Nuclear Reactor Laboratory

Facilities and Resources

The MIT Nuclear Reactor Laboratory (NRL) is an interdepartmental center that operates a 5 MW research reactor (MITR) in support of MIT's educational and research initiatives and goals. For 46 years, NRL has provided faculty and students from MIT and other institutions with a state-of-the-art neutron source and the infrastructure to facilitate its use. During this time, NRL has supported educational training as well as cutting-edge research in the areas of nuclear fission engineering, radiation effects in biology and medicine, neutron physics, geochemistry, and environmental studies. In addition, MIT undergraduate and graduate students have benefited tremendously from their association with NRL and the hands-on experience they have gained utilizing the reactor's unique capabilities.

The primary role of NRL has always been to support MIT's education and research missions as well as other local area universities, hospitals, and industries. A secondary, but no less important role has been to educate the general public about the benefits of maintaining a strong nuclear science program in the United States. This has been accomplished by providing tours and lectures that describe and clarify different nuclear science and technology programs. During the past year, NRL staff, along with faculty members from the Department of Nuclear Science and Engineering (NSE) have worked to expand these objectives by offering NRL's resources as a national user facility that will support research and development for the next generation of nuclear power technology, also known as the Generation-IV (Gen-IV) initiative. This initiative is a direct result of a collaboration with the Department of Energy's (DOE) newly formed Idaho National Laboratory, Battelle Energy Alliance (BEA), and MIT.

Reactor Administration and Organization

David E. Moncton is the director of NRL. He, along with John A. Bernard, director of reactor operations; Lin-Wen Hu, head of research development; Ed Lau, superintendent of reactor operations; Thomas Newton, reactor engineer; and Susan E. Guralnik, administrative officer, comprise NRL's senior management team. They have and will continue to effectively contribute to maintaining the highest level of operation at NRL.

NRL currently employs 50 individuals. This is broken down into six groups which include: 5 previously mentioned senior staff; 4 research staff; 7 technical staff; 8 technical support staff; 1 administrative staff; 3 administrative support staff; 2 technicians; 15 part-time student/operators and 5 student trainees. In general, NRL support staff, student employees, and technicians have specific responsibilities to reactor administration, research development, reactor engineering, or reactor operations.

Reactor Utilization and Research Development

In the past, NRL senior staff divided their expertise in four areas: reactor administration, reactor engineering, reactor utilization, and reactor operations. However, due to the increased volume of research being conducted at NRL and the prospect of even more research developing should it become a national user facility, it was determined that reactor utilization should be expanded to include research development. Dr. Lin-Wen Hu is the new head of research development at NRL, and she and her staff will ensure that MIT and outside users of NRL have the best possible assistance in utilizing the reactor and its irradiation facilities. Tasks assigned to this group include:

- Developing NRL into a premier National User Center
- Building a national user facility for advanced fuel and materials research
- Supporting the Neutron Capture Therapy (NCT) User Center for animal irradiations and chemical compound development
- Providing a research and service infrastructure that utilizes MITR 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

Reactor Engineering

Dr. Bernard continued to teach subject 22.921 Nuclear Power Plant Dynamics and Control, and to offer review classes on engineering fundamentals for NSE students in the radiological sciences. Both activities make use of the reactor for illustrating theoretical concepts. Reactor engineering staff include Mr. Thomas Newton, Dr. Gordon Kohse, and Mr. Yakov Ostrovsky.

Reactor Operations

Leadership is provided by John A. Bernard, director of reactor operations and by the reactor superintendent, Mr. Edward S. Lau. The group consists of both full-time employees (mostly ex-Navy nuclear-qualified personnel) and part-time 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 30 licensed individuals (15 full-time employees, 15 part-time students). All, including the management team, perform reactor shift duties to support the 24 hours/day, 7 days/week operating schedule. In addition to the operators, there are two full-time technicians for reactor mechanical maintenance.

Reactor Student Operators

MITR has traditionally hired several undergraduates per year, usually at the end of their freshmen year. NRL is currently training five MIT students to become reactor operators. During this reporting period, 12 part-time students obtained their reactor operator license and four staff obtained their senior operator license. The training program, which is directed by Mr. Frank Warmsley, 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 MITR. 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 during the semester at 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. Last year one student operator received her SRO. This training program is an excellent educational opportunity because it combines theoretical study with actual work experience in the MIT tradition of graduating students who know both how to design and build systems. In addition, the students that receive the SRO license obtain management experience because they are employed as shift supervisors. Students who have completed this training program regularly state that it was one of the high points of their MIT experience.

Organizational Diversity

NRL supports MIT's affirmative action goals. Currently there are 28 full-time and 18 part-time employees at NRL. Twenty-five positions are held by women and/or minorities; of these, out of a total of 16 engineering and management positions, five are held by women and/or minorities. Long-term employees include an engineer who is a woman and a minority; the superintendent of operations, who is a minority; and the neutron activation analyst, who is a woman and a minority. As part of NRL's ongoing mission to train reactor operators, there is always a rotating group of MIT students. The current roster of 16 active students includes seven women, of whom six are minorities, and nine men, of whom 4 are minorities. NRL participated in the DOE's 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.

