THE NEW FISSION CONVERTER BASED EPITHERMAL NEUTRON IRRADIATION FACILITY AT MIT

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1. Introduction

A new type of reactor produced epithermal neutron beam based on a sub-critical fission converter and called the FCB, has been constructed at the MIT Research Reactor (MITR). The use of a fission converter source was originally suggested by Rief [1]. In this approach, a large area thermal neutron beam impinges upon fissionable material, generating a fission neutron spectrum that is moderated and filtered to produce an epithermal neutron beam of high intensity and purity. Figure 1 shows the FCB irradiation facility. This paper summarizes the neutronic and engineering aspects and the performance of this facility which was recently, (June 2000), put into operation at the Massachusetts Institute of Technology's research reactor, MITR.

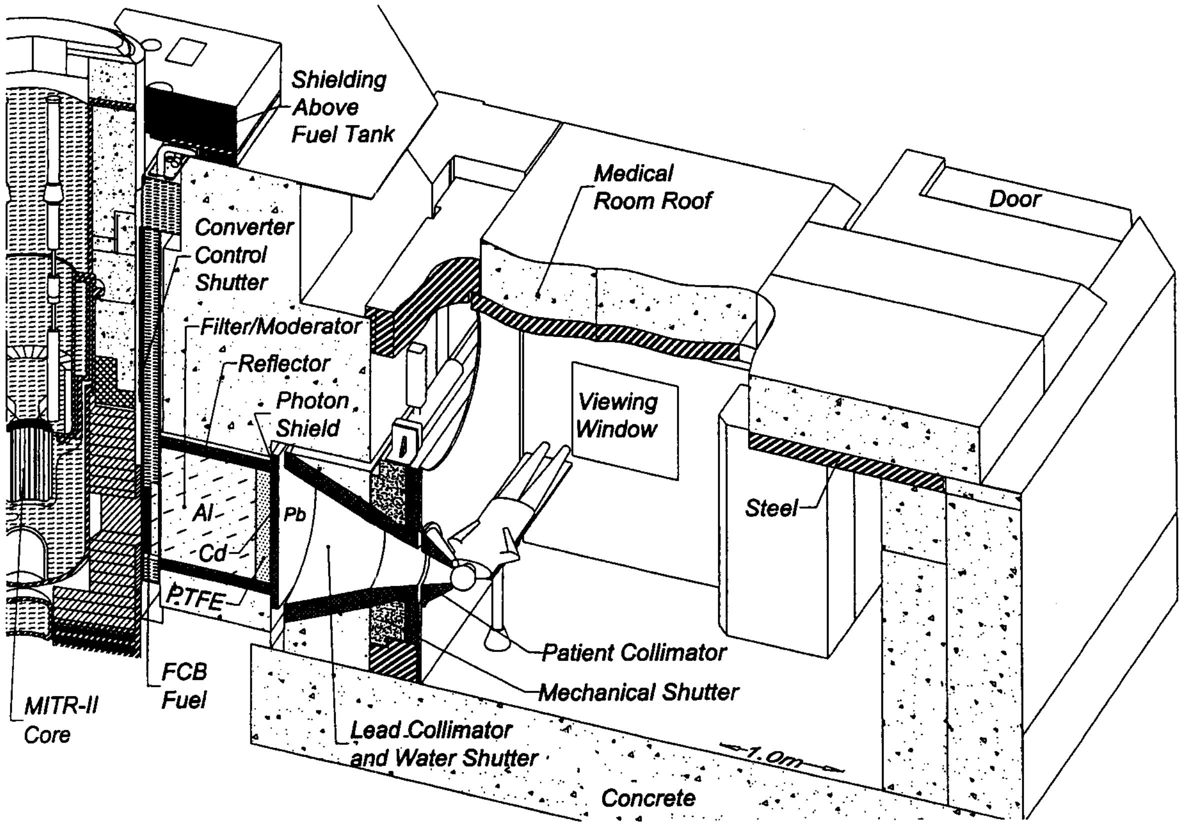

Figure 1. The MIT fission converter based epithermal neutron irradiation facility.

