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. For 47 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 and cutting-edge research in the areas of nuclear fission engineering, radiation effects in biology and medicine, neutron physics, geochemistry, and environmental studies. As a result, countless undergraduate and graduate students have benefited from their association with NRL. Through the years, these students have been offered an opportunity to pursue their research by utilizing a research reactor that has provided a unique hands-on environment.

The primary role of NRL has always been to support the education and research missions of MIT as well as other local-area universities, hospitals, and industries. A secondary but no less important role of NRL has been educating 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.

Reactor Administration

NRL's organizational structure comprises 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. (Robert Davine has replaced the recently retired Susan E. Guralnik as NRL's administrative officer.) This leadership team works to sustain NRL's long-standing record of safe operation, continuously maintain and improve upon the state-of-the-art reactor facility, and 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 6 previously mentioned senior staff, 6 research staff, 6 technical staff, 8 technical support staff, 1 administrative staff, 3 administrative support staff, 2 technicians, 13 part-time student/operators, 2 technical support staff trainees, and 5 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. Currently there are 34 full-time and 18 part-time employees at NRL. Twenty-eight positions are held by women and/or minorities, and of the total of 18 engineering and management positions, 5 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 18 active students includes 7 women, of whom 5 are minorities, and 11 men, of whom 6 are minorities. NRL participated in the US Department of Energy's (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.

Reactor Operations

Leadership is provided by John A. Bernard, director of reactor operations, and by reactor superintendent Edward S. Lau. This group, the largest at NRL, is responsible for supporting all activities related to operation and maintenance of NRL's 5 MW research reactor (MITR). 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, and most hold a senior reactor operator license. At present, there are 29 licensed individuals (16 full-time employees, 1 part-time employee, and 12 part-time students). All, including the management team, perform reactor shift duties to support the 24-hour-per-day, 7-day-per-week operating schedule. In addition, there are two full-time technicians to support reactor mechanical maintenance.

The MIT reactor completed its 47th year of operation (its 31st since the 1974–1975 shutdown for upgrading and overhaul). The reactor operated continuously (seven days per week) to support major experiments. On average, the reactor was operated at its design power level of 3.85 MW. This is less than the nominal 5 MW power level because of time spent for operator training, startups, and evaluation of in-core experiments at reduced power levels. There were 11 unexpected shutdowns, of which four were the result of a loss of off-site power, something over which we have no control. Energy output for the current fiscal year was 22,300 MWH.

Reactor operating activities during the past year included:

- Two major and six minor maintenance outages covering key maintenance, including a building pressure test, charcoal filter test, chemical cleaning of heat exchangers, repairs to primary pump MM-1A and the shield piping, and replacement of 28 emergency battery cells
- Fission converter tank refueling
- Ten reactor refueling operations, including installation and removal of three different types of in-core experiments (in-core sample assembly, High Temperature Irradiation Facility [HTIF], and advanced clad irradiation, as described in later sections)
- Two shipments of spent fuel to DOE
- Maintenance of ISO 9001 certification for the neutron transmutation doping (NTD) silicon program

- Swapping out of the 4DH4 port plug for diffractometer installation
- Receipt of a National Institute of Standards and Technology (NIST) diffractometer and relocation of the silicon corral and a platform support I-beam to accommodate its installation
- Replacement of the MTS-1 capillary tube with three thermocouples
- Continued support by reactor staff of all use of the reactor, including in-core experiments, neutron activation analysis (NAA) and isotope activation irradiations, handling of radioactive material and its off-site shipment, and NTD silicon production
- One Nuclear Regulatory Commission (NRC) inspection on radiation protection and reactor security and one independent audit, both resulting in positive evaluations
- Site visits by state police, the Federal Bureau of Investigation, the Department of Homeland Security, and NRC in response to an ABC News Primetime special report
- Other major visits by NRC commissioner Gregory Jaczko, NRC commissioner Peter Lyons and staff, staffers from Representative Michael Capuano's office, staffers from the Senate Environment and Public Works Subcommittee, State Representative Martha Walz, and Idaho National Laboratory associate director Bill Rogers
- Many educational visits and tours for local and national schools hosted by reactor staff

In addition, a major service provided by the NRL reactor is production of NTD silicon. This service provides commercial income (approximately $1.2 M annually) that is used to offset operating costs.

As in the past, upgrades and improvements to MITR systems and instruments were made this year. For example:

- The control room center annunciator panel was replaced.
- The pneumatic tube system blower was upgraded with a vacuum fluorescent display control unit, and the pneumatic tube to the NW13 hot lab blower was upgraded.
- The control room air conditioning was replaced by a unit that is independent of the reactor secondary system.
- A portable backup control room air conditioner was installed, and the MITR's building pressure test equipment was upgraded to solid-state remote sensing.

Among others, upgrades to the reactor's emergency battery system and to the liquid CO_2 tank, feed line, and flow measurement are in progress.

Reactor Operations has traditionally hired several undergraduates each year, usually at the end of their freshman year. The training program, which is directed by 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 the 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 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. All 12 of the September 2005 candidates passed their NRC exams. This training program is an excellent educational opportunity for MIT undergraduate students because it combines theoretical study with actual work experience in the MIT tradition of graduating students who know how to both design and build systems. In addition, students who 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.

During this reporting period, five part-time students and one technical staff member obtained their reactor operator licenses and six part-time students obtained their SROs. Reactor Operations is currently training five MIT students as well as two reactor support staff to become reactor operators. Five existing student operators are being trained for upgrade to SRO licenses.

The relicensing of the MITR with a concomitant upgrade in power is in progress. It was previously determined that the MITR 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 MW 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, 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 the associate director of the Research, Development, and Utilization Group at NRL. 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 (Generation-IV) 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 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 (IAP) lectures, hosting Undergraduate Research Opportunities Program (UROP) students, and offering lab courses for professionals and undergraduates
- Expanding the user base for underutilized facilities

The reactor was well used during the year. Some research and utilization highlights achieved during the past year include:

- Completion of a three-month in-core irradiation utilizing the HTIF for evaluating candidate Generation-IV (Gen-IV) materials by means of graphite and SiC composite specimens. These samples were irradiated in-core at temperatures in the range of 1,000 ºC to 1,400 ºC.
- In February 2004, a new type of in-core experiment was used to test the performance of an innovative annular fuel design as a part of the Gen-IV power reactor research effort by the MIT Department of Nuclear Science and Engineering(NSE). This experiment continued into FY2005. It is the first irradiation of a fueled test capsule at the MIT reactor and one of very few undertaken at any university reactor.
- Neutron activation analysis to evaluate the connection of vanadium to the occurrence of amyotrophic lateral sclerosis (ALS) through biopsy-derived mouse brain tissues, animal models, and human scalp and genital hair samples.
- An inductively coupled plasma spectrometer (ICP-OES) was installed to complement NRL's trace element analysis capability.
- A new project was initiated to provide routine ultra-trace element analysis in enriched B-11.

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. A grant to NRL reimburses us 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 30 other educational institutions benefited from visits to and use of the MITR during the past year.

Most participants in the Reactor Sharing Program wish to perform NAA, conduct laboratory exercises for their classes, or take tours. However, the 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. The MITR is equipped with neutron spectrometers for both diffraction and inelastic scattering measurements. These facilities are currently underutilized, and it is our 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.

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 using the iLab interface and an expanded DOE-sponsored outreach program called Harnessed Atom.

Reