Nuclear Reactor Laboratory

Facilities and Resources

The MIT Nuclear Reactor Laboratory (NRL) is an interdepartmental center that operates a 5 MW research reactor in support of MIT's educational and research initiatives and goals. Its mission is to provide faculty and students from MIT and other institutions with both a state-of-the-art neutron source and the infrastructure to facilitate use of that source. In addition to the NRL's role as a major center for neutron research, the staff of the NRL is also committed to educating the general public about the benefits of maintaining a strong nuclear energy program by promoting education and training in the nuclear sciences and technologies within the United States.

The reactor, which is designated as the MITR-II, is the major experimental facility of the NRL. It is a heavy-water reflected, light-water cooled and moderated nuclear reactor that utilizes flat, plate-type, finned, aluminum-clad fuel elements. The average core power density is about 70 kW per liter. The maximum thermal neutron flux available to experimenters is $5x10^{13}$ neutrons/cm^2s. Experimental facilities available at the MITR include two medical irradiation rooms, beam ports, automatic transfer facilities (pneumatic tubes), and graphite-reflector irradiation facilities. In addition, several in-core sample assemblies are available. The MITR-II is the second of two research reactors that have been operated by NRL. The original reactor (the MITR-I) achieved criticality in 1958. In 1973 the MITR-I was shut down to allow conversion to the MITR-II, which offered a higher neutron flux level.

The NRL, which will soon celebrate its 50th anniversary, has a long history of providing faculty and students from MIT and other institutions with a state-of-the-art neutron source along with an extensive infrastructure to facilitate its use. Its principal mission has been to support educational training and cutting-edge research in the areas of nuclear fission engineering, radiation effects in biology and medicine, material studies, neutron physics, geochemistry, and environmental studies. Through the years, several thousand undergraduate and graduate students have benefited from their association with NRL by being offered an opportunity to pursue their research by utilizing a research reactor that has provided a unique hands-on environment.

Reactor Administration

NRL's organizational structure is comprised of four groups that work as a team to meet the short-term operational demands and long-term strategic challenges involved in operating a nuclear research reactor in the current environment. These groups are Reactor Operations; Research, Development, and Utilization; Engineering; and Administration. David E. Moncton is the director of NRL. He and John A. Bernard, Lin-Wen Hu, Edward S. Lau, Thomas H. Newton, and Robert Davine make up NRL's senior management team. This leadership team works to sustain NRL's long-standing record of safe operation, to continuously maintain and improve upon the state-of-the-art reactor facility, and to provide an environment of support and excellence for researchers and students.

NRL currently employs 52 individuals. The staff is broken down into six groups that include the previously mentioned six senior staff, six research staff, five technical staff, nine technical support staff, one academic staff, three administrative support staff, two technicians, 14 part-time student/operators, and six student trainees. In general, NRL support staff, student employees, and technicians have specific responsibilities to a particular group.

NRL supports MIT's affirmative action goals. There are 20 full- and part-time positions held by women and/or minorities, and of the 18 engineering and management positions, five are held by women and/or minorities. Long-term employees include a research staffer who is both a woman and a minority; the superintendent of operations, who is a minority; a neutron activation analyst, who is both a woman and a minority; the training coordinator, who is a minority; and the Q/A supervisor, who is a woman. As part of NRL's ongoing mission to train reactor operators, there is always a rotating group of MIT students that includes women and/or minorities. NRL participated in the US Department of Energy's (DOE) program for minority training in reactor operations. One of our current senior reactor operators is a graduate of this program and has become our training coordinator.

Reactor Operations

Leadership is provided by John A. Bernard, director of reactor operations, and by reactor superintendent Edward S. Lau. The reactor operations group, the largest at NRL, is responsible for supporting all laboratory activities, with priority on the operation and maintenance of the 5 MW research reactor. The group consists of full-time employees and part-time undergraduate MIT students. All members of the group are licensed by the US Nuclear Regulatory Commission (NRC), and most hold a senior reactor operator license. At present, there are 34 actively licensed individuals. All perform reactor shift duties to support the 24-hours-per-day, seven-days-per-week operating schedule. In addition, there is one full-time project mechanic to support reactor mechanical maintenance.

The MIT reactor completed its 49th year of operation (its 33rd since the 1974–1975 upgrade and overhaul). Beginning in 1994, the reactor adopted a schedule of continuous operation to support major experiments and utilization. The reactor was nominally maintained at a full power of 4.8 MW. Total energy output for fiscal year 2008 was 28,250 megawatt-hours. This translates roughly to 5,950 hours of operation at full power.

