DOE/ER/61612--1

TECHNICAL PROGRESS REPORT FOR THE
PROJECT ENTITLED
"AN ACCELERATOR NEUTRON SOURCE
FOR BNCT"

Contract No. DE-FG02-93ER61612

Project Period: 1 June 1993 to 31 May 1994

THE OHIO STATE UNIVERSITY

PRINCIPAL INVESTIGATORS:

THOMAS E. BLUE

KAMBIZ VAFAI

MECHANICAL ENGINEERING DEPARTMENT

THE OHIO STATE UNIVERSITY

206 WEST 18TH AVE, COLUMBUS, OHIO 43210

February 1994

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

db
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

INTRODUCTION

This is the progress report for the project entitled, "An Accelerator Neutron Source for BNCT." The progress report is for the period from July 1, 1993 to date. The overall objective of our research project is to develop an Accelerator Epithermal Neutron Irradiation Facility (AENIF) for Boron Neutron Capture Therapy (BNCT). The AENIF consists of a 2.5 MeV high current proton accelerator, a lithium target to produce source neutrons, and a moderator/reflector assembly to obtain from the energetic source neutrons an epithermal neutron field suitable for BNCT treatments. Our project goals are to develop the non-accelerator components of the AENIF, and to specifically include in our development: 1) design, numerical simulation, and experimental verification of a target assembly which is capable of removing 75 kW of beam power; 2) re-optimization of the moderator assembly design based on in-phantom dose assessments using neutron spectra calculated in phantom and an energy-dependent neutron Relative Biological Effectiveness (RBE); 3) construction of a prototype moderator assembly and confirmation of its design by measurements; 4) design of the shielding of the accelerator and treatment rooms for an AENIF; and 5) design of a high energy beam transport system which is compatible with the shielding design and the thermal-hydraulic design.

ACCOMPLISHMENTS

In this section the accomplishments related to the five project goals listed in the previous section are described. The accomplishments are organized according to those goals, with the goals as subheadings.

Design and Experimental Verification of Target Assembly

Our design of a target capable of removing 75 kW of beam power which is uniformly distributed over a 25-cm-diameter circular spot is based on a disk-shaped heat pipe. We have chosen to cool the target with a heat pipe as opposed to flowing liquid heavy water, because the heat flux limit for a heat pipe can be made substantially larger than the heat flux limit (i.e. the heat flux for departure from nucleate boiling) for a system cooled by flowing liquid heavy water. Our work to date has centered around an analytical investigation and conceptual design of a disk-shaped asymmetrical heat pipe. Using the conservation formulations for the steady incompressible vapor and liquid flow for a disk-shaped heat pipe, an in-depth analysis has been applied. Analytical results for the asymmetrical vapor velocity profile, the vapor and liquid pressure distributions, and the vapor temperature distribution in the heat pipe have been obtained and compared to those of a rectangular flat-plate heat pipe.

Our analysis establishes the physics of the process and the intra-wick interactions for the disk-shaped heat pipe. The effects of variations in the thicknesses of the vapor channel and the wick, as well as the heat pipe, on the performance of both disk-shaped and rectangular flat-plate heat pipes has been analyzed in detail. The factors limiting heat pipe performance have

been obtained. Our results to date show that the disk-shaped heat pipe has a significantly larger heat flux capability than rectangular flat-plate heat pipes. We (K. Vafai, N. Zhu and K. Wang) are the first investigators to analyze disk-shaped heat pipes comprehensively, and are also the first investigators to present analytical solutions for disk-shaped heat pipes. These solutions are included in Publication 4 of the Publications section of this report. It should be noted that this is the first time the conceptual design of the disk-shaped heat pipe is presented. Because Publication 4 is under review, we have only listed it by title, and not included a copy of the manuscript.