Safety and Security

Operational Safety

Many years ago, MIT established a very effective means of insuring safe operation of the reactor by appointing independent individuals to a committee known as the MIT Reactor Safeguards Committee (MITRSC). Members of that committee are from MIT as well as from industry. They meet regularly during the year and these meetings are comprised, depending on subject matter to be discussed, of a full committee or established standing subcommittees. They are ultimately responsible for overseeing all nuclear safety issues related to the reactor and insuring that reactor operation is consistent with MIT policy, rules, operating procedures, and licensing requirements. However, each and every member of the NRL organization is keenly aware that safe operation of the nuclear reactor at MIT is their top priority. This level of awareness is achieved by the excellent guidance and continuous training provided by the NRL 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 the NRL's outstanding safety and operating record, which is evidenced by the results of inspections by the NRC. These results are shown in Table 1.

Table 1. MITR inspection record, 1998–2004.

Inspection Date	Inspection Type	Result
09/08/98	Licensing exams	4 ROs[a] + 3 SROs[b], all passed
10/21/98	Visit on fission converter safety analysis report	Discussion only
12/07/98	Inspection on emergency preparedness/ RRPO[c]	No deficiencies
03/30/99	Inspection on special nuclear material	No deficiencies
06/28/99	Inspection on RRPO/requalification/ safeguards	No deficiencies
09/30/99	Licensing exams	3 ROs + 1 SRO, all passed
04/28/00	Inspection of fission converter	No deficiencies
09/05/00	Licensing exams	3 ROs + 4 SROs, all passed except one SRO
01/22/01	Inspection on reactor operations/ requalification/safeguards	No deficiencies
06/25/01	Inspection on RRPO	No deficiencies
10/28/01	Inspection on RRPO/security	No deficiencies
09/04/01	Licensing exams	3 ROs + 2 SROs, all passed
05/06/02	Inspection on reactor operations/ requalification/emergency preparedness	No deficiencies
07/09/02	Inspection on RRPO	No deficiencies
09/03/02	Licensing exams	6 ROs + 3 SROs, all passed except one RO who passed a subsequent makeup exam, and one SRO
11/04/02	Inspection on boron neutron capture therapy facilities using fission converter	No deficiencies

06/23/03	Inspection on security/safeguards	No deficiencies
06/25/03	Inspection on reactor operations	No deficiencies
02/02/04	Licensing exams	4 ROs + 1 SRO, all passed except two ROs, one of whom passed a subsequent makeup exam
03/29/04	Inspection on RRPO/special nuclear material/reactor operations	No deficiencies
06/07/04	Inspection on reactor operations	No deficiencies
08/05/04	Special inspection on safeguards	No deficiencies
09/07/04	Licensing exams	8 ROs + 5 SROs, all passed

[a] Reactor operator
[b] Senior reactor operator
[c] Reactor Radiation Protection Office

Modern approaches to safety combine personal expertise and strong training with a methodology for continuous improvement. During the past year, NRL senior staff worked with members of MITRSC to identify improved approaches to safety. A task force under the leadership of Frank Warmsley and Judith Maro was formed that included John DiCiaccio, Doug LaMay, Paul Same, and Yakov Ostrovsky. As a result of their efforts, plans to implement a Continuous Improvement Program (CIP) is currently in place. CIP has three major goals: (1) reduce unplanned shutdowns, (2) minimize environmental releases, and (3) limit personnel exposures per the "as low as reasonably achievable" principle. The program will be computer based and allow 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 will be the driver for a series of assessment and follow-up actions.

After the 9/11 terrorist attacks on the United States, security and operating procedures at nuclear power plants and nuclear research facilities—including university research reactors—were intensely scrutinized. Consequently, NRL staff have had to take on the additional task of educating various regional and local government officials and the media regarding concerns and issues of safely operating a research reactor within the confines of a highly populated metropolitan area. In addition, NRC advisement of increased security at NRL has resulted in several upgrades. These include a new electronic gate that is opened with transponders assigned to NRL employees. A keyless electronic entry system for doors leading into areas with access to the reactor, and a monitoring system for the parking lot, front door, and backyard area of the reactor.

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 complements includes a deputy director for EHS serving as the reactor radiation protection officer (Frederick F. McWilliams), an EHS officer serving as the assistant reactor radiation protection officer (Douglas W. LaMay), 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 the 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 the NRL under the EHS-Management System organizational structure.