Major maintenance projects performed during FY2008 are described in this section. These were planned and performed to improve safety, reliability, and efficiency of operation of the MIT Research Reactor, and, hence, improve the predictability of the reactor operating schedule. Additionally, reactor staff provided major support for all installations and removals of reactor experiments, including segregation of their highly activated internal parts into various hot cells and designated storage locations. Reactor staff also provided monitoring of the following continuously-operating experiments:

- Advanced Clad Irradiation (ACI) Experiment—This is the longest-running in-core experiment for the reactor. During the beginning of this fiscal year, the experiment developed a leak and was removed for repair in mid-July. It was reinstalled in late July, and operated to completion in mid-October when it was removed after a total of about nine months of irradiation in core.

- 4DH4 Diffractometer—Reactor staff designed, fabricated, and installed the key rotating drum shutter mechanism and continued to support the development and testing of the diffractometer. Several new procedures were developed for testing at various power levels, including verification of beam centerline and measurement of beam spread vs. distance. These measurements provided crucial data for fabrication of a new beam stop structure.
- 4DH1 Student Spectrometer—Reactor staff installed safety railings, locking gates, and tall Plexiglas shields all around the spectrometer in order to prevent inadvertent entry into the beam path.

Major maintenance items performed in FY2008 are summarized as follows:

For continuous support of neutron transmutation doping of silicon, reactor staff created and upgraded many operational procedures and record keeping practices. There is an annual external audit to review the program for continuation of ISO 9001 certification. Preventive maintenance on conveyor machinery was performed during each scheduled outage. During this fiscal year, both servers for computer control and monitoring software were upgraded for improved redundancy. Additionally, the two silicon storage corrals on the reactor floor were rearranged for improved material flow and inventory control. Their walls were reoriented to provide better radiation shielding for personnel. The silicon workbench on the reactor floor was fitted with a Plexiglas shield to minimize spread of contamination during handling of activated containers and silicon ingots. A new area radiation monitor was mounted at the workbench to provide real-time dose information to workers.

The Fission Converter secondary system cooling pumps were rebuilt and their shafts replaced to prevent shaft seal leaks. These pumps had been in service since 1999.

The reactor cooling towers went through a two-week-long five-year maintenance service. Four of the 16 fan motors were rebuilt with improvements such as better windings and bearing components, and another four were done at a later time. Additionally, new epoxy was applied to the internal honeycombs within the towers to repair leakage. Some internal components were also replaced to improve air flow paths inside the towers.

Three major secondary coolant system valves (HV-3B, HV-4, and HV-4B) were replaced. These valves have to be manipulated every startup and shutdown. The new valves are much easier to operate, reducing equipment room stay-time and dose exposure to personnel operating them. These new valves are also designed to seal better for shutdown isolation.

Solenoid valve AV-35 was replaced with a hydraulic-operated automatic valve designed for fluid systems. This valve automatically secures city water supply to the containment if a high level is detected in the equipment room wet-sump.

Over a dozen surveillance cameras were installed to monitor exterior views. Reactor staff installed all the associated mount points, conduits, and wiring. This represents an important security upgrade.

The NW12 steam boiler was replaced with a new high-efficiency unit. This boiler now provides the main steam heat to the reactor intake air in the winter. Automatic transfer valves were installed to allow backup steam from MIT's central steam supply in case this boiler fails. New pressure gauges and pressure switches were also installed for better monitoring and control. The new boiler performed satisfactorily throughout the winter, with minor adjustments occasionally required.

The reactor's emergency batteries were checked under load using infrared imaging. No hot spots or ground fault deficiencies were identified.

Analog displays for five pneumatic instruments in the control room (core tank level ML-3B, secondary coolant flow HF-6, primary coolant storage tank level, shield coolant storage tank level, and reflector D_2O dump tank level) were replaced with new digital indicators. This replacement became a necessity as analog components became less available. The pneumatic function of these devices remained unchanged, providing continuous indication when there is a loss of electric power. All poly tubing for the pneumatic signals was also replaced.

The reactor containment elevator lifting jack and its jacket were replaced with a double-walled unit to meet new Massachusetts elevator safety codes. The replacement was completed in several stages, each requiring reactor shutdowns for access to the elevator controller and hydraulic box. Additionally, the controller was upgraded and the hydraulic oil was replaced.

The hydraulic motor starter/contactor for the reactor exhaust ventilation damper was replaced with a current industrial-grade unit for improved reliability. It was also repositioned, for greater accessibility for routine inspection and maintenance.

Shim blades #2 and #3 were replaced as preventive maintenance.

Three riser pipe sections of the shield coolant manifold in the equipment room were replaced as preventative maintenance.

Six new radiation area monitors were installed to supplement the existing area monitor system. Additionally, the existing units were retrofitted for wireless transmission to a new telemetric computer logs data logging and routes visual display information to the control room.