There are, unfortunately, no experimental measurements with which we can compare our work for the disk-shaped heat pipe. The closest work is that of Maezawa *et. al.* (1981), who studied the heat transfer characteristics of a disk-shaped rotating wickless heat pipe. Unfortunately, the physical mechanism of the heat transfer process of their rotating wickless heat pipe is different from that of the heat pipe in our study. Again, the reason for not finding any work to compare with our results is the uniqueness of the design of our heat pipe, which is proposed and analyzed for the first time in Publication 4. Consequently, a part of our research plan is an experimental testing program to verify our numerical calculations of the heat pipe performance.

Re-optimization of the Moderator Assembly Design

Our assessment of moderator assembly designs has thus far been based on two Figures of Merit (FOMs) in air. In our assessment, we have treated the neutron RBE as a parameter ranging from 2 to 4.5. However, a limitation of this approach (of treating the neutron RBE as a parameter) is that the neutron

RBE is truly a function of the neutron spectra, and the neutron spectra are truly functions of the moderator/reflector materials and the moderator material thickness. To correct this limitation in our approach we intend to reassess the optimum moderator assembly moderator/reflector material selection and moderator material thickness, with the neutron RBE calculated consistently for the appropriate neutron spectra.

In order to calculate the average neutron RBE, $\langle \text{RBE}_n \rangle$, consistently for the appropriate neutron spectra, we must know $\text{RBE}(E_n)$, the neutron RBE as a function of neutron energy E_n . We have calculated $\text{RBE}(E_n)$ by using an empirical RBE-LET (linear energy transfer) relationship, and normalizing the resulting relationship for $\text{RBE}(E_n)$ and E_n to measurements of $\langle \text{RBE}_n \rangle$ in the Brookhaven Medical Research Reactor (BMRR). This analysis is contained in Publication 1 of the Publications section of this report.

Besides reassessing the moderator assembly design by including an RBE which depends on neutron energy, we are reassessing the moderator assembly design based on dose distributions in phantom, instead of based on the dose distribution in air. We have already developed the formalism for assessing moderator assembly designs in phantom. This formalism is the subject of Publication 2 of the Publications section of this report.

Prototype Moderator Assembly Measurements and Design Confirmation

A prototype moderator assembly has been designed based on an in-air assessment of the neutron field, and assuming that the neutron RBE equals 4.5. The prototype moderator assembly represents a trade-off between moderator material expense and moderator assembly function. Deuterium oxide (D_2O) was chosen as the moderator material because it was available to

us at no cost. Although beryllium oxide (BeO) is potentially a better moderator material, it was available to us only at a cost so high that we could not justify the expense. Similarly, natural lithium carbonate (LiCO_3) was chosen as the reflector material in our moderator assembly because its cost was very much less and its performance was nearly as good as the combination of magnesium oxide (MgO) and lithium enriched in Li-6 .

The moderator assembly prototype will be tested with the Ohio University Van de Graaff accelerator, which can deliver a proton current of about $20 \mu\text{A}$. Although the moderator assembly prototype will be built to interface with a large target, the testing of the moderator assembly prototype will be carried out with a small target. The large target is not necessary for heat removal at the levels of proton currents to be used for testing the prototype. The small target has been built and loaded with lithium.

Regarding measurements, we have purchased and tested a small ^3He -filled proportional counter to map the thermal neutron fluence distribution in phantom. Also, we have purchased a 2-dimensional positioning system and controller to position the ^3He detector in the phantom.

Design of Shielding

An issue of concern for an AENIF for BNCT is radiation shielding. Our general goal is to develop an AENIF for BNCT which can be used to treat patients in hospitals. Ideally, one would like to have three rooms available for the installation of an AENIF for BNCT: a control room, an accelerator room, and a treatment room. We have begun a study of the adequacy of the shielding of the treatment room using the Monte Carlo computer code MCNP. For this study, a radiation therapy technician in the control room is

the focus of our concern, and the patient acts as an effective source of scattered neutrons, as the neutrons leaving the moderator assembly scatter in the patient's head and body. We are conservatively designing the shielding to conform to the 1990 ICRP recommended dose limits for non-occupational persons. A phantom has been modeled in MCNP to serve as an effective neutron source for shielding calculations. The computer code SABRINA was used to visualize and verify the MCNP geometry description of the phantom. This phantom model in MCNP will be used for a second time when we study the whole-body dose to the patient and the adequacy of the shielding of the moderator assembly. We have not yet begun a study of the shielding of the accelerator room, except insofar as the shielding of the accelerator room depends on the high-energy beam transport design, which we have begun.