2. Description of the Facility

The neutronic and engineering design of the FCB is based upon a series of studies [2,3,4] which investigated the options for various fuels, fuel configurations, coolants, moderators, filters and beam collimators. Based on neutronic performance, fuel cost, availability, safety, and ease of handling, we chose to use spent fuel from the MITR was chosen for our initial fuel loading. In the FCB a linear array of 10 MITR elements produces a fission neutron source 60 cm high by 74 cm wide in the thermal column of the MITR. Heavy water coolant is used to reduce the moderation in the fuel tank to a minimum. This configuration results in a calculated k_{eff} of 0.26, which is very far from critical. With 10, 35% burned MITR fuel elements containing a total of ~3380 g U-235, this converter generates ~85 kW of fission energy, at a reactor power of 5 MW. Substantial additional converter power can be obtained, if it is ever needed, by using fresh MITR fuel, or fuel specifically designed for this application. The current design will accommodate a converter power up to 250 kW, which would result in a factor of three increase in flux.

The beamline, starting at the converter fuel, is comprised of 81 cm of aluminum, 13 cm of PTFE (®Teflon) and 0.5 mm of cadmium to moderate and filter the neutron beam. The aluminum and fluorine in the PTFE provide most of the filtration needed to produce the epithermal neutron beam in the desired energy range of $1\ \text{eV} \leq E \leq 10\ \text{keV}$. The irradiation performance of PTFE is known to be poor, therefore, its suitability for this application was verified in tests with exposures an order of magnitude higher than those expected over the life time in this application [5]. A 6 cm thick lead shield is used to reduce photon contamination in the beam and a lead collimator with 15 cm thick walls directs the epithermal neutron beam to the medical irradiation room. The measured epithermal neutron intensity and specific fast neutron and gamma dose rates at this location are respectively, $\phi_{epi} = 9 \times 10^9\ \text{n/cm}^2\text{-sec}$ and $D_{\gamma,fn} / \phi_{epi} \leq 2\text{x}10^{-11}\ \text{cGy-cm}^2$. A 38 cm long cone-shaped patient collimator has been added at the end of the beamline to allow easy patient positioning at essentially any angle between the beam and the axis of the patient, see Fig. 2. With a 15 cm diameter aperture the irradiation time to reach normal tissue tolerance with a boron containing drug like boronophenylalanine (BPA) is calculated to be 3.5 minutes. The near optimum purity of the FCBs beam permits irradiations with therapeutic effectiveness to a depth greater than 9 cm and an average therapeutic ratio (dose to tumor divided by dose to normal tissue) of 6/1 using the current generation boron capture agent BPA. With advanced capure agents now under development, the useful beam penetration approaches 12-13 cm and the average therapeutic ratio is greater than 10/1. Details of patient collimator design, and beam performance as well as collateral dose issues are discussed in references [6,7] and will soon be the subject of a comprehensive journal publication.

Beam delivery is controlled by an automated system that uses redundant programmable logic controllers, PLCs, to assure that the correct neutron fluence is delivered to the patient. This system is discussed in reference [8]. The beam monitoring system controls three shutters. The first shutter is a cadmium/boron shutter which is located in front of the converter fuel, a 68 cm water shutter is located in the lead collimator and a 40 cm thick heavy concrete and lead fast acting mechanical shutter is located at the entrance to the irradiation room. The mechanical shutter operates in ~9 seconds and determines the start and finish of the patient irradiation. The other shutters operate more slowly, ~1-2 minute and serve to lower the dose rates in the medical irradiation room to levels which allow extended occupancy by the supporting staff.

A heavily shielded patient irradiation room has been constructed (Fig.2). Visual observation of the patient during irradiation is possible through a large area shielded window as well as by strategically placed TV cameras. The medical room walls and door are constructed of heavy concrete, ($4\ \text{g/cm}^3$), and steel which attenuate the radiation from the FCB to less than 10^{-5} Sv/hr. A 2.5 cm borated polyethylene layer lines all inside surfaces of the medical room and acts to reduce activation to the concrete and steel walls.