Research And Development

Generation-IV Program

In addition to providing a first-class, state-of-the-art facility for research that responds to present day issues and concerns, NRL is also looking ahead in order to meet future challenges. One particular challenge that needs to be addressed is the US reliance on fossil fuels. Currently, only 20% of the US's energy resources are provided by nuclear power. Reluctance to increase that percentage is due to the public's concern that nuclear energy is not a safe or environmentally sound alternative. The proposed Generation-IV (Gen-IV) Program, which is a major research and development initiative to design, build, and operate Gen-IV reactors that will provide the United States with an economical, safe, and reliable energy source, will counter that perception. NRL is uniquely qualified to be a key contributor to the design and performance of experiments for the evaluation of the advanced materials and fuels that are needed for Gen-IV reactors.

The DOE recently reorganized Idaho National Engineering and Environmental Laboratory and Argonne National Laboratory-West to create a new laboratory—Idaho National Laboratory (INL)—that will be the lead institution for nuclear engineering and reactor development. On March 3, 2003, MIT signed an agreement with Battelle Memorial Institute to partner in a bid for the contract to operate the newly formed national laboratory whereby MIT would lead a consortium of universities intended to provide the intellectual driving force for the mission of this new laboratory, namely the development of a new generation of nuclear power reactors. Members of NRL and NSE collaborated closely with Battelle in the preparation of a major proposal to bid on this contract. That proposal was submitted to DOE and BEA was chosen to manage INL. Research on materials and fuels for both existing and Gen-IV reactors would benefit from an MITR-INL association, because the relatively low-cost MITR could be used for fast turnaround irradiations and innovative research. This opportunity presents definite advantages to the operation of NRL, such as:

- Funding for materials research experiments
- Hiring of staff to support experimenters
- Opportunities for innovations in other research areas
- Contributions to a new research reactor that may be built at INL

Innovations in Nuclear Infrastructure and Education Program

The Department of Energy established the Innovations in Nuclear Infrastructure and Education (INIE) Program in order 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. This program is in its third year and, to date, has been exceptionally beneficial to NRL and to the researchers who utilize the reactor's facilities. The following is a synopsis of INIE-funded research being conducted at NRL.

—*NCT User Facility.* This portion of the MITR INIE Program is led by Professor Otto K. Harling. He is assisted by Dr. Kent Riley and Dr. Peter Binns. The MITR staff person who interfaces with the Boron Neutron Capture Therapy (BNCT) group is Mr. Thomas Newton. The following is a list of upgrades made to the NCT User Facility that were funded by the INIE grant:

- The medical room was cosmetically refurbished for the first time in 40 years. A new dropped ceiling was installed and a false wall was added to hide the additional shielding installed in previous years. An epoxy-based terrazzo floor was also laid in which boron was incorporated as shielding material to reduce activation of the inner room surfaces.
- An Li-6 filter was built, installed, and tested in the fission converter beam. The 0.8 cm filter is easily removable, depending upon clinical needs, and provides enhanced penetration of the thermal neutron flux in the beam by approximately 1.0 cm. Beam characterization measurements were performed to assess the performance of the filter and the results match those predicted by our design calculations. This work formed the basis of an SM degree.
- Two patient collimators were constructed for the thermal neutron beam. These are detachable devices that affix externally to the ceiling below the lowest shutter. Circular fields of 12 and 8 cm are provided using a combination of sandwiched annuli constructed of lithiated polyeythlene and bismuth. Precollimation is provided by a bismuth and borated polyethylene collimator that locates inside the new neutron shielding shutter installed last year. This precollimation is interchangeable with the animal shielding box.. Dosimetric measurements were performed in an ellipsoidal water phantom to confirm the performance of the collimators and showed that a thermal flux of $2x10^9$ n $cm^{-2}s^{-1}$ is realizable for patient irradiations with the reactor operating at 5 MW.
- High resolution quantitative autoradiography is being established in the laboratory to image the uptake of boron at the cellular level in tissue samples and the ensuing radiation tracks that result from thermal neutron irradiations. This is a unique analytical tool that will be essential for the interpretation of future experimental results with prospective capture compounds. To this end, a microtome for tissue slicing, a freezer, and a digital microscopy camera and image frame grabber software were purchased. The system is being commissioned as part of a graduate student's PhD research thesis.

—*Neutron Interferometry.* This portion of the INIE Program is directed by Professor David Cory. He is assisted by graduate student Dmitry Pouchine. The MITR staff person who interfaces with this project is Mr. Thomas Newton. The INIE funds for the project were used to support Mr. Pouchine. The objective of this research is to develop the theory, experimental apparatus, and methods of reciprocal encoding of spatial information for neutron imaging and incoherent scattering. Some accomplishments include:

- Development of a coherent, reciprocal space approach to neutron imaging that has the promise of higher resolution than incoherent measurements based on imaging plates. The method relies on neutron interferometry and makes use of a spatial grating of the neutron phase established in one arm of the interferometer.
- Description of a method for measuring the transverse coherence length of neutrons in a three-blade interferometer and calculatation of the expected Wigner functions for these. The measurements will be completed in October.
- Demonstration that an extension of the above neutron coherence length measurements enable the creation of a beam of neutrons that are in a coherent superposition of spatially separated beams with a displacement between 0 and about 300 Å. In a four-blade interferometer, such a beam can be used for coherent neutron scattering. Efforts are underway to set up this experiment.

