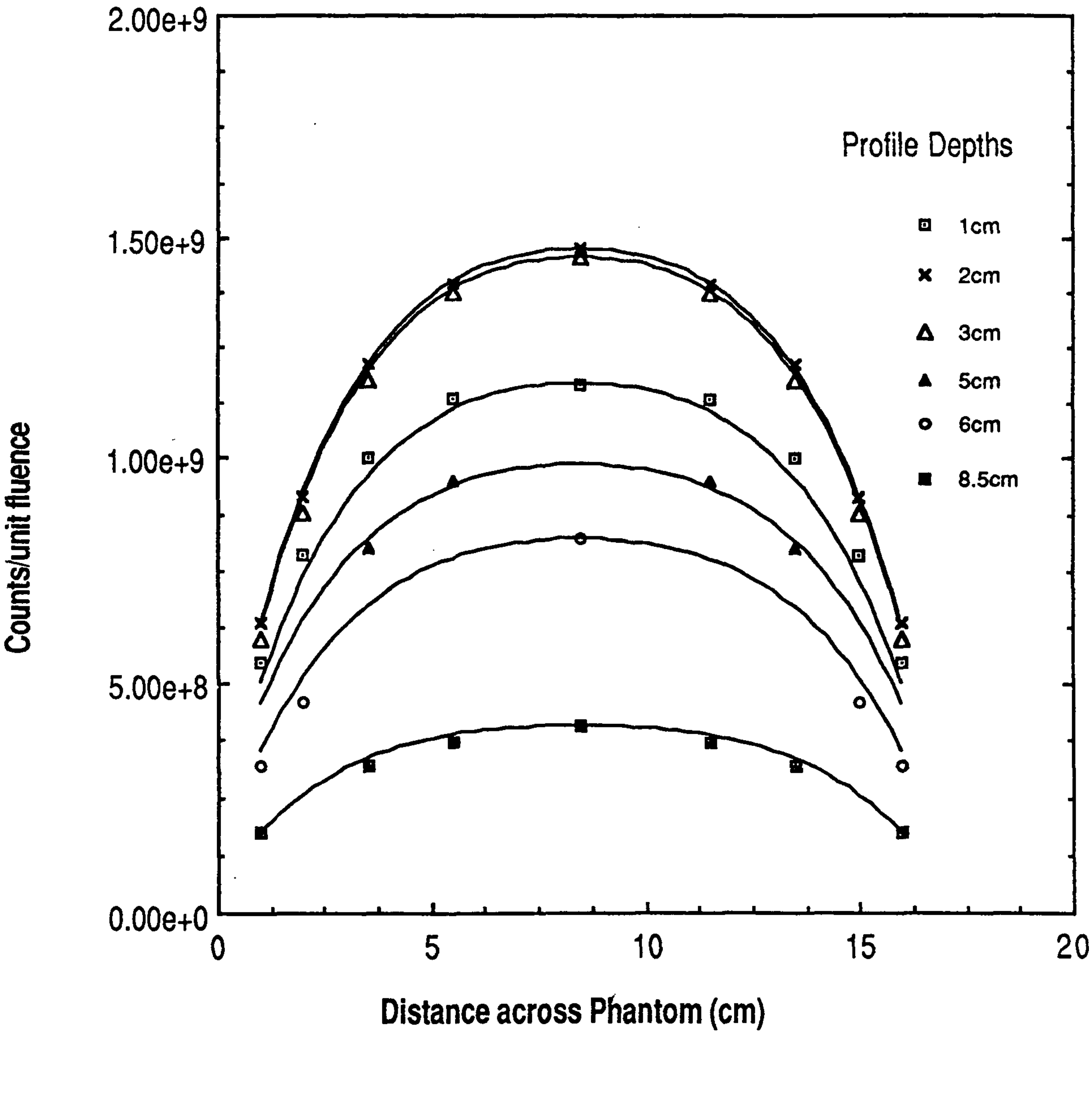

FIG. 2. The Dose Profile Scans at different depths across a 17cm x 15cm x 17cm water phantom..