A significant maintenance focus over the course of FY2008 was on shipping low-level waste to reduce the inventory on site. The two shipments included 41 55-gallon drums of liquid, and 36 55-gallon drums of solid waste. Additionally, other bulk-volume low-level solid waste was sorted and packaged into five B-25 containers (12,000 pound capacity, certified for use in Type A packaging) and five B-12 containers (approximately half the size). These 10 containers are now sealed airtight as per manufacturer's specification. They have been weighed and gamma-characterized, and will be shipped in the near future.

A bypass system was designed and installed to provide CO_2 cover gas to the reactor's graphite region without use of its original gasholder. Evaluation of this system has been underway for several months and remains ongoing. The ultimate goal is to retire the gasholder and dismantle it in order to provide space for installation of new heat exchangers.

A rainwater leak at the back stairwell's outer wall was repaired. This required digging a trench approximately 10 feet long and more than two feet deep along the outside of the wall, and then sealing the wall seams below grade with cement sealant. This corrected a chronic seepage problem which had finally worsened to the point where the source could be identified.

The low-temperature sensor for the containment building's ventilation intake was replaced with a new digital unit.

One of the two large air conditioning units for the containment building ventilation system was replaced on the rooftop of the utility room. It had been damaged beyond repair by an early-spring snowstorm when an avalanche of ice that had collected on the containment building landed on top of it. There have been no previous examples of anything similar happening on that roof. The new air conditioning unit was installed farther from the containment wall to prevent a recurrence.

The variable frequency drive controllers for the primary pumps were thoroughly inspected and tested. The controller for pump MM-1A was found to have an intermittently faulty block switch, which was then replaced with an upgraded unit.

The ion column for the reactor primary coolant system was repacked and replaced five times during the fiscal year. The D_2O reflector system's ion column was repacked, deuterized, and replaced. The spent fuel storage pool's ion column was repacked and replaced. The shield system's ion column was also repacked and replaced after more than three years in service.

A full-size wooden mockup was constructed of the proposed design for the secondary chemistry hot cell in the reactor's basement. The new manipulator was mounted on the mockup to make sure that its designated position will allow it to reach all the key points inside the new cell. This provided significant data for the new design, which is intended to improve radiation protection, ventilation, lighting, and manipulator capability for post-irradiation sample handling for neutron activation analysis.

Reactor staff coordinated with a certified contractor to inspect the polar crane in the containment building. For this year, we had the contractor include a dye penetration test on the hook and shackles.

The main intake and exhaust ventilation dampers were cleaned, lubricated, and vacuum-tested satisfactory. This is a scheduled preventive maintenance item to ensure reliable operation for containment isolation when needed.

All reactor pump motors, shafts, and bearings were inspected and lubricated twice during the year. This represents an upgrade in preventive maintenance practice for over a dozen pumps and blowers.

Reactor Operations provides a major service in the production of neutron transmutation doping silicon for international suppliers. This silicon is currently used primarily for power devices such as thyristors in hybrid cars, for solar power panel development, and for the production of memory chips. This service provides commercial income (approximately $1.2 million annually) that is used to offset operating costs.

To fulfill one of the stated missions of NRL, Reactor Operations trains up to six MIT undergraduates each year, typically starting in their freshman years, to obtain an NRC license to operate the MIT Reactor. The training program is rigorous and covers reactor dynamics, radiation detection, radiation safety, and reactor systems. The level of instruction is comparable to that offered in undergraduate MIT courses that cover these same topics. In addition, students are taught how to operate the MITR-II. Upon completion of the training program, a two-day examination is administered by the NRC (one day written, one day oral). Successful candidates receive a reactor operator license and are employed part-time during the semester at the MITR. After the students gain experience, most are offered the opportunity to participate in a second training program that leads to a senior reactor operator (SRO) license. This training program is an excellent educational opportunity for MIT undergraduate students because it combines theoretical study with hands-on experience in the MIT tradition of graduating students who know how both to design and build systems. In addition, students who receive the SRO license obtain management experience by serving as shift supervisors. Students who have completed this training program regularly state that it was one of the high points of their MIT experience.

During this reporting period, two sets of NRC exams were administered on site. Four students obtained reactor operator licenses, three students were upgraded to SRO licenses, and three reactor staff members obtained their licenses. Five MIT students are currently in training for license exams in September 2007.

The relicensing of the MITR-II with a concomitant upgrade in power is in progress. It was previously determined that the MITR-II could operate at a maximum power of 6 to 7 MW with the existing heat removal equipment. A decision was subsequently made to submit the licensing documents for a power increase from 5 to 6 MW. On July 8, 1999, a formal application was submitted to the NRC to relicense the reactor for an additional 20 years and to upgrade the power level to 6 MW. The relicensing package included a complete rewrite of the Safety Analysis Report and the Technical Specifications. Until the relicensing approval process is completed, the NRC has authorized the continued operation of the MITR. This mode of operation has been ongoing since 1999.