—*Phase Contrast Imaging.* This project is directed by Dr. Richard Lanza. The MITR staff person who interfaces with this project is Mr. Edward Lau. The purpose of this project is the utilization of MITR to demonstrate phase contrast radiography in order to possibly detect very small (~10 µm) internal cracks in metals and measurement of internal stress. This technique has the potential to detect much smaller changes in materials from phase shifts than is practical with transmission methods, which detect only absorption. The following is a list of activities supported by INIE during the past year:

- Continued development of the beam and detector system for producing phase contrast images.
- Acquisition of two new detection systems: a Fuji BAS-2500 imaging plate system and a Thales FlashScan 33. Initial measurements using the Fuji system were made using an existing beam line. Although performance has not been completely characterized, it appears that the resolution specification of 50 µm appears to be obtained. The major limit to this system lies in the large data files (60 Mb) and the relatively slow readout times, ~5 min for images taken at full resolution (50 µm pixels, 16 bit). The Thales FlashScan 33 detector is still being evaluated. This detector is 30 x 50 cm with 127 µm pixels. The system uses a Gadox screen as a neutron detector. Its primary advantage in our application is the faster readout, approximately 1.5 sec for a full-screen image. Our initial measurements have shown that performance appears to be within specification. We have not yet characterized completely either detector with respect to spatial resolution and noise characteristics.
- Redesign of a new beam port using a pinhole collimator with bismuth and sapphire filters.

—*In-Core Loops.* This portion of the MITR program involves the design and construction of a post-irradiation examination (PIE) facility for in-core irradiations of both advanced fuels and materials. The advanced fuels work is directed by Professor Mujid Kazimi. The materials studies are coordinated by Professor Ronald Ballinger. Both are assisted by Dr. Gordon Kohse and Mr. Yakov Ostrovsky. The MITR staff person who interfaces with these projects is Dr. Lin-Wen Hu.

Neutron Capture Therapy

Neutron capture therapy (NCT) for cancer research, directed by Professor Otto K. Harling, is the leading BNCT research program in the United States and is considered to be among the top in this field worldwide. A Phase I/II trial for glioblastoma multiforme and metastatic melanoma in 2003 and results from this study are presently being analyzed as follow-up finishes. The epithermal neutron irradiation facility has continued to operate reliably and is able to safely administer the neutron fields required for BNCT clinical investigations.

DOE-supported upgrades of BNCT facilities at MITR are complete. A high-intensity and high-purity thermal neutron beam is now available at MITR and is presently employed for basic research related to BNCT. The upgraded facility is also fully licensed for clinical trials and includes all capabilities required for irradiating human subjects. The fission converter-based epithermal neutron beam line (FCB) 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%.

The neutron facilities at MITR have been extensively utilized under the DOE (INIE)–supported user facility that opens these unique facilities and specialized expertise to researchers both within and outside MIT. Research groups based at universities and national laboratories from around the country have extensively used the NCT facilities for in-vitro and in-vivo experiments that are designed to investigate the efficacy of new, tumor-seeking capture compounds and to study the radiobiology of neutron capture therapy.

Neutron Capture Therapy User Center

The NCT User Center is the only such facility in the United States and is essential for a viable research and clinical program in NCT. Irradiation facilities and in-house services such as dosimetry expertise and assistance with the design and manufacture of experimental jigs for holding samples and animals were made available for use to the greater BNCT scientific community. Radiobiology expertise was also provided to assist with surgical procedures related to animal experiments as were facilities for housing animals on campus. Beam time applications were requested at six-month intervals. In response to the requests received it became apparent that as well as the services offered some prospective outside experimenters required radiobiological facilities as well as expertise. This is particularly true of chemists who are developing the next generation of capture agents for NCT. Screening these compounds requires skills that these developers do not possess and, accordingly, the radiobiology initiative that commenced last year has continued.

