Current Activities at the MIT Research Reactor

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The MIT Research Reactor (MITR) is a 5 MW nuclear research reactor that is owned and operated by the Massachusetts Institute of Technology to further its educational and research goals at both the undergraduate and graduate level. The reactor first achieved criticality in 1958. It was largely rebuilt in 1973/1974 by MIT staff and students, and its current license expires in August 1999. The current facility, which is designated as the MITR-II, uses a compact core with finned, aluminum-clad, plate-type fuel that is cooled and moderated by light water and reflected by heavy water. The reactor core can hold twenty-seven fuel elements. However, the normal configuration is twenty-four elements. A maximum of four fuel elements can be replaced with in-core experimental facilities. A unique feature of the MITR-II's design is that fixed absorber plates can be inserted in the upper half of the core. These cause the flux to peak in the lower half which beneifits experimenters and also facilitates a fuel strategy that involves inversion of fuel elements midway through their life cycle. The MITR-II currently operates continuously for four weeks followed by shutdown of a few days for maintenance.

This paper provides an overview of current activities at the MITR including preparations for relicensing. The status of an on-going Phase-I clinical trial of boron neutron capture therapy for both glioblastoma multiforme and metastatic melanoma is described as well as the design of a fission converter facility for BNCT. Environmental research using neutron activation analysis is summarized as well as in-pile research focussed on LWR water chemistry and structual materials.

Reactor Relicensing

Currently we are planning a power upgrade to the maximum level (6-7 MW) that can be safely supported by the existing heat removal equipment. Preliminary thermal-hydraulic analysis for the upgrade was performed based on the existing heat removal system [1]. The reactor core power distribution was determined using MCNP. The MULCH-II code [2], which was written to model the MITR-II, was used for the thermal hydraulic calculations. Figure 1 is a comparison between the LSSS determined in 1970 for the MITR-II SAR and those for the proposed upgrade. Both were calculated for a primary coolant flow rate of 1800 gpm, a constant coolant level of 4" below overflow, and the same set of engineering hot channel factors. The current LSSS (denoted 1970) was derived analytically to determine onset of nucleate boiling (ONB) based on a very conservative approach. For example, it was assumed that the highest clad temperature occurred at the hot spot. Also, extra margin was arbitrarily added to allow for uncertainty in the nuclear hot channel factor determination. The new LSSS (denoted 1997) was calculated using the MULCH-II code, which models both the average and hot channels with each channel divided into small axial nodes. The result is a more realistic calculation of the conditions actually present in the fuel channels. Also, because of an improved computational tool (the Monte-Carlo based MCNP code vs. the diffusion theory-code CITATION) and the availability of actual flux measurements performed during the initial startup test in 1975, the nuclear hot channel factor can now be used without excess margin. However, other conservative assumptions are still retained in the current calculations. First, the hottest channel is assumed to be the channel which receives the minimal primary flow. This is because of the difficulty in predicting core flow distribution. Second, 100% of the fission power is assumed to be deposited in the fueled region. Also, the engineering hot channel factors are combined cumulatively, which is believed to be an overly conservative approach [3]. The new LSSS is proposed to be set at 7 MW and 70 °C compared to the current values of 6 MW and 60 °C as shown in Figure 1.

Other issues such as Xenon poisoning, Ar-41 production, liquid effluent releases, solid waste generation, design basis accident, emergency core cooling, auxiliary heat removal