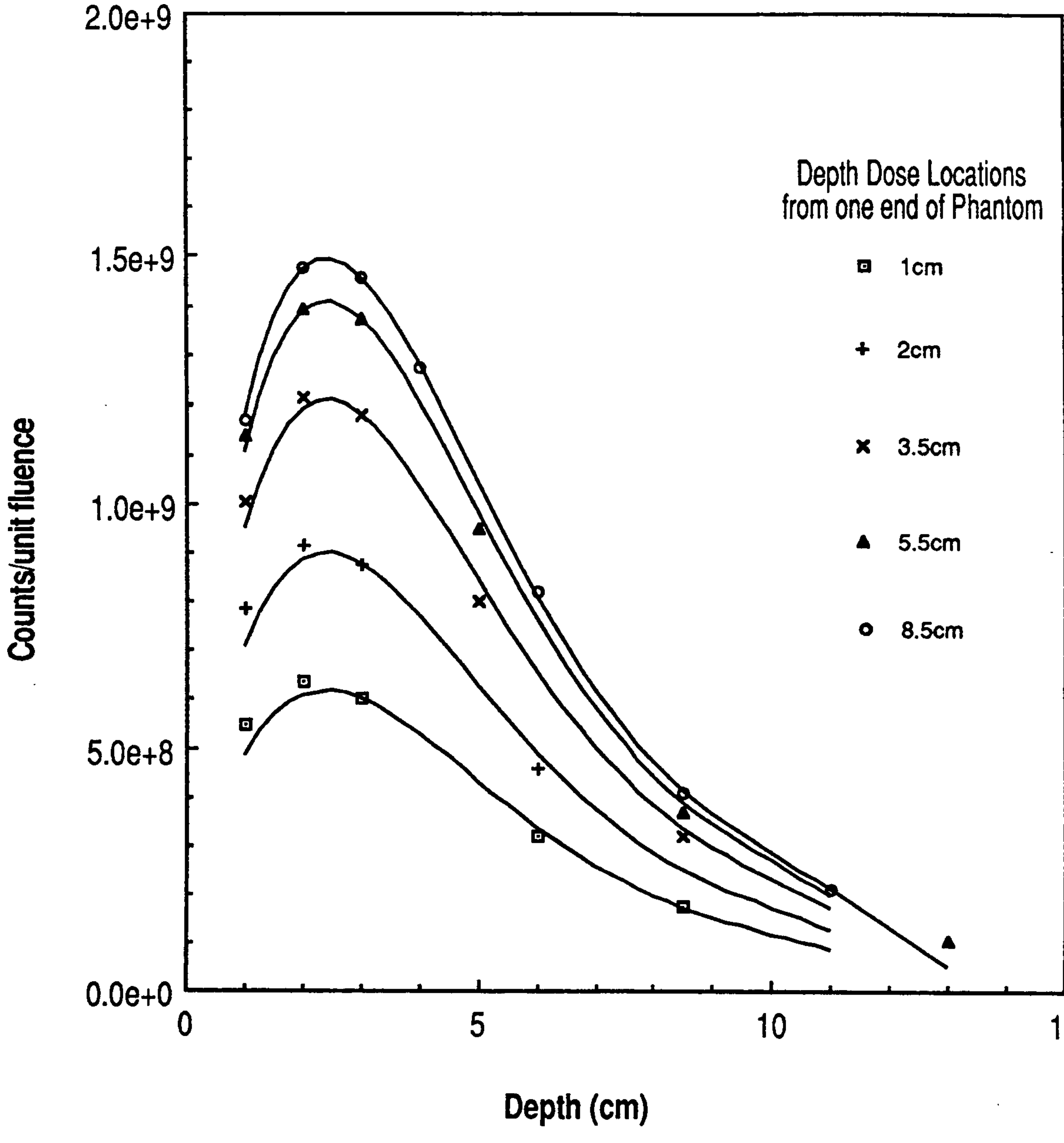

FIG. 3. The Depth Dose Distributions acorss a 17cm x 15cm x 17cm water phantom.