The NCT User Center is comprised of several state-of-the-art neutron facilities for NCT research that have been developed and are in operation at MITR. They include:

- The epithermal neutron irradiation facility (FCB), which is licensed by NRC. It has an intensity of ~$5x10^9$n/cm^2-sec with low inherent beam contamination which approaches the theoretical optimum. If FCB is used at maximum intensity, tissue tolerance can be reached in less than 10 minutes. The high beam purity results in a useful treatment depth of ~9 cm, using current capture compounds. Therefore, FCB is well suited to treating deep-seated cancers. FCB is currently the only operating U.S. epithermal neutron beam which is suitable for clinical studies. It is also currently the best NCT epithermal neutron beam in the world.
- A high intensity, ~$1x10^{10}$n/cm^2-s, and low-contamination thermal neutron beam is also available at MITR. This facility has its own medical irradiation room separate from the FCB irradiation room. The thermal neutron facility is well suited for small animal studies and for clinical studies of NCT where tumors are less than ~4 cm deep. There is currently no other comparable facility for thermal neutron irradiations in the US.
- The third neutron facility available at MITR is a prompt gamma neutron activation analysis facility. This facility is designed for rapid ^{10}B analyses in small samples of blood and tissue. These analyses are essential for NCT research and for accurate dosimetry in clinical studies. A high sensitivity of ~18 cts/s/µgm allows rapid and accurate analyses of samples as small as 0.1 ml with typical ^{10}B concentrations of 10 ppm. An inductively coupled plasma–atomic emission spectrometer and inductively coupled plasma–mass spectrometer are also available at NRL and are particularly well suited to very small samples (<0.1 ml).
- A specialized irradiation facility for use in high-resolution track etch autoradiography is also available at MITR. High-resolution quantitative track etch autoradiography developed in the joint NRL-Harvard program permits the mapping of the microscopic boron concentration in tissue with a spatial resolution of about 2 micrometers. This is an invaluable aid in determining the potential effectiveness of neutron capture compounds.

Radiation Science Technology

NRL supports a subdiscipline in the Department of Nuclear Science and Engineering, radiation science technology, by providing relevant research opportunities. NRL also contributes to a specially designed laboratory and demonstration course. This course, 22.09 Principles of Nuclear Radiation Measurement and Protection, is appropriate for all NSE students. Research topics and support for health physics students were provided by NRL projects, especially the BNCT and Dose Reduction projects of Professor Otto K. Harling.

Dr. John A. Bernard, who is certified as a health physicist by the American Board of Health Physics, continued to teach course 22.581 Introduction to Health Physics. This course uses the MIT Research Reactor to provide practical examples of health physics issues.

In-core Loop and Materials Studies

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 Gen-IV reactors. MITR offers a unique technical capability that involves the use and installation of in-core loops that replicate pressurized water reactor (PWR)/boiling water reactor (BWR) conditions to study the behavior of both advanced materials and microparticles of advanced fuels for Gen-IV reactors. 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 [LWR]), the capability to control the chemistry and thermal conditions to reflect prototypic conditions, its easy access geometric configuration, and space for up to three independent irradiation tests. While similar studies could in principle be carried out at certain national laboratory reactors such as the Advanced Test Reactor (ATR), the costs would be far greater. The reason is that large national laboratory reactors are optimized for large scale, fully integrated tests and not the smaller scale, faster-turnaround basic studies needed at the earlier stages of research. Access to the high flux in the core is also much more difficult in the larger reactors because of pressurization of the core. MITR is unpressurized and the core is only about 12 feet below the lead reactor lid.

To support the advanced materials and fuel research program, MITR is equipped with 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 at 3-ton and 20-ton capacity, 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 being refurbished with INIE funds. Additional equipment upgrades/purchases to support PIE, such as manipulators, alpha detectors, and ventilation, are also being funded by INIE.

The following is a list of activities and research being conducted at the NRL:

—*Advanced Materials Testing Facility.* In 2001, MIT recognized the need for an advanced materials test facility (AMTF) and proposed to DOE the assembly of such a facility at MITR. This proposal was approved as part of the INIE award that MIT subsequently received as the lead member of the New England INIE consortium (the other members are Rhode Island Nuclear Science Center and University of Massachusetts-Lowell.) Procurement and installation of the equipment is ongoing, as is an upgrade of MITR's existing hot cells, which are used to support in-core experiments. The combination of an AMTF and MITR will be ideal for carrying out the more basic components of the research on materials in a radiation environment. This type of facility would complement the testing capabilities of large national laboratory reactors such as ATR, which are best suited for fully integrated experiments. In most cases the MIT AMTF would be relatively inexpensive for basic research projects, saving three to 10 times the cost of doing the same type of basic research at a large national laboratory reactor. On the other hand, the large reactors are essential for integrated testing because those types of experiments cannot be carried out at a university research reactor.

—*High Temperature Irradiation Facility.* This project is directed by professors Ronald Ballinger and Mujid Kazimi, and Dr. Gordon Kohse. The high-temperature irradiation facility is designed to provide an environment appropriate for test irradiations of high-temperature, gas-cooled reactor materials. Development and in-pile testing of high-temperature resistant materials are essential for the Gen-IV reactor programs. An initial run is planned to test the facility and verify the temperatures that can be achieved at the sample positions. If the projected temperatures are reached, irradiation will continue for approximately eight weeks with a variety of silicon carbide and nonfueled TRISO particle specimens at temperatures between about 1,000 and 1,400 °C.