Reactor Research, Development, and Utilization

Dr. Lin-Wen Hu is NRL's associate director of the Research, Development, and Utilization group. She and her staff have developed a strong program that assists MIT faculty, researchers, and students as well as those outside of NRL in their use of the reactor and its irradiation facilities. Some of the tasks assigned to this group include:

- Supporting research in the area of advanced materials and fuel research
- Providing researchers with a service-based infrastructure that supports the US initiative for designing and building the next generation of nuclear reactors as a means of reducing the country's reliance on fossil fuels
- Supporting the Neutron Capture Therapy (NCT) User Center for animal irradiations and chemical compound development
- Providing researchers with a service-based infrastructure that utilizes the MITR-II for trace element analysis, isotope production, and irradiation services
- Supporting an outreach program to the educational community to encourage understanding of nuclear energy and its applications
- Supporting MIT's educational missions by providing Independent Activities Period lectures, hosting Undergraduate Research Opportunities Program students, and offering lab courses for professionals, undergraduates, and advanced secondary school students
- Expanding the user base for underutilized experimental facilities

The reactor was well-utilized during the year. ACI, an irradiation experiment led by Dr. Gordon Kohse and Professor Mujid Kazimi to study the response of SiC/SiC composite materials to pressurized water reactor (PWR) conditions was the major in-core experimental activity. These materials have been proposed as a replacement for Zircaloy fuel-cladding for PWRs in order to improve fuel performance in loss-of-coolant accidents and thus allow for increased reactor power and higher fuel burnup. A Phase I irradiation was completed in September 2006 and samples were removed for examination at MIT and mechanical property testing at Oak Ridge National Laboratory. A Phase II irradiation was started in December of 2006 containing some new specimens and other specimens continued from Phase I. Phase II irradiation continued through October 2007. This project is supported by the DOE and Westinghouse. Several graduate students have participated in both the experimental work and associated fuel clad behavior modeling studies. The irradiation studies at MIT under realistic PWR in-core conditions have been key to the continued interest of DOE in this development. Additional funding from nuclear industry is expected to continue this study.

Other research and utilization highlights achieved during the past year include:

- Neutron activation analysis (NAA) to provide routine ultra-trace element analysis of semiconductor dopant materials
- An inductively coupled plasma spectrometer was utilized for a variety of trace element analysis studies. Notable applications included boron in tissue in support of boron neutron capture therapy applications, nanoparticle colloids

being studied for heat transfer enhancement, and gold in drug delivery compounds.

- Creation of several protactinium-233 sources for the Woods Hole Oceanographic Institute (WHOI). The researchers use the sources to study ocean circulation and its relation to abrupt climate change.
- Activation of welding fume, fine, and ultra-fine particulates, and nanoparticles for radiotracer animal study at Harvard School of Public Health
- Neutron transmutation doping of silicon wafers for neutrino detector development
- Medical isotopes production such as activation of gold seeds for brachytherapy; iridium wires and yttrium foils are irradiated periodically at research quantities for clinical trials. There has also been a trial irradiation of xenated seed for radioactive iodine production to determine feasibility of possible commercial production.

The MITR-II was used for experiments and irradiations in support of research, training and education programs at MIT and elsewhere. Irradiations and experiments conducted in FY2008 include:

- Use of the thermal neutron beam for the irradiation of Si photodetectors for Boston University researchers testing detectors for the use in proton accelerators and colliders
- Activation of uranium foils for detector calibration at the Los Alamos National Laboratories and other national DOE facilities
- Activation of ocean sediments for the WHOI and the University of British Columbia
- Experiments at the 4DH1 radial beam port facility by MIT undergraduates, including: measurements of leakage neutron energy spectrum to determine reactor temperature; measurement of neutron wavelength and time-of-flight; and measurement of attenuation coefficients for eight shielding materials
- Use of the reactor for training MIT student reactor operators and for MIT nuclear engineering classes (courses 22.05, 22.06, 22.09, 22.921, and the Reactor Technology Course for nuclear power executives)
- NAA of Charles River sediments for the investigation of semiconductor industry pollution for MIT Department of Civil and Environmental Engineering
- Gamma irradiation of sensor materials for MIT Department of Chemistry
- NAA of crushed filtration beads samples for determination of iron content for the Harvard School of Public Health
- Neutron transmutation doping of Si wafers for Lawrence Berkeley National Laboratory. These wafers were then used for further neutrino detector research
- Activation of nanoparticles for radiotracer study of nanomaterial toxicity study for Harvard School of Public Health

- Testing of carbon composites as neutron shielding for portable electronic devices

A number of reactor irradiations and services were performed for research groups outside MIT. Whereas most of the outside users pay for irradiation services at the reactor, educational institutions needing such services for their own academic or research purposes are assisted in this regard by the DOE through its Reactor Sharing Program. This grant reimburses NRL for the costs of providing irradiation services and facilities to other not-for-profit institutions (including teaching hospitals, high schools, and universities). Under this program, 500 students and 50 faculty and staff from more than 40 other educational institutions benefited from visits to and use of the reactor during the past year.