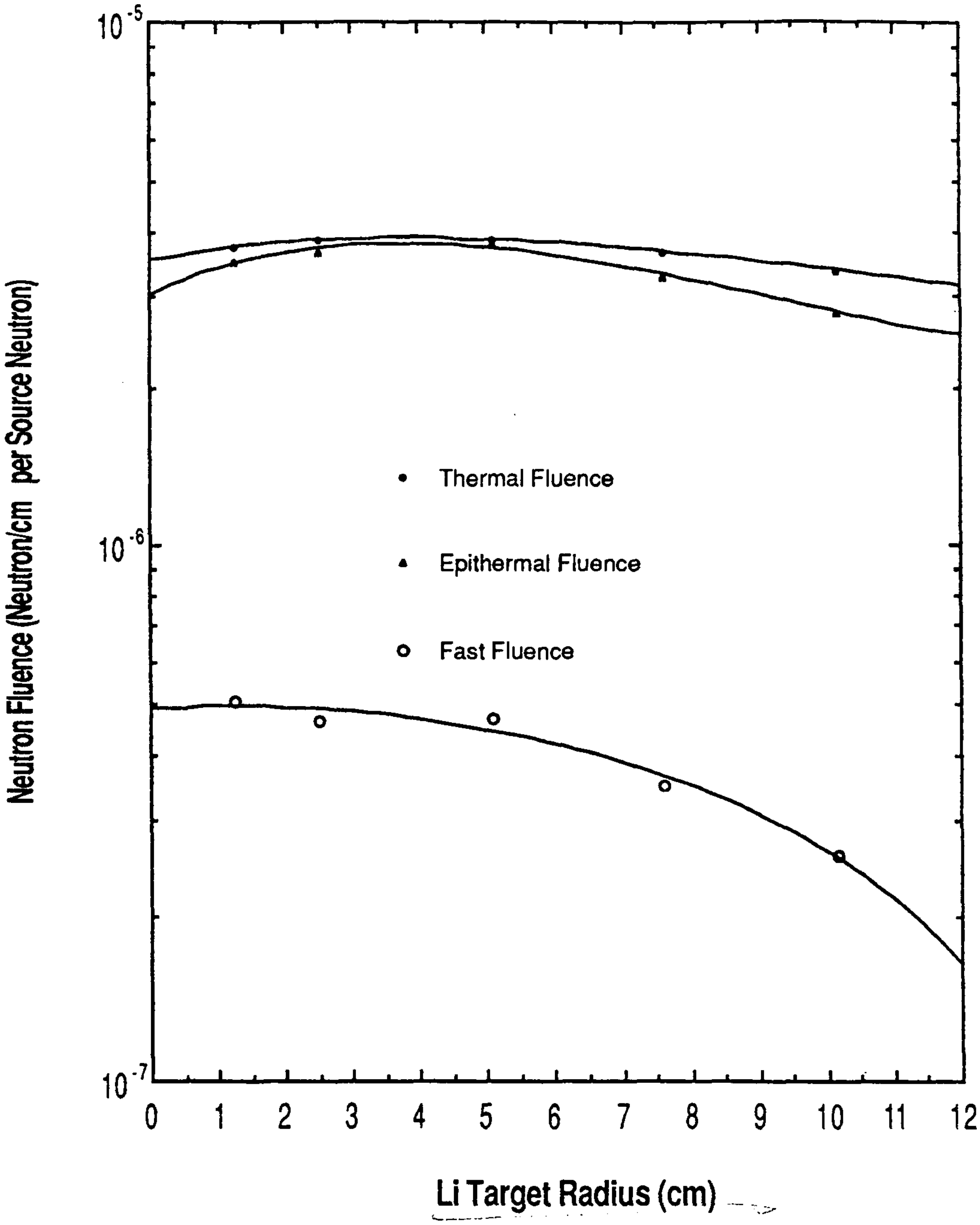

FIG. 4. The nuetron fluence at the surface of the head phantom vs. the radii of the Lithium target in the AENIF moderator assembly.

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