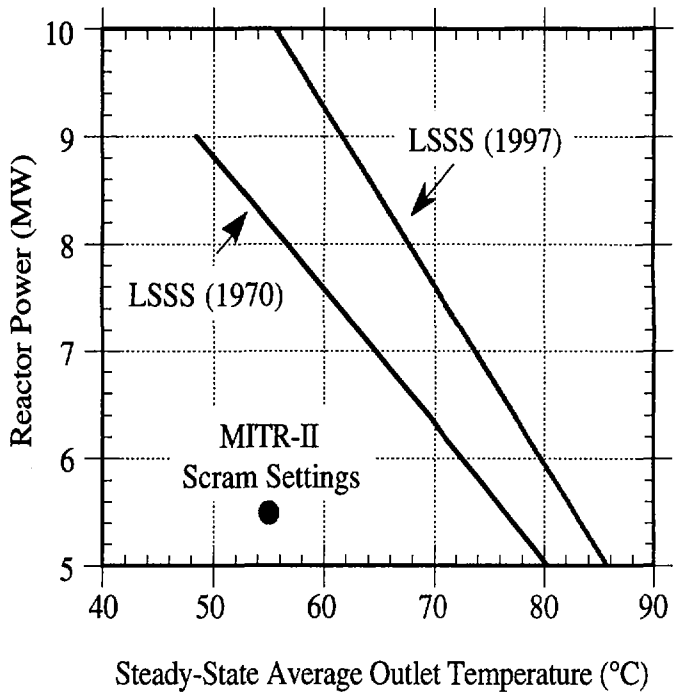

Figure 1. Comparison of the Calculated LSSS using MULCH-II and the LSSS used in the MITR-II SAR.

systems, shielding, and radiation effects in materials which may be affected by the upgrade have also been reviewed. Results show that the impact of proposed upgrade is insignificant and/or within regulatory limits.

Phase I Clinical Trial of BNCT

Neutron capture therapy (NCT) is a binary cancer therapy that entails the administration of a tumor-seeking boronated drug followed by the irradiation of the tumor region with neutrons. The neutrons cause boron nuclei to fission and thereby release densely ionizing helium and lithium nuclei (high LET), which destroy cancerous cells causing significantly less damage to adjacent normal cells. Neutron capture therapy is being tested on glioblastoma multiforme (brain tumors) and metastasized melanoma (skin cancer on the extremities and in brain). Both Brookhaven National Laboratory and MIT conducted trials of NCT more than thirty years ago. These were

unsuccessful because the available boron drugs did not concentrate sufficiently in tumor and because the thermal neutron beams that were used did not enable neutrons to travel deep enough into the brain. Many improvements have occurred since that time including Monte-Carlo based codes for neutron transport calculation, improved imaging techniques, microdosimetry methods that allow boron location to be determined at the cellular level, new drugs for the delivery of boron to tumor, and the design of epithermal neutron beams that allow delivery of dose to deep in the brain while also avoiding the need for surgery.

On February 16, 1993, the U.S. Nuclear Regulatory Commission (NRC) issued an amendment to the operating license of the MITR-II for the use of its medical therapy facility's epithermal neutron beam for the treatment of humans using neutron capture therapy. This was followed on July 20, 1993, by a parallel amendment to the license of our medical partner. In April 1994, the U.S. Food and Drug Administration (FDA) approved a melanoma protocol for BNCT. On September 6, 1994, MIT and its medical partner jointly initiated the first step in a phase-I protocol for the evaluation of NCT for metastatic melanoma. Phase-I protocols are a requirement by the U.S.. Food and Drug Administration (FDA). Their purpose is to determine the safety of a new experimental therapy. This protocol specified three subjects per dose level and a starting dose of 1000 RBE-cGy.

In July 1996, the FDA approved a protocol for the use of BNCT for glioblastoma multiforme (brain cancer). The initial dose was 880 RBE-cGy with dose-escalations of 10% per level. Irradiations were begun under this protocol in July 1996. As of the end of 1997, five human subjects had been irradiated under the melanoma Phase-I dose escalation protocol, three to a healthy tissue dose of 1000 RBE-cGy and two to a dose of 1250 RBE-cGy. Eleven human subjects have been irradiated under the brain cancer Phase-I protocol with the latest at the 1170 RBE-cGy level.

Table One summarizes the melanoma Phase-I trial. In one case there was significant shrinkage of the tumor and in another the tumor disappeared. Table Two summarizes the brain cancer Phase I trial as of December 31, 1997.