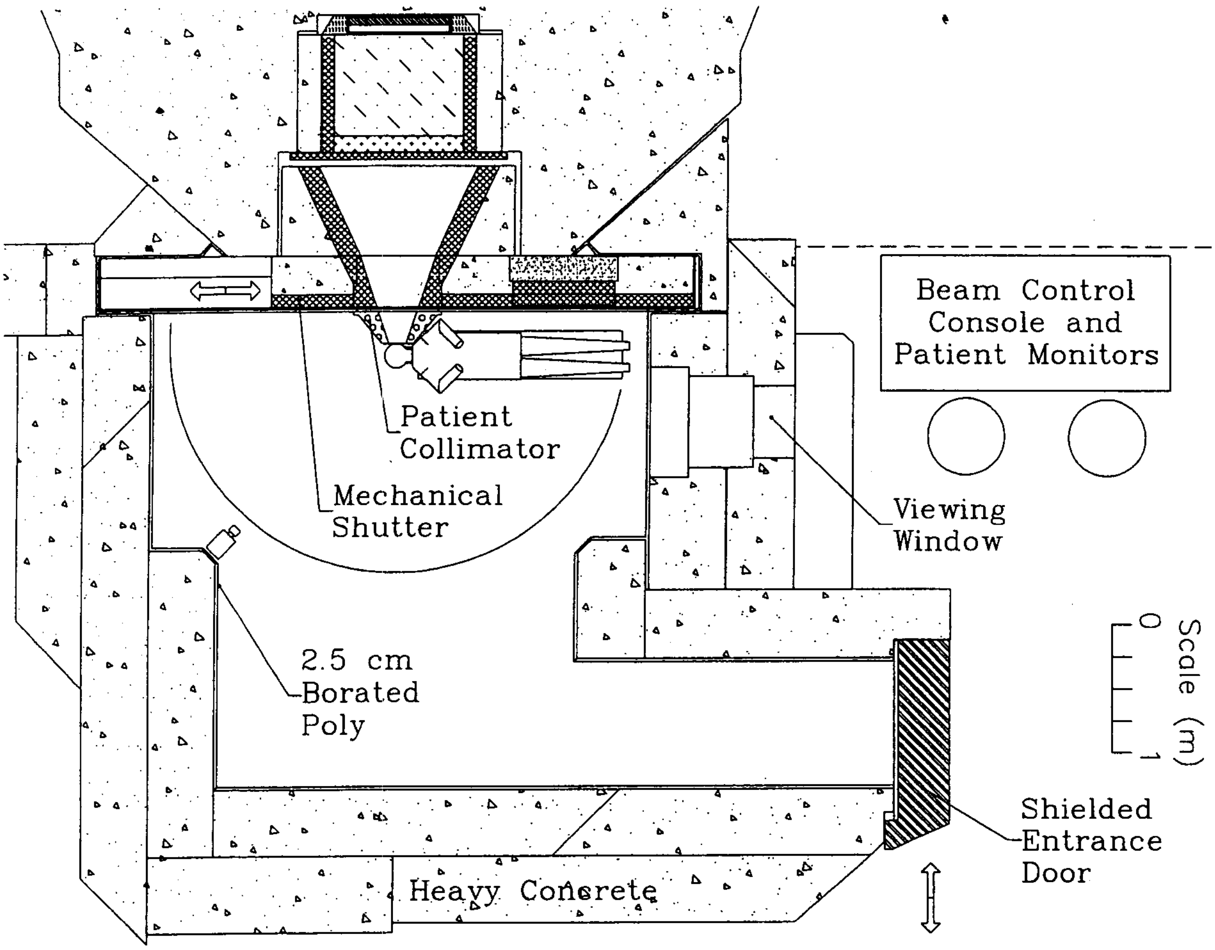

Figure. 2 Irradiation room of the MIT FCB.

The nuclear safety of the FCB has been extensively investigated [4]. All conceivable accident scenarios including loss of flow and even a somewhat incredible scenario involving rapid loss of all coolant in the converter tank have been analyzed. No accident scenario has been found which is able to cause fuel disruption. The U.S. Nuclear Regulatory Commission granted approval to load fuel and to operate the FCB in December 1999. We have applied to the NRC for approval to irradiate patients and have recently received this approval. The FCB licensing process has been discussed in more detail in another paper [9].