For education of the general public and students at all levels in local and other New England schools, the reactor staff provides lectures and tours periodically throughout the year.

Several new initiatives are also under development by this group, including design and construction of a new in-core cladding testing facility, neutron beam research utilizing NRL's soon-to-be-implemented neutron diffractometer, neutron phase contrast imaging, a web-enabled student spectrometer, and an expanded DOE-sponsored outreach program called the Harnessed Atom.

Partnership Between Test Reactors to Support Nuclear Energy Research

The Advanced Test Reactor National Scientific User Facility (ATR NSUF), centered at Idaho National Laboratory, and MITR have announced a partnership designed to increase user access to national reactor irradiation and testing capability. The NSUF test space at both reactors is made available at no cost to external users whose projects are selected via a peer review process. This partnership with MITR is the first in an expected series of national partnerships designed to enhance the NSUF infrastructure and capability. The MITR will offer a portion of its test capability to the NSUF experimenters.

Reactor Engineering

Dr. Thomas H. Newton is the associate director of reactor engineering at the NRL. This group's activities include experimental support and development for in-core sample assembly, nanofluids, high temperature irradiation facility, ACI, irradiation of fusion insulation materials, and neutronic modeling of proposed experiments. In addition, Dr. Newton is the principal investigator for two research projects that have been funded by Argonne National Laboratory that will eventually enable the MITR-II (along with the other research reactors within the high powered reactor group—University of Missouri Research Reactor Center, National Institute of Standards and Technology (NIST), High Flux Isotope Reactor, and Advanced Test Reactor) to be converted from High Enriched Uranium to Low Enriched Uranium (LEU) fuel. These research activities which involve neutronic and thermal-hydraulic modeling and the design of the LEU fuel and core for future use in the MITR are of significant importance because the DOE has made a commitment to convert all research reactors to LEU fuel by 2014.

This group is also providing the engineering upgrades necessary for the installation of a neutron diffractometer that was obtained from NIST last fall. Other activities of this group include the supervision of the management of fuel in the reactor and Fission Converter, overseeing shipments of spent fuel as well as other engineering services, such as the revamping of pressure test measurements and calculations.

Research Programs and Facilities

NRL has a strong materials and in-core loop program that supports research in the areas of advanced materials and advanced fuels that are necessary for both existing and advanced power reactors. MITR offers a unique technical capability that involves the design and use of in-core loops that replicate PWR/boiling water reactor conditions to study the behavior of advanced materials and scoping study of advanced nuclear fuel. With rekindled national interest on the part of DOE and the nuclear industry in next-generation nuclear power systems, many using novel materials and advanced forms of fuels, facilities are needed to test material and fuel behavior in a variety of radiation environments. MITR is arguably the best-suited university reactor for carrying out such basic studies because of its relatively high-power density (similar to a light water reactor), the capability to control chemistry and thermal conditions to reflect prototypic conditions, its easy-access geometric configuration, and space for up to three independent irradiation tests.

To support the advanced materials and fuel research program, MITR-II is equipped with post-irradiation examination (PIE) facilities that include the following: two top-entry hot cells with manipulators (1,000 Ci capacity each), a lead-shielded hot box (20 Ci capacity) with manipulators, an overhead crane with 3-ton and 20-ton capacities, and several transfer casks. There is also a fracture-toughness testing capability available to support irradiation testing. Our hot cell facilities can accommodate a Charpy testing machine that could be used for on-site testing of irradiated materials. The PIE facilities are currently refurbished with funds from DOE's Innovations in Nuclear Infrastructure and Education (INIE) Program. Additional equipment upgrades and purchases to support PIE, such as manipulators, alpha detectors, and ventilation, are also being funded by INIE, and another DOE grant.

A new activity related to the in-core experiment program is the design and construction of a new in-core sample assembly as a general purpose irradiation facility. New design features include gamma heating susceptor to allow irradiation at higher temperature for advanced reactor instrumentation tests.