Table One

Melanoma Protocol Phase-I Trial

Subject	Irradiation Start	Tumor Location	Normal Tissue Dose (RBE-cGy)	Number of Fractions
1*	9/6/94	Right Foot (Plantar)	1000	4
2	10/24/94	Inside Left Calf	1000	4
3	12/5/94	Outside Left Calf	947	4
4	9/26/95	Outside Right Knee	1250	4
5**	5/9/96	Outside Left Ankle	1055	1

*Shrinkage of tumor
**Complete tumor regression.

Table Two

Brain Protocol Phase-I Trial

Subject	Tumor Type	Date	Irradiation Type	Healthy Tissue Peak Dose (RBE-cGy)	(mg/kg) BPA	Results as of 12/31/97
1	GBM	7/25/96	Bilateral	880	250	Survived Nine Months
2	GBM	7/1/96	Bilateral	880	250	Temporary Improvement
3	GBM	11/22/96	Bilateral	880	250	Survived Ten Months
4	GBM	1/30/97	Bilateral	970	250	Survived Two Months
5	GBM	2/28/97	Bilateral (Frontal/Side)	970	250	Recurrence Seen
6	MM	3/6/97	Bilateral	970	250	Survived One Year
7	GBM	4/10/97	Bilateral	1065 (Two Fractions)	250	Survived Six Months
8	GBM	4/24/97	Bilateral (Planned)	916	250	Post-Irradiation Edema
9	GBM	9/11/97	Unilateral	1065	250	Returned to Prior Status
10	GBM	9/18/97	Unilateral	1065	250	Returned to Prior Status
11	GBM	12/18/97	Bilateral	1170 (Two Fractions)	300	Returned to Prior Status

Design and Construction of a Fission Converter Based Epithermal Beam for Neutron Capture Therapy

The MITR's current epithermal neutron beam (M67) has an epithermal neutron flux of 2.1×10^8 n/cm^2 s. It takes approximately 2.5 hours to deliver a normal tissue tolerance dose of about 1000 RBE cGy. Because of the long irradiation time, a fission converter epithermal neutron beam, which is capable of treating a patient in a few minutes, was designed for advanced clinical trials and for routine therapy. Figure 2 shows the top view of the planned fission converter facility.

Design studies of the fission converter facility were performed for both spent and fresh MITR-II fuel elements using either D_2O or H_2O as the coolant. Table 3 summarizes the fission converter power calculated using MCNP with the MITR core at 5 MW. The calculated epithermal neutron flux at the patient position is about 1×10^{10} n/cm^2 s with the MITR core at 5 MW with specific fast neutron and specific incident photon doses lower than 2×10^{-11} cGy cm^2 /epi n (i.e., negligible non-selective dose components). An epithermal neutron flux at this intensity would result in an irradiation time on the order of minutes. Irradiation times in this range are typical of those used with conventional external beam irradiation facilities such as linacs and are important to patient comfort and needed for eventual high throughput of patients.

Table Three
Calculated Fission Converter Power [4]

Coolant	Fuel (g ^{235}U)	Fission Converter Power at 5 MW Reactor Power (kW)
D_2O	312 (Spent MITR-II Fuel)	81.5 ±0.3%
D_2O	510 (Fresh MITR-II Fuel)	105.4 ±0.2%
H_2O	312 (Spent MITR-II Fuel)	83.4 ±0.2%
H_2O	510 (Fresh MITR-II Fuel)	125.5 ±0.2%

Note: The statistical uncertainties listed as a percent for each value represent one standard deviation

