Reconstitution and Upgrade of the Thermal Neutron Irradiation Facility in the Basement
Medical Room of the MIT Research Reactor

Final Report

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Abstract

The M-011 thermal neutron beam has been reconstituted and upgraded to provide a high intensity and high quality facility for preclinical and certain clinical studies. Intensities of thermal neutrons in the beam range from $5.0\text{-}8.5 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$. Beam contamination is at a low level where it has no practical influence on beam performance. New computer controlled dose and beam monitoring systems have been implemented which assure precise dose delivery and redundant safety interlocks. An additional beam shutter and massive shielding in the back of the medical room have been added which significantly reduce room background and now permit staff entry without the necessity for lowering the reactor power. This system is needed for BNCT research by the MIT group as well as other US groups. This need became acute with the closure of the BMRR which previously had the only high quality thermal neutron irradiation facility for BNCT in the USA.

I. Introduction

A high intensity and high quality thermal neutron irradiation facility is needed for the development of neutron capture therapy (NCT). Thermal neutrons are required for the irradiation of small animal models and cell cultures to test new compounds, to explore and optimize boron compound delivery systems, and to study the radiobiology of NCT. Thermal neutron beams are also needed for clinical NCT studies of superficial malignancies. The need for such a facility is not limited to MIT NCT researchers; it is a national need. The thermal neutron irradiation facility, which is described in this report is the only such facility available in the USA since the closure of the BMRR.

The approach used in developing the thermal neutron irradiation facility at the MIT Research Reactor (MITR) is based upon reconstruction of the vertical medical beam line below the core of MITR. This beam line originally was designed for thermal neutron irradiations in the medical room below the MITR-II's core. Figures 1 and 2 show the facility, known as the M-011 beam, configured for thermal neutron irradiations. In the late 1980's and early 1990's this beam line was converted to an epithermal beam, M-067. This modification, see Figure 3, permitted irradiation of deep-seated tumors such as GBM¹. However, the M-067 beam precluded the use of the facility for thermal neutron irradiations. A much improved epithermal neutron irradiation facility, the FCB^{2,3,4}, was completed at the MITR a few years ago. With the advent of the FCB it became possible to reconstruct the original M-011 thermal irradiation facility at the MITR.

The reconstitution of the thermal irradiation facility was proposed to USDOE and after funding was obtained this work was initiated in 2001 and successfully completed in 2003. This document is the final project report for reconstituting and upgrading the thermal neutron irradiation facility at the MITR.

II. Reconstruction and Upgrade of the Thermal Neutron Irradiation Facility

1. Reconstitution of the M-011 beam line and additional shielding to reduce radiation exposures to clinical and research staff.

The first major activity in this task involved high radiation work to remove the radioactive filter materials in the M-067 beam line. This required reactor shut down and cool down for several days to minimize radiation levels from the direct beam originating in the fission products of the reactor's fuel. As a preliminary to this work, procedures and tooling were developed to help assure ALARA conditions. Thanks to these preparations and the original design of the M-067 beam line which provided for future changes, this activity was accomplished with low dose commitments to the MIT staff. With the removal of the epithermal filters and the installation of the original bismuth photon shield, the beam line configuration was returned to that shown in Figure 2 for the M-011 beam.

A relatively high background of radiation was originally present in the medical room even when all the shutters shown in Figure 2 were closed. This necessitated a large reduction in reactor power whenever staff activities required entry into the medical room. Two major changes were made to obviate the need for expensive "sole use" reactor charges resulting from the need to lower reactor power. A 7.6 cm thick boron loaded polyethylene shutter was installed below the previously existing shutter. This reduced leakage from fast neutrons in the beam line by a factor of approximately 5. Radiation from the fission converter of the FCB had resulted in relatively high levels of neutron and gamma radiation in the back half of the medical room. A massive shield assembled from lead bricks and borated polyethylene (totaling 11.8 Tons) was installed to greatly attenuate this radiation from the fission converter. The lead and borated polyethylene was obtained as surplus material and represents a savings of about \$20,000 to the project. These changes were successful in reducing medical room radiation intensities to acceptable levels for staff entry even with the reactor at full power. Staff can now work for extensive periods of time in the medical room without the costly need for sole reactor use charges.