This facility will be a valuable test facility for high-temperature resistant materials research. (Oak Ridge National Laboratory [ORNL] is currently developing a similar facility at their test reactor, the High Flux Isotope Reactor). Researchers from national laboratories, such as INL, have expressed interest in using this facility, if it is demonstrated successfully.

Design work for this loop has been completed as part of the INIE program. Approval of the Reactor Safeguards Committee was received in May. Construction of this facility is near completion and the in-core irradiation is planned to start in July 2005. Two types of materials will be tested during the initial irradiation—graphite and silicon carbide composite specimens provided by Knolls Atomic Power Laboratory, and nonfueled coated particles from a gas reactor fuel manufacturer.

—*Investigation of Nanofluids for Nuclear Applications.* Dr. Lin-Wen Hu and Professor Jacopo Buongiorno are pursuing an experimental study of water-based nanofluid heat transfer enhancement. Nanofluids are engineered colloids made of a base fluid and nanoparticles (1–100 nm) in various forms. The presence of the nanoparticles produces four major effects on 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. The occurrence and magnitude of these effects depends on nanoparticle loading, material, and shape in ways that are not clear yet. Given their potential for superior heat removal performance, nanofluids are being investigated for numerous applications, including electronics, manufacturing, chemical processes, cosmetics, pharmaceuticals, and power generation. A research program has been initiated to assess the feasibility of nanofluids for nuclear applications. In principle, the use of water-based nanofluids could improve the performance of any water-cooled nuclear system that is heat-removal limited. Potential applications include PWR primary coolant, standby safety systems, accelerator targets, plasma divertors, etc. The program comprises the following activities, currently sponsored by INL, AREVA/Framatome, and INIE:

- Construction of two out-of-pile loops to investigate the nanofluids heat-transfer enhancement
- Procurement of water-based nanofluids (i.e., C, SiO_2, ZrO_2, Al_2O_3)
- Property measurements: thermal conductivity (transient hot wire method) and viscosity (ultrasonic viscometer)

- Property modeling with molecular dynamics simulations
- Single-phase heat transfer and pressure drop measurements in flow loop
- Single-phase heat transfer modeling, both conceptual and computational fluid dynamics
- Critical heat flux measurements: experiments with heated wire, and in flow loop with PWR-equivalent annulus and zircaloy-heated surface
- Nuclear applications: subchannel, safety, and neutronic analyses of PWRs with nanofluid coolant.

—*Materials Irradiation Facility for the ORNL Heavy-Section Steel Irradiation Program.* This proposed project is directed by Ronald Ballinger and David Moncton. The aim is for MITR to provide services and facilities for the Heavy-Section Steel Irradiation (HSSI) Program to irradiate specimen capsules. The objective of these experiments is to investigate the response of the fracture toughness of reactor pressure vessel steel to various irradiation parameters, such as temperature, neutron fluence and flux, and annealing and reirradiation. The HSSI irradiation studies are part of a research program funded by NRC at ORNL. The proposed period is for three years with the expectation of a renewal. The HSSI Program plans are to irradiate specimens in one capsule at or near 288 °C for existing power reactors pressure vessel steel. A second capsule may be used by a related program or the HSSI Program to irradiate specimens. If used by a related program, the second capsule may require specimen temperatures of 650 °C for Gen-IV reactor research. If used by the HSSI Program, irradiations will be at or near 288 °C.

—*SiC Duplex Clad Irradiation.* This project is directed by Dr. Gordon Kohse and Professor Mujid Kazimi. It involves the production and testing of candidate duplex SiC/SiC composite cladding materials for LWRs. These materials have potential advantages over conventional metal alloy cladding materials in both improved an safety margin and higher burnup. Irradiation testing in prototypical PWR and BWR coolant conditions will be performed at MITR. PIE is planned to measure weight loss, thermal conductivity changes, mechanical property tests, and scanning electron microscopy. The irradiation testing and some of the PIE are planned for NRL using MITR's in-core loop facilities and hot cells.

A workshop on SiC cladding applications for advanced nuclear reactors was held on May 5, 2005 to present initial out-of-pile testing results of SiC cladding development, and to discuss the future testing development. This workshop was sponsored by Gamma Engineering Inc., Westinghouse Electric, Nova Tech, and was cohosted by MIT's Center for Advanced Energy Systems and ORNL.

Initial funding has been received to design and plan for the upcoming irradiations. Funding for the initial three-month irradiation has been allocated and additional funding is being sought to extend the irradiation test to 12 months. The SiC cladding irradiation is scheduled to begin in December 2005.

—*High Performance Fuel Design for Next Generation PWRs.* This project is directed by professors Mujid Kazimi and Pavel Hejzlar, and Dr. Gordon Kohse. An internally and externally cooled annular fuel concept proposed for investigation by MIT could provide a substantial power density increase. The goals of this project are to develop and optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins. Irradiation testing was performed at MITR to study the characteristics of the annular fuel. The objectives of this project are to: determine fission gas release rates and fuel dimensional and structural changes during irradiation; and achieve a range of burnups to identify potential performance differences among the fuel types. The annular fuel specimens are designed so that, with the combination of enrichment, inner and outer annulus dimensions, and gap thermal properties, the fuel meat temperature would be similar to that of a reference reactor design.