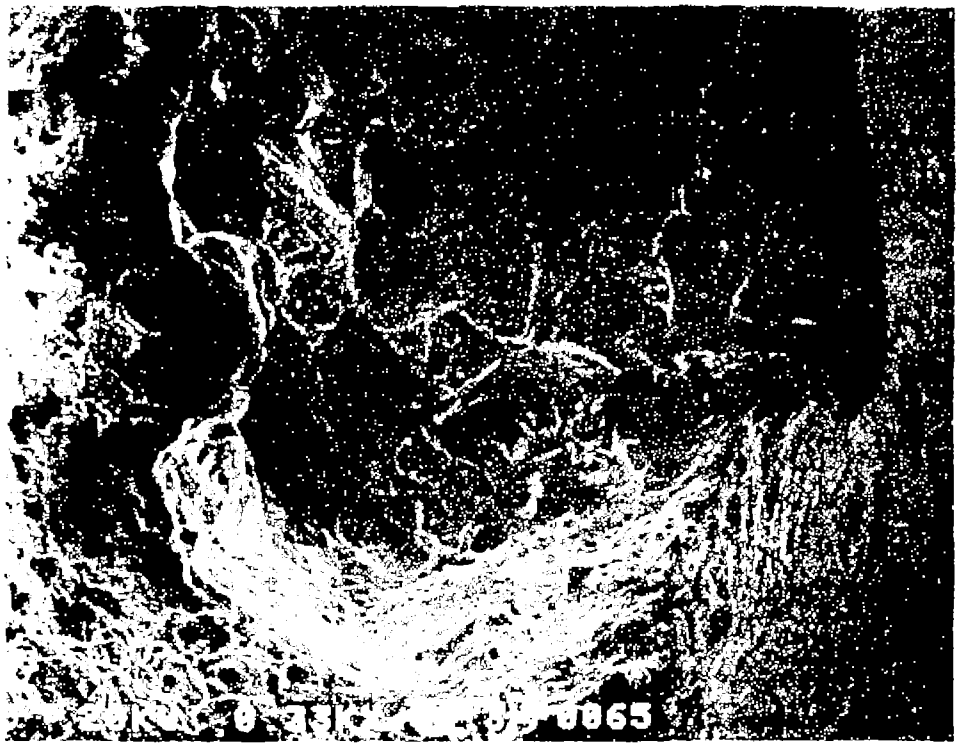

Figure 4. Fracture surface of a commercial purity 304 SS specimen pre-irradiated to 0.8×10^{25} n/m^2 and tested at slow strain rate in-core under BWR conditions.

prefer reactor-based projects because they provide them with an opportunity to utilize and synthesize the theoretical material that they have learned in relevant experimental tests. For example, those working on the reactor redesign can combine their understanding of reactor physics, thermal hydraulic engineering, and radiation safety. Another advantage of reactor-based thesis research is that it provides students with an opportunity to develop practical skills including measurement techniques and machining. A second educational use of the reactor is to support laboratory courses with exercises such as time-of-flight neutron spectrum measurements, subcritical multiplication, spectra unfolding, etc. A third use is that a small number (three or four per year) of highly motivated students are chosen for employment at the reactor. These students spend four months in an intensive training program and then take a two day exam administered by the U. S. Nuclear Regulatory Commission for a reactor operator's license. A year later they are

The new beam design is based on a fission converter made of MITR-II fuel elements which are driven by the neutrons from the reactor core of the MITR-II. Neutrons from the reactor are converted to a fission spectrum by the fission converter. A filter/moderator is then used to tailor the neutron spectrum to eliminate unwanted fast neutrons and photons without significantly decreasing the epithermal neutrons (1 eV to 10 keV) [5-7]. The cooling of the fuel contained in the fission converter will be provided by forced convection of either H_2O or D_2O enclosed in a tank.

A Safety Evaluation Report (SER) and associated Technical Specifications for the fission converter facility were submitted to the U. S. Nuclear Regulatory Commission in October 1997, as part of a request for a facility operating license amendment. A three year contract has been awarded by the Department of Energy (DOE) for construction and startup of the fission converter facility. Construction of the facility is currently in progress.

Environmental Research and Radiochemistry

Instrumental Neutron Activation Analysis (INAA) is one of the most sensitive, selective, and reliable trace element analysis techniques available. It is also nondestructive, and capable of detecting over 40 elements. In order to take full advantage of INAA, the MIT Nuclear Reactor Laboratory operates a radiochemistry laboratory where INAA is used to support research in materials science, biomedical and environmental studies, and the earth sciences.