Investigation of Nanofluids for Nuclear Applications

Dr. Lin-Wen Hu and Professor Jacapo Buongiorno of the Department of Nuclear Science and Engineering NSE led a research group to study the heat transfer enhancement of nanofluids. Nanofluids are engineered colloids made of a base fluid and nanoparticles (1–100 nm) in various forms. The presence of the nanoparticles alters the thermal-hydraulic behavior of the fluid: increased thermal conductivity, increased viscosity, increased single-phase convective heat transfer, and increased departure from nucleate boiling heat flux. Given their potential for enhanced heat removal performance, nanofluids are being investigated for numerous applications including electronics, manufacturing, chemical processes, and power generation. A collaborative NRL/NSE research program has been initiated to assess the feasibility of nanofluids for nuclear applications. Potential applications include PWR primary coolant, standby safety systems, and severe accident cooling. Another application being evaluated is to utilize the nanofluids to pre-treat heated surface for enhance heat transfer and corrosion control. The program comprises the following activities, currently sponsored by AREVA/Framatome, Electric Power Research Institute, King Abdulaziz City of Science and Technology in Saudi Arabia, a gift from a private donor, NSF, a DOE Nuclear Engineering Education Research grant, and INIE.

Neutron Capture Therapy Program

Directed by Professor Otto K. Harling (NSE), NRL's Boron Neutron Capture Therapy for cancer research is the leading NCT research program in the United States and is considered to be among the top in this field worldwide. Professor Harling's group maintains, develops, and operates high-performance irradiation facilities for NCT-related research utilizing the MITR. This research program has been supported primarily by DOE and comprises the following facilities and capabilities:

- High intensity, high purity beams of thermal and epithermal neutrons that approach the theoretical optimum for Boron Neutron Capture Therapy (BNCT)
- Physical and computational dosimetry associated with experimental (and clinical) studies
- Bulk analysis of boron distributions in tissue specimens using prompt gamma neutron activation analysis (PGNAA) or inductively coupled plasma atomic emission spectroscopy
- A working cell culture laboratory supporting murine tumor cell lines
- Assistance with designing and performing animal or cell culture experiments to test new boron tumor targeting agents or translational research to initiate new clinical trials in BNCT
- A high-resolution polymer track etch technique for viewing boron capture reactions in stained tissue sections

The thermal and epithermal neutron medical irradiation facilities are the only beams licensed by the NRC for clinical trials. The fission converter-based epithermal neutron beam line has been augmented to include an optional lithium filter that improves beam penetration and increases the therapeutic ratio for deep-seated tumors by as much as 15% and was refueled in the previous fiscal year, increasing beam intensity by 20%.

This project supports, maintains, and operates the reactor's Fission Converter, PGNAA, and the thermal neutron beam facilities that are used primarily for boron drug testing and characterization. Dedicated laboratory space in NW13 is used to support these experiments by, for example, maintaining cell lines and injecting animals prior to irradiation as well as harvesting samples and preparing them for analysis. Laboratory equipment such as a cryostatic microtome and a newly acquired optical microscope with precision stage and image analysis software are used to perform high resolution quantitative autoradiography (HRQAR). This technique can image boron-capture events in polymer track detectors superimposed on stained tissue sections with microscopic resolution, and this capability exists only at MIT.

Innovations in Nuclear Infrastructure and Education Program

The DOE established the INIE Program to provide qualified universities and reactor facilities with funds to improve instrumentation, maintain highly qualified research reactor staff, establish programs that fully integrate the use of university research reactors with nuclear engineering education programs, and establish internal and external user programs. The decision to implement this program is proving to be a good first step toward ensuring that the United States preserves its worldwide leadership role in the field of nuclear science and engineering. Prior to INIE, university nuclear science and engineering programs were waning, undergraduate student enrollment was down, and university research reactors faced the real possibility of closure. The INIE Program has started the process of drawing a new blueprint with positive goals and objectives that will support educators, students, and researchers today as well as in the future.

Now in its fifth and final year, this program has led to renewed interest in utilization of the MITR. INIE has supported numerous research initiatives conducted by NSE faculty members and researchers as well as graduate student research assistantships.

NCT User Center

INIE provided funds to begin offering facilities at MIT as a NCT User Center. It is the only such program in the United States and is essential for a viable research and clinical program in NCT. The center in operation at the MITR comprises high performance neutron beam facilities and scientific expertise specializing in NCT research. INIE funds supported the following studies utilizing the User Center during the past year:

- HRQAR was performed on biodistribution samples to determine the uniformity of tumor boron uptake of boronated liposomes. (Professor Hawthorne, University of Missouri)
- Boron quantification in newly synthesized boronated metalloporphyrin compounds as possible tumor targeting agents for BNCT (Michi Miura, Brookhaven National Laboratory)
- Completion of Part II of the International Dosimetry Exchange for BNCT. This is a major advance for the experimental radiotherapy enabling for the first time a common evaluation of absorbed dose specification between all clinical facilities in Europe and the US. This study is being led by MIT and is an ongoing worldwide collaboration involving participants from Finland, Sweden, the Netherlands, the Czech Republic, the UK, Argentina, and Japan as well as the US.
- Biodistribution experiments including HRQAR that investigated the ability of boronated nitroimidazoles to target hypoxic regions of F98 brain tumor in rats (Dr. W. Yang, Ohio State University; Dr. Peter Binns, MIT; Professor David Lee, Harvard Medical School)
- Studies to develop carbon nanotubes as radiation detectors using both neutron and gamma irradiation facilities (Professor Timothy Swager, MIT)

- Further in vivo studies to develop a new peptide under development that selectively targets tumor acidosis as a possible agent for BNCT (Professor Yana Reshetnyak, University of Rhode Island; Professor Don Engelman, Yale University; Dr. Kent Riley, Radiation Monitoring Devices)
- Preparations of organically modified silica nanoparticles were assayed using PGNAA to evaluate boron concentrations as a possible delivery vehicle for NCT (Dr Rajiv Kumar, State University of New York, Buffalo)
- Completed MSc thesis research for an MIT student showing that selective irradiation of the blood vessels using boron confined to the blood stream produced localized radiation damage in the endothelial cells of vasculature and quantified the magnitude of the effect
- A Masters and two Doctoral degrees were completed by MIT students who utilized the unique irradiation facilities of the User Center with the financial support of the INIE program.

The neutron irradiation facilities were also used for non-NCT applications including:

- Feasibility studies for performing neutron phase contrast imaging
- Testing detectors for neutron radiography and characterizing the quality of the existing thermal neutron beam for transmission radiography
- Evaluated available thermal neutron beam for trial neutron radiography with a prospective industrial partner
- Investigated radiation damage from thermal neutrons in silicon photomultipliers together with the associated front-end electronics developed for installation in the Compact Muon Solenoid of CERN's Large Hadron Collider (Professor James Rohlf, Boston University)

In-Core Loops

This portion of the MITR INIE program involves the in-core irradiations for of both advanced fuels and materials. The advanced fuels work is directed by Professor Mujid Kazimi. The materials studies are primarily coordinated by Professor Ronald Ballinger. Both are assisted by Dr. Gordon Kohse and Yakov Ostrovsky. The MITR staff person who interfaces with these projects is Dr. Lin-Wen Hu.

Educational Innovations

NRL hosted nuclear engineering students from across the US who participated in a thermal hydraulics experiments course for nuclear engineers that utilized NRL's INIE-funded Thermal Hydraulics Laboratory.

Infrastructure Enhancements

INIE funds were responsible for several important upgrades to the MITR. The improvements include:

- A new manipulator in reactor floor hot cell #1

- Repair of hot cell #2 manipulators
- Local and remote area radiation monitors for hot cells now functional
- Parts purchase for repair of shim blades/regulating and position indicators
- A new HPGe detector for NAA activities

Environmental Research and Radiochemistry

Dr. Lin-Wen Hu has taken on the role of overseeing the operation of NRL's environmental research and radiochemistry laboratories. The MITR-II is currently equipped for both prompt and delayed gamma NAA. For the former, a prompt gamma spectrometer was built as part of the NCT program to measure the boron content in the blood and tissue of patients and experimental animals. The facility is available to other users. Relative to the latter, the MITR-II is equipped with five pneumatic tubes that can be used for NAA. One offers a thermal flux of $5x10^{13}$; the other four offer thermal fluxes of 4 to $8x10^{12}$. One of the tubes is automated so that samples can either be ejected to a hot cell within the reactor containment or transferred via a pneumatic tube to a laboratory in an adjacent building. In addition to the pneumatic tubes, there are four water-cooled facilities in which large numbers of samples can be simultaneously irradiated in a uniform flux. Samples in these facilities are rotated.

NRL makes its NAA facilities and expertise available to industry, other universities, private and governmental laboratories, and hospitals. Research- and/or service-oriented collaborations were continued with several MIT research laboratories as well as with other educational and research institutions, including Harvard, the California Institute of Technology, Tufts University, the University of Connecticut, and WHOI.

New Research Initiatives

Neutron Spectrometer Experimental Facility

One of the initiatives during the past year has been to improve the reactor's infrastructure by upgrading and web-enabling an existing neutron spectrometer system. This program is an important educational outreach activity for NRL. The objective is to refurbish a neutron time-of-flight spectrometry experiment that is installed on one of the thermal neutron beams at the MITR, with the addition of capability to operate the experiment interactively over the internet as part of MIT's iLab program. An initial implementation of the LabVIEW controlled experiment was installed and tested during the spring term of 2006–2007. Student response was positive, and hardware and software upgrades are currently underway to improve reliability and add functionality in preparation for putting the experiment online. Experiments online will be adapted for students at the high school, undergraduate, and graduate levels.

Neutron Scattering

Although neutron scattering had a long and distinguished history at NRL, it was not actively pursued after the retirement of Professor Cliff Shull. However, a revitalization of NRL's neutron scattering program was initiated three years ago under the direction of Professor Moncton with the assistance of Dr. Boris Khaykovich. As a result of their efforts, this NSF-funded project (which includes installation of new neutron scattering instruments; a neutron diffractometer with polarizing capabilities; and a neutron optics test station) is now nearing completion. A new program to develop specialized neutron optics was recently funded by DOE.

Neutron scattering and spectroscopy are among the preeminent tools for studying the structure and dynamics of matter at the atomic and molecular scales. A powerful new neutron facility, the Spallation Neutron Source (SNS), is currently under construction at the Oak Ridge National Laboratory and is widely anticipated to revolutionize this field and enable the United States to regain leadership lost to Europe decades ago. The SNS will catalyze a new generation of instrument development, a new generation of neutron scientists, and therefore scientific research with neutrons.

NRL envisions the following programs resulting from this initiative: education and training for students in basic concepts of neutron scattering; enhanced production of new materials at MIT and elsewhere by allowing rapid evaluation via neutron scattering; development of novel neutron optics components; conceptual development of a new imaging instrument—a neutron microscope in absorption and phase contrast—for future installation at the SNS; and establishment of a user facility designed to allow users from outside of MIT to conduct early phases of some experiments more quickly than at large facilities and to test and develop new neutron optics components.

Safety and Security

Operational Safety

Many years ago, MIT established a very effective means of ensuring safe operation of the reactor by appointing independent individuals to a committee known as the MIT Reactor Safeguards Committee. This committee, whose members are from MIT as well as from industry, is ultimately responsible for overseeing all nuclear safety issues related to the reactor and ensuring that reactor operation is consistent with MIT policy, rules, operating procedures, and licensing requirements. However, *all* members of the NRL organization are keenly aware that safe operation of the nuclear reactor at MIT is their top priority. This level of awareness is achieved through the excellent guidance and continuous training provided by NRL's management team. An environment of cooperation and attentiveness to detail among reactor employees and experimenters regarding all reactor safety matters is essential. As a result of this approach to safety, each and every individual employed at the reactor can be proud of NRL's outstanding safety and operating record, which is evidenced by the results of NRC inspections.

Modern approaches to safety combine personal expertise and strong training with a methodology for continuous improvement. NRL is now utilizing a continuous improvement program that has three major goals: reducing unplanned shutdowns, minimizing environmental releases, and limiting personnel exposures as per the "as low as reasonably achievable" principle. The program, which is computer based, allows all NRL employees to provide input on how to improve reactor operations and safety whenever they see a "condition" of concern, including nuclear, radiological, and industrial safety. Condition reporting is the driver for a series of assessment and follow-up actions.

Reactor Radiation Protection

Radiation protection coverage is provided by the Reactor Radiation Protection Program of the Environment, Health, and Safety Office (EHS), a separate organization within MIT. Personnel include a deputy director for EHS serving as the reactor radiation protection officer (Frederick F. McWilliams); an EHS officer (Patricia Drooff); two technicians; and part-time secretarial support. Routine activities include but are not limited to radiation and contamination surveillance, experimental review and approvals, training, effluent and environmental monitoring, internal and external dosimetry programs, radioactive waste management, emergency preparedness, and ensuring that all exposures at NRL are maintained as low as reasonably achievable in accordance with applicable regulations and Institute committees. In addition to the above, the deputy director also serves as the EHS lead contact to NRL under the EHS Management System organizational structure.

Professional Activities in Support of NRL's Mission

NRL has always maintained a close working relationship with the Organization of Test Research and Training Reactors, (TRTR) which represents research reactor facilities across the nation from government, major universities, national laboratories, and industry. TRTR chair John Bernard, along with the management of NRL, is looking forward to hosting the 2008 TRTR Annual Meeting which will take place September 27 through October 2, 2008. TRTR's primary mission is education, fundamental and applied research, application of technology in areas of national concern, and improving US technological competitiveness around the world. Participants will include managers and directors of research reactors, educators, administrators, regulators, and research scientists and engineers. This meeting also presents an opportunity for the research reactor community to meet with individuals who work for the DOE and the NRC.

David E. Moncton
Director

More information about the Nuclear Reactor Laboratory can be found at http://web.mit.edu/nrl/www/.