Phase I irradiation of two vibrational packing specimens was performed from March through September 2004. These specimens were then stored in the MITR core tank for cooling and were removed to the spent fuel pool in April 2005. These specimens are awaiting movement to the reactor floor hot cell for PIE prior to transfer to INL.

Neutron Beam Tube Research

The prompt gamma neutron activation analysis facility was used both for research and in support of the neutron capture therapy clinical trials.

Environmental Research and Radiochemistry

Dr. Lin-Wen Hu has taken on the role of overseeing operation of NRL's environmental research and radiochemistry laboratories. MITR is currently equipped for both prompt and delayed gamma neutron activation analysis. Relative to the former, a prompt gamma spectrometer was built as part of the Neutron Capture Therapy 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, MITR is equipped with five pneumatic tubes that are used for neutron activation analysis (NAA). One offers a thermal flux of $5x10^{13}$; the other four offer thermal fluxes of $8x10^{12}$. Several of the tubes are 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.

The NRL NAA laboratory has four Hp(GeLi) detector systems with Genie 2000 software. A new computer and new software were installed. Two detectors were rebuilt and installed this year. MIT also participates in DOE's Reactor Sharing Program and the bulk of those funds is used to cover irradiation charges for NAA-based research.

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, California Institute of Technology, Tufts University, University of Connecticut, and Woods Hole Oceanographic Institute.

The following list represents some of the ongoing research activities conducted at NRL utilizing NAA:

- Environmental biomonitoring of chromium and arsenic in shallow groundwater utilizing NAA and secondary mass spectrometry in order to discriminate between groundwater versus foliar uptake of Cr and As in oak trees. The long-term goal of this study is to develop a tool for biomonitoring metal-contaminated systems by utilizing tree-ring chemistry. This study, conducted by Daniel Brabander, assistant professor of geosciences at Wellesley College, will enable future work to be done at other sites with Cr contamination, which is common to areas around tanneries and Cr-plating facilities.
- NAA was used as a technique for measuring mercury and other metals in comparative tissue from autistic and control patients to study the role of heavy metal exposure, especially mercury, in order to explain the documented rise in the prevalence of autism. In addition, hair samples from autistic patients and a control group also underwent NAA as a means to monitor mobilization/excretion of mercury and other metals. This research involves two separate pilot studies, each conducted by Dr. John Machuzak, of Lincoln Laboratory, and Dr. George Grady, of University of Massachusetts Medical School.
- NAA will be used to measure vanadium and other metals to determine whether there is a significant difference between levels found in hair samples from patients with amyotrophic lateral sclerosis as compared to 100 control subjects. This study is being conducted by Dr. Robert H. Brown and Dr. Xudong Huang, of Massachusetts General Hospital
- Trace element analysis was conducted on various types of fish to demonstrate the advantages of using NAA to determine methyl mercury contamination which is severely neurotoxic, particularly to human fetal development. This demonstration is a hands-on exercise that serves as an educational tool that underscores the FDA's warning against fish consumption by pregnant women. This exercise is being conducted by Lin-Wen Hu.
- Tours of MITR, along with NAA of sediment from rivers and estuaries in the Boston metropolitan region, were provided for the purpose of educating MIT undergraduate students about the basics of NAA and how a nuclear research reactor can be utilized for such analysis. This program—initiated by professors Frederick A. Frey, Samuel A. Bowring, and Timothy L. Grove, Department of Earth, Atmospheric, and Planetary Sciences—serves as a solid foundation for graduate students who utilize the reactor in support of their research and thesis activities. Two such research projects are: the Hawaiian Scientific Drilling Project and Ocean Drilling cruises; and studies of lavas erupted in the southern Indian Ocean that are related to the long-lived Kerguelen hotspots (a feature analogous to Hawaii. In both of these projects, NAA is used to determine trace element abundances.

New Initiatives

Neutron Scattering

Neutron scattering had a long and distinguished history at NRL, but has not been actively pursued since the retirement of Professor Cliff Shull. However, a revitalization of the neutron scattering program has begun under the direction of Professor David Moncton, with the assistance of Dr. Boris Khaykovich, as they recently obtained NSF funding to install a diffractometer at NRL.