A recent research program was completed at the MITR-II using INAA to study trace elements in atmospheric particulate matter across the upper New York State region of the United States. The primary goals of this program were to identify the significant regional sources of these elements and to establish their ambient background concentrations. From October 1991 through September 1993 daily samples of fine and coarse atmospheric particulate material (diameters less than 2.5 μm, and between 2.5 μm to 10 μm, respectively) were collected at five remote locations in upper New York State. Approximately 1400 of the fine fraction samples were analyzed for elemental composition by INAA. The sources of these particulates were identified by applying Factor Analysis (FA) and using known and inferred elemental markers. The absolute contributions

to the ambient elemental concentrations from each source type or group were calculated by the method of Absolute Factor Score-Multiple Linear Regression (AFS-MLR) analysis.

Of the sources identified by the analysis, U.S. regional sources, which are primarily well-aged, coal combustion emissions from the midwestern U.S., accounted for about 50% of the Se, Mo, and Sb; 35% of the Mn, Fe, Co, Zn, and As; and about 25% of the V, Cd, La, Ce, and Sm. Crustal material contributed about 50% of the Sc, Ce, and Sm; and between 20 and 35% of the Mg, Al, Mn, Fe, Zn, Se, Br, Sb, and La. About 60% of the Na and Cl were associated with a Canadian regional group of sources, probably due to marine aerosols originating from the Hudson Bay. Other sources which were identified to be responsible for significant amounts of one or two elements each were : 20% of the V from oil-related combustion and refining, 60% of the Cr and 70% of the Au from precious metal works, and 25% of As and Cd from smelter emissions [8].

Because of its well known toxicity, the sources and ambient concentrations of mercury were of particular interest in this study. It was found that approximately 55% of the fine particulate mercury originated from smelters in Ontario and Quebec, and 25% from a mixture of regional sources in the Midwestern U.S. [9]. A decline in the average measured particulate Hg concentration, beginning in February 1993, has tentatively been attributed to reduced emissions from one or more of the major Canadian smelters, which at that time undertook changes in operating conditions or emissions controls over the course of the study. Figure 3 shows the temporal variation of mercury concentrations at the five sampling sites.

Light Water Power Reactor Coolant Chemistry Studies and In-Pile Mechanical Property Testing

A number of unique experimental water loop facilities for the study of boiling water and pressurized water power reactor coolant chemistry have been installed and operated in the MITR-II. The in-core portions of the loops are exposed to a radiation environment very similar to that of a commercial light water reactor (LWR). Generally, the experiments are installed in aluminum containment thimbles and inserted into a dummy fuel element in an in-core fuel position. An