The new shutter contains a section of the patient collimator that aligns with a fixed downstream portion (see Section II.4) when the beam is turned on for clinical irradiations as shown in the detailed view of Figure 4. The collimator section in the shutter is removable so that animal jigs (see Section II.3) can be accommodated for irradiations in the higher flux regions near the top of the shutter.

2. Dose monitoring and control system

New fission counters, with improved operating characteristics were obtained from an instrumentation laboratory of the Argentinean Atomic Energy Commission. These were installed for beam monitoring, and are shown in Figure 4, at the edge of the neutron beam. The four beam monitors are located at 90 degree intervals around the beam to monitor integrated intensity as well as beam symmetry. Signals from neutron induced fissions are amplified, discriminated to eliminate unwanted events from gamma rays and alphas and then presented to two independent programmable logic controllers (PLCs). Figure 5 provides a block diagram of the electronic systems used to monitor the irradiations, to insure accurate neutron fluence (proportional to dose) delivery, and to check that all safety systems are operative. The dose monitoring and safety system, which was implemented for the thermal beam is similar to that already operative and proven for the FCB⁵. Since the FCB and the thermal beam now have control systems with identical major components, fewer spare modules are needed as back-up in the event of failures. Adequate spares for electronic modules were purchased as part of this project.

3. Small animal irradiation system

We have constructed a system, which facilitates the irradiation of small animals, mice and rats and of cell cultures. Figure 6 shows two anesthetized rats that are positioned for a brain irradiation on the lid of a lithiated polyethylene box. Figures 7 and 8 show the beam's eye view of the same rats. The slit in the polyethylene box lid was carefully designed using the Monte Carlo beam model, which was developed for the reconstituted M-011 beam. Experimental measurements have

verified the design of this system. A thermal neutron flux of $8.5 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$ is incident on the surface of the experimental animals. This allows irradiations using typical boron compound concentrations to be completed in only several minutes. Short irradiations are desirable for several reasons not least of which is the need to limit the length of time that laboratory animals are placed under general anesthesia. Figure 9 shows the complementary irradiation rig that was designed and constructed for *in-vitro* cell culture irradiations in the thermal beam.

4. Collimators for large animal and human clinical irradiations

Collimators were designed for use in large animal irradiations and for clinical studies of shallow tumors. The experimentally bench marked Monte Carlo model of the M-011 beam line was used in the collimator design. Figures 10 and 11 show the installation of one of these collimators, which are fabricated from layers of lithiated polyethylene and bismuth. Figure 12 shows a view directed vertically up the beam line of a fully installed collimator. Two collimator diameters, 8 and 12 cm, have been constructed. These can easily be interchanged or fully removed. Other collimator sizes and shapes can readily be implemented as needed.

III. Performance of the reconstructed M-011 thermal neutron beam

The performance of the reconstituted M-011 beam has been determined through measurements of the thermal neutron flux, fast neutron and gamma dose rates. RBE weighted boron dose rates for a currently used compound have also been calculated from the thermal flux. Measurements are performed for the M-011 beam free in air and in a water filled ellipsoidal head phantom⁶ using MIT's well established mixed field dosimetry techniques⁷ and the 12 cm diameter patient collimator.

Beam contamination, measured free in air, provides a good first order indicator for beam quality. The specific beam contamination is 0.8 and $2.1 \times 10^{-11} \text{ cGy cm}^2$ respectively for fast neutrons and gamma rays. Specific contamination at these levels is an order of magnitude lower than the inherent non-specific background

resulting from neutron irradiations in tissue. The M-011 is for practical purposes a contamination free beam.