High-Energy Beam Transport (HEBT) System

The high energy beam transport (HEBT) system consists of bending and focusing magnets and a drift tube through which the protons stream. This drift tube will penetrate the ceiling separating the accelerator room from the treatment room. The treatment room will house the moderator assembly and, of course, the target assembly. The large target diameter demanded by the thermal design considerations makes the shielding of the structures in the accelerator room more demanding. In particular the HEBT system design may be affected by shielding considerations, since neutron activation of the magnets should be minimized. Target thermal design considerations affect the HEBT system design more directly by the thermal design requirement that the proton beam power be uniformly distributed in space and in time over the target surface. A graduate research assistant (Mr. Michael Christian

Dobelbower) spent the month of January working at Los Alamos National Laboratory with the staff of the AT-1 Division. There he learned to run the HEBT design code PARMILA, which he brought back to OSU. He designed a HEBT system which uses static magnetic fields to spread the beam uniformly (the power peaking factor equals ~ 1.4) over a 25 cm diameter target. For specificity, he assumed input parameters for the HEBT system design which are consistent with the output of an RFQ. As a next step, Mr. Dobelbower will investigate the inclusion of a 90° bend in the beam line.

REFERENCES

S. Maezawa, Y. Suzuki and A. Tsuchida, "Heat Transfer Characteristics of Disk-shaped Rotating Wickless Heat Pipe," Proc. IV Int. Heat Pipe Conf., Pergamon Press, Oxford, pp. 725-733, 1981.

PUBLICATIONS

1. "A Calculation of the Energy Dependence of the RBE of Neutrons," T. E. Blue, N. Gupta and J. E. Woollard, *Physics of Medicine and Biology* 38: 1693-1712 (1993).
2. "Dose Prescription in Boron Neutron Capture Therapy," N. Gupta, R. A. Gahbauer, T. E. Blue and A. Wambersie, *International Journal of Radiation Oncology, Biology and Physics* 28 (1994).
3. "Expanded, Circular, Uniform Beams," R. W. Garnett and M. C. Dobelbower, Technical Note AOT-1:94-026, Accelerator Operations and Technology Division, Los Alamos National Laboratory (1994).
4. "Analysis and Conceptual Design of Asymmetrical Disk-shaped and Flat Plate Heat Pipes," K. Vafai, N. Zhu and W. Wang, submitted for journal publication.
5. "Passive Alteration and Control of Convective Heat Transfer Using Alternate Porous Cavity/Block Wafers," P. C. Huang and K. Vafai, *Inter. Journ. of Heat and Fluid Flow* (in press).
6. "Internal Heat Transfer Augmentation in a Parallel Plate Channel Using an Alternate Set of Porous Cavity-Block Obstacles," P. C. Huang and K. Vafai, *Numerical Heat Transfer Journal* (in press).

7. "A Monte Carlo Design Study of an Accelerator Epithermal Neutron Irradiation Facility for Boron Neutron Capture Therapy," T-X Qu, Doctoral Dissertation, The Ohio State University (1993).

PERSONNEL, 1993

Thomas E. Blue, Associate Professor, Nuclear and Mechanical Engineering

Kambiz Vafai, Professor, Mechanical Engineering

Michael C. Dobelbower, Ph.D. candidate, Nuclear Engineering

Nilendu Gupta, Ph.D. candidate, Biomedical Engineering

Tanxia Qu, Ph.D. , Nuclear Engineering

Jeffrey E. Woollard, Ph.D. candidate, Nuclear Engineering

Nanquiang Zhu, Ph.D. candidate, Mechanical Engineering

GRADUATE DEGREES EARNED, 1993

Tanxia Qu, Ph.D. , Nuclear Engineering, December, 1993