Neutron scattering and spectroscopy are among the preeminent tools for studying the structure and dynamics of matter at the atomic and molecular scale. A powerful new neutron facility, the Spallation Neutron Source (SNS), is currently under construction in ORNL and is widely anticipated to revolutionize this field and to enable the U.S. to regain leadership lost to Europe decades ago. SNS will catalyze a new generation of instrument development, 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 by 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 SNS
- Establishment of a user facility to allow users from outside MIT to conduct early phases of some experiments more quickly than at larger facilities, and to test and develop new neutron optics components

Development of a Virtual Laboratory for X-ray and Neutron Research Education

Professor Moncton and Dr. Khaykovich submitted a proposal to NSF that would utilize cyberinfrastructure to educate, inform, and involve a new generation of scientists in the use of scattering facilities at remote locations. This project, in collaboration with Indiana University, will focus on involving scientists, students, and others who are not experts in scattering technique and will allow them to participate, at a level consistent with their knowledge and experience, in the planning, conduct, and analysis of scattering experiments. It will also enable expert users to conduct experiments by remote access.

In-core Sample Assembly and Cooled Irradiation Facility

A titanium tube has been built for the insertion of samples into the reactor core for high flux irradiations. This project, funded by Composite Technology Development Inc., and under the direction of Thomas Newton, is intended to test fusion magnet insulation materials for suitability in simulated fusion radiation environments. A water-cooled lead shield has been developed to lower the reactor gamma component and provide a cooled environment for the sample irradiations.

Relicensing and Redesign

The relicensing of MITR with a concomitant upgrade in power is in progress. It previously was shown that MITR could operate at a maximum power of 6–7 MW with the existing heat removal equipment. A decision subsequently was made to submit the licensing documents for a power increase from 5 MW to 6 MW. On 8 July 1999, a formal application was submitted to 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. The process of relicensing is long and arduous and involves many interactions and communications between NRL and NRC. One major form of communication is a series of questions (from NRC) and answers (provided by NRL) on technical specifications and safety analyses. NRL has responded to the third installment of the first set of questions received from NRC. Until the relicensing approval process is completed, NRC has authorized the continued operation of MITR. This mode of operation has been ongoing since 1999.

Reactor Upgrades

In addition to the previously reported upgrades made in conjunction with the reactor's relicensing (i.e., cooling towers), a significant number of reactor systems were upgraded, augmented, and/or replaced during the past year. These include:

- Heavy water replaced
- Reflector pumps replaced/rebuilt
- Variable-frequency drive controllers installed for the new reflector pumps
- Shim blade and magnet replaced (completed)
- Regulating rod replaced (completed)
- New neutron flux monitoring picoammeters installed
- New digital primary temperature and pressure indicators installed
- New emergency power transfer switch installed
- Integrated security system upgrade (in progress)
- Cooling tower upgrade and five-year maintenance (in progress)

Reactor Irradiations for Groups Outside MIT

A number of reactor irradiations and services were performed for research groups outside MIT. Whereas most outside users pay for irradiation services at the reactor, educational institutions needing such services for their own academic or research purposes receive assistance through the DOE's Reactor Sharing Program. A grant to NRL reimburses us for the costs of providing irradiation services and facilities to other not-for-profit institutions (including teaching hospitals and middle and high schools). Under this program, 500 students and 50 faculty and staff from over 30 other educational institutions benefited from visits to and use of MITR during the past year.

Most participants in the Reactor Sharing Program wish to perform NAA, utilize the fission spectrum facilities, conduct laboratory exercises for their classes, or take tours. However, MITR is capable of providing support for other types of activities, such as the use of neutron scattering for research in chemistry, physics, and materials science.

MITR was designed as a beam tube facility and is equipped with neutron spectrometers for both diffraction and inelastic scattering measurements. These facilities are currently underutilized and we hope to stimulate research in this area.

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.

Major Reactor Services

MITR produces about $1.2 million worth of neutron-transmutation-doped (NTD) silicon per year. This is commercial income and the funds are used to offset operating costs. The market for NTD silicon remains strong despite improvements in the chemical production of the material and the MIT program continued for a successful ninth year.

Approximately 10 metric tons of silicon crystals were accurately irradiated in shielded, automated irradiation facilities at MITR.

MIT Research Reactor

The MIT research reactor completed its 46th year of operation (its 30th since the 1974–75 shutdown for upgrading and overhaul). The reactor operated continuously (seven days per week) to support major experiments. On average, it was operated 103 hours per week at its design power level of 5 MW. Energy output for MITR-II, as the upgraded reactor is now called, totaled 618,400 megawatt-hours as of June 30, 2005. MITR-I generated 250,445 megawatt-hours in the 16 years from 1958 to 1974.

To summarize briefly, the reactor was well utilized during the year, although still more experiments and irradiations can be accommodated because of the number and versatility of the many experimental facilities. The number of specimen irradiations was 251 on a total of 566 samples; 54 of these irradiations were in the medical rooms, many in support of the NCT program for the treatment of brain cancer and subcutaneous melanoma. Theses and publications on research supported by the reactor are running at about five and 20 per year, respectively. Approximately 1,470 people toured the MIT Research Reactor from July 1, 2004 through June 30, 2005.

David E. Moncton
Director

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