The thermal neutron flux as a function of depth in the ellipsoidal water phantom is presented in Figure 13. Peak flux at the surface exceeds $5 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$ at 5 MW reactor power. Flux levels which are considerably higher $8.5 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$ were measured at the surface of rat phantoms, which were mounted in the small animal irradiation box shown in Figures 7 and 8.

Figure 14 presents the depth versus dose distribution for the M-011 beam in the water head phantom using a currently available boron compound, a 3.5:1 tumor to normal tissue concentration ratio and a readily achievable $52.5 \text{ } \mu\text{g/g}$ boron concentration in tumor. We have assumed RBEs of 3.2 and 1.0 respectively for neutrons and photons and to be conservative the same RBE of 3.8 for normal tissue, skin, and tumor. The ADDR of approximately $210 \text{ RBE-cGy min}^{-1}$ indicates that the M-011 beam has an intensity, which allows irradiations to tolerance levels of 1200 RBE-cGy in about six minutes with a useful penetration, (therapeutic ratio ≥ 1.0) of 3.6 cm. Tumors located within the first centimeter would receive a dose of approximately 3200 RBE cGy in this hypothetical scenario for a thermal neutron irradiation.

The new automated, PLC controlled irradiation system the operating logic of which is shown in Figure 5 has been extensively tested to determine its accuracy and reliability. This system has functioned reliably and has delivered the preset neutron fluence to within one percent. The safety interlocks, which guard against accidental overexposure to experimental subjects and to operations staff have also functioned flawlessly. Redundancy in the control and monitoring system has provided the desired defense in depth.

The dose monitoring and control systems as well as the fixtures for small animal irradiations have already received extensive testing. Research groups from several non-MIT institutions as well as MIT research groups have used the reconstructed and upgraded M-011 irradiation system. This system has met all of our expectations for a versatile, intense and contamination free thermal neutron irradiation facility.

IV. References

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Figure 1: Isometric view of the thermal neutron irradiation facility at MITR-II showing the relative location of the core, the heavy water filter, the light water shutter tank, the graphite collimator and the final beam shutters.

Figure 2: Neutron beam line for thermal neutron irradiations. This beam configuration is known as the M-011 beam.

Figure 3: Configuration of the vertical beam line used to produce epithermal neutrons with a filter of aluminum, sulfur, cadmium and lead. This beam configuration is called the M-067 beam.

Figure 4: Detailed view of the end of the current M-011 beam line configuration for clinical irradiations. This figure shows the new boron loaded polyethylene shutter with patient collimator installed.

Figure 5: Block diagram of the logic contained in each of the 2 PLCs that are used to control irradiations with the M-011 thermal neutron beam. The two PLCs each also receive the neutron detection signals from every beam monitor. This design assures a high degree of redundancy and safety.

Figure 6: Two rats mounted on the lithiated polyethylene lid of the small animal irradiation box.

Figure 7: Beam's eye view of two rats positioned for brain irradiations.

Figure 8: An overall view of the small animal irradiation box with two rats positioned for brain irradiations.

Figure 9: Arrangement used for cell culture irradiations at the reconstructed M-011 thermal neutron beam.

Figure 10: Installing a patient collimator in the reconstructed M-011 beam.

Figure 11: A patient collimator installed in the reconstructed M-011 thermal neutron beam.

Figure 12: Axial view of a fully installed patient collimator in the reconstructed M-011 thermal neutron beam.

Figure 13: The 2200 m s^{-1} flux measured along the central axis of the medium ellipsoidal water filled head phantom for the M-011 beam using a 12 cm aperture with no air gap.

Figure 14: Depth dose distributions in an ellipsoidal, water head phantom with assumed boron concentrations and RBEs and using the 12 cm diameter patient collimator. The resultant figures of merit or advantage parameters are an AD of 3.6 cm, an ADDR of 210 RBE cGy min⁻¹ and an AR of 2.9.