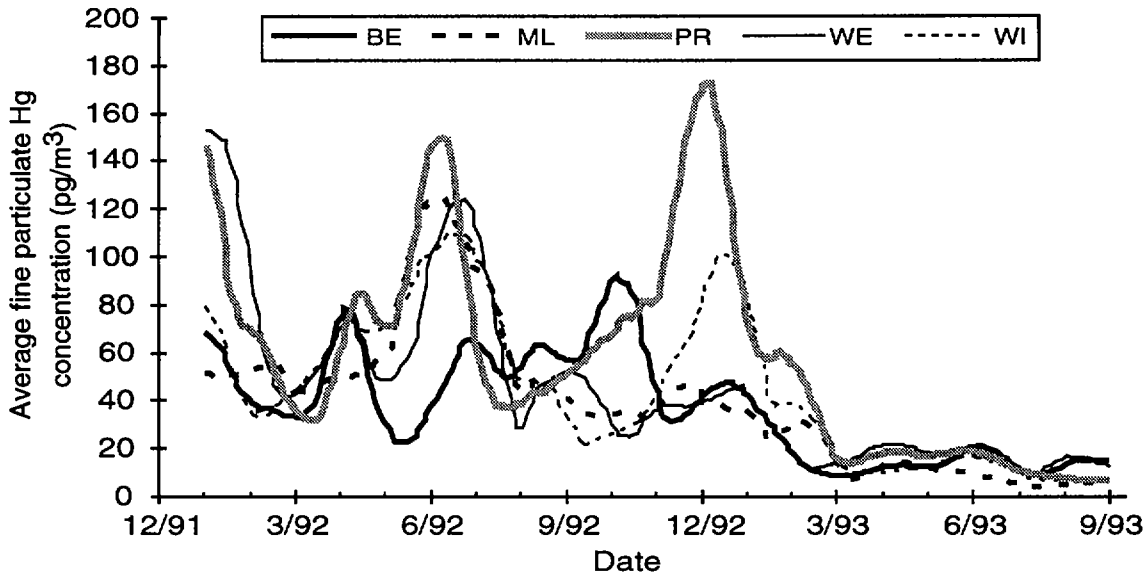

Figure 3. Smoothed, monthly average, fine particulate mercury concentrations at five sampling sites in Upstate New York, showing the common source influences among the sites, and an overall decline in concentrations beginning in early 1993.

insulating gas gap isolates the rig internals from the MITR-II primary coolant to allow operation in a temperature and pressure range of 280-325 °C and 7-16 MPa, again representative of commercial LWR conditions. The capabilities and the research objectives addressed by some of these facilities are briefly summarized below.

The first of the in-core loops was initially operated in 1989 and has been used for several programs studying the effect of PWR primary coolant chemistry on radiation product transport [10,11]. The PWR Coolant Chemistry Loop (PCCL) is designed to simulate, at about one third scale, a single flow channel in a PWR primary coolant loop. The temperatures, heat fluxes, coolant velocity, and area ratios of the wetted materials (zircaloy, inconel, and stainless steel) are closely simulated. In addition, the loop is designed to permit removal and replacement of all high temperature tubing for each irradiation run. Activity distribution throughout the entire loop can therefore be determined following irradiation, and subsequent runs are not compromised by residual activity or by corrosion film changes caused by decontamination procedures. Optimum

coolant pH and the use of zinc injection to reduce corrosion product transport have been studied using the PCCL.

A companion loop, the BWR Coolant Chemistry Loop (BCCL), makes use of technology similar to the PCCL and can be installed in the same core position using many of the same support facilities [12,13]. It is not designed to simulate the entire BWR coolant circuit but can be configured to simulate several regions of interest, including in-core boiling and bypass channels. In-core boiling and steam/water separation are achieved. A variety of on-line chemistry and activity monitors are provided. The BCCL has been used to study the radiolysis chemistry of water, with particular emphasis on computer code benchmarking, to investigate ways to reduce radioactive nitrogen carryover into the steam phase under normal and hydrogen water chemistry, and to evaluate alternatives to hydrogen for reducing the electrochemical corrosion potential of stainless steel in the BWR primary circuit.

In the past several years, the emphasis of the in-core LWR experimental program has been on the use of an in-core, actively loaded mechanical test facility [14]. Like the CCL experiments, this facility uses a high pressure, high temperature recirculating water coolant system to provide an environment representative of LWR primary coolant. One or more specimens can be loaded in the in-core or near-core water environment using a computer controlled Instron servo-mechanical testing machine mounted on the reactor core tank lid. The system has been operated with a single specimen, slow strain rate mode to study irradiation assisted stress corrosion cracking of pre-irradiated specimens, and in a multi-specimen, constant load mode to study BWR core shroud cracking. Figure 4 shows a scanning electron micrograph of the fracture surface of a 304 SS specimen tested to failure in the in-core test facility. Transgranular and intergranular cracking regions indicative of environmentally assisted cracking are observed.

Educational Uses

The MITR-II is used for education at MIT in three distinct ways. First, the major projects provide thesis research at the B.S., M.S., and Ph.D. level for graduate students. Many students