3. Summary and Discussion

Neutron capture therapy requires epithermal beams with adequate intensity and purity. Reactors have been used directly as the source for these beams in the past. Since these reactors were not specifically designed for epithermal neutron beam production, compromises in beam performance had to be accepted. For example, the moderator often cannot be rigorously minimized between the fuel elements and the beam line, which results in a loss of neutrons from the desired epithermal energy range. The fission converter approach provides another option for some existing research reactors. The first demonstration of this approach is the MIT FCB. This facility provides a high intensity beam of near theoretically optimum purity. It is currently the highest intensity epithermal beam available and is capable of irradiating patients to tolerance, in a single fraction in just a few minutes. Further increases in intensity are allowed by the operating license and might be used to allow further filtration and/or collimation.

The FCB represents a significant advance in the development of epithermal beams for neutron capture therapy. It is expected that the FCB will play an important role in the worldwide effort to develop neutron capture therapy as an accepted modality for cancer treatment. The main challenges for NCT are now expected to be in the development of improved neutron capture drugs and in the execution of well planned and rigorously executed human clinical trials.

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REFERENCES:

[1] **H. Rief, R. Van Heusden, and G. Perlini**, “Generating Eithermal Neutron Beams for BNCT at TRIGA Reactors,” draft report for Pavia Workshop on New Clinical Applications and Neutron Sources for BNCT (June 1991).

[2] **W.S. Kiger III, S. Sakamoto, and O.K. Harling**, “Neutronic Design of a Fission Converter-Based Epithermal Neutron Beam for Neutron Capture Therapy,” *Nuclear Science and Engineering*: **131**, 1-22 (1999).

[3] **S. Sakamoto, W.S. Kiger, III, and O.K.Harling**, “Sensitivity Studies of Beam Directionality, Beam Size, and Neutron Spectrum for a Fission Converter-Based Epithermal Neutron Beam for Boron Neutron Capture Therapy,” *Medical Physics*, **26** (9), 1979-1988, September 1999.

[4] **Balendra Sutharshan**, "Engineering Design of a Fission Converter-Based Epithermal Beam for Neutron Capture Therapy," Doctor of Philosophy thesis, Dept. of Nuclear Engineering, Massachusetts Institute of Technology, February 1998.

[5] **O. Harling, G. Kohse, K. Riley, and S. Sakamoto**, “The Use of Polytetrafluoroethylene (Teflon) Containing Filter/Moderators for Epithermal Neutron Beam Production,”8th International Symposium on Neutron Capture Therapy, LaJolla, CA, 86, September 1998.

[6] **K.J. Riley, S.J. Ali and O.K. Harling**,"Collimator Optimization Studies for the New MIT Epithermal Neutron Beam," Massachusetts Institute of Technology, Nuclear Reactor Laboratory, in *Program and Abstracts of the 9th ISNCT Symposium on Neutron Capture Therapy for Cancer,* 233-234, Osaka, Japan (2000).

[7] **K.J. Riley, P.J. Binns, M. Ledesma, B. Sutharshan and O.K. Harling**, “Shielding and Beam Performance of the New Epithermal Neutron Beam at the MITR-II," Massachusetts Institute of Technology, Nuclear Reactor Laboratory, in *Program and Abstracts of the 9th ISNCT Symposium on Neutron Capture Therapy for Cancer,* 235-236, Osaka, Japan (2000).

[8] **B.A. Wilson, K.J. Riley, and O.K. Harling**, "Automatic Control and Monitoring of the MIT Fission Converter Beam," Massachusetts Institute of Technology, Nuclear Reactor Laboratory, in *Program and Abstracts of the 9th ISNCT Symposium on Neutron Capture Therapy for Cancer,* 237-238, Osaka, Japan (2000).

[9] **J.A. Bernard, L-W. Hu, T.H. Newton and O.K. Harling**, "License Requirements for the MITR Fission Converter," Massachusetts Institute of Technology, Nuclear Reactor Laboratory, in *Program and Abstracts of the 9th ISNCT Symposium on Neutron Capture Therapy for Cancer,* 189-190, Osaka, Japan (2000).