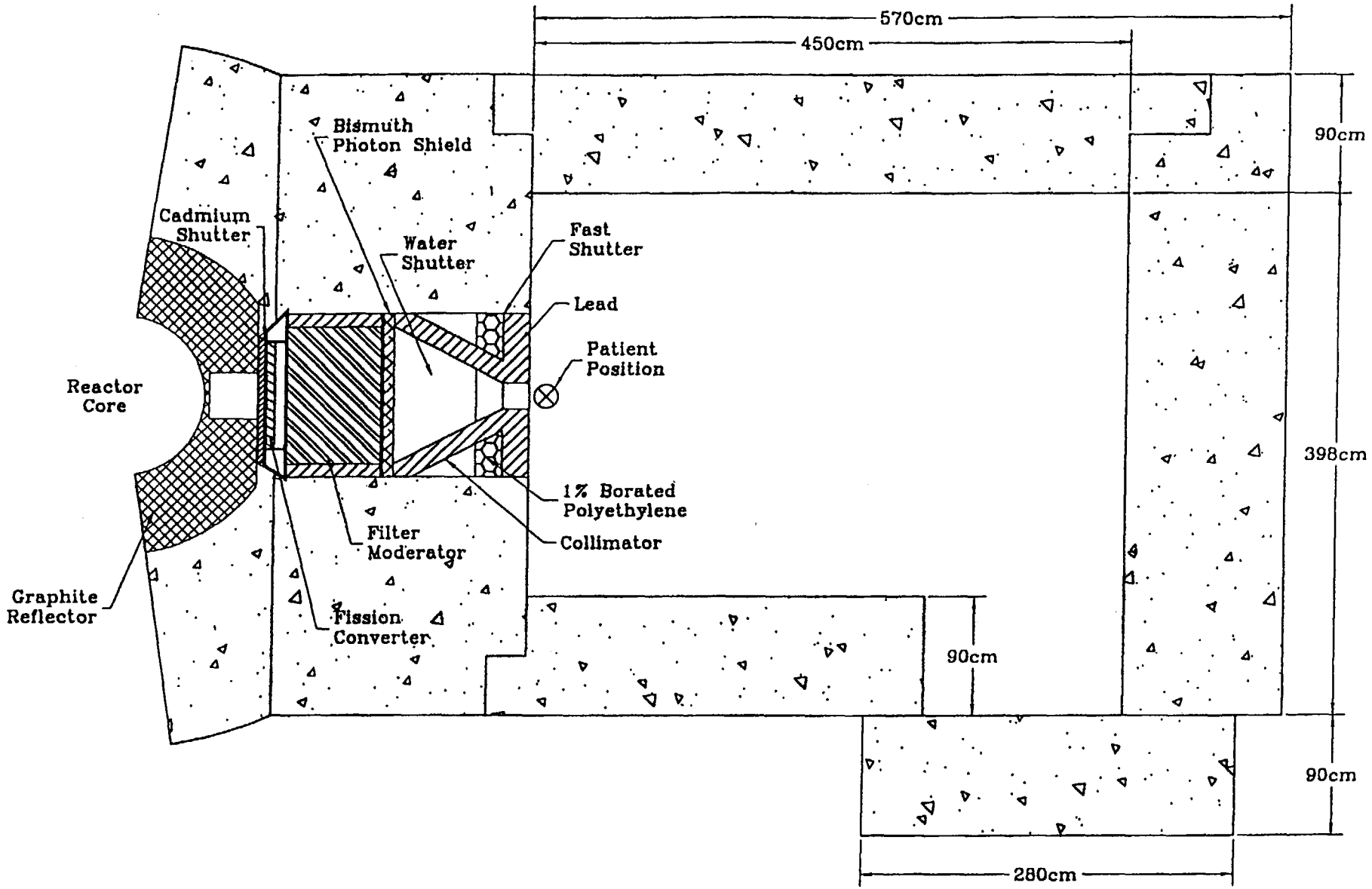

Figure 2. Top View of the Fission Converter Facility.

eligible to obtain a senior operator's license and may participate in a second training cycle for that purpose. Students who are involved in this program consistently state that the experience was the high point of their MIT education.

The MITR-II also serves as a regional educational facility. Tours are available to high school students, a lecture series on the applications of neutrons is offered to local-area science teachers, and visiting universities utilize the facility for both research and laboratory exercises [15,16].

Conclusion

The MITR continues to function, as it has for the past forty years, as an important facility for both education and research at the Massachusetts Institute of Technology for the Northeastern USA. This vitality exists because research reactors are themselves instruments, albeit very large ones, that allow scientists to investigate the nature of matter. New applications of neutrons for research continue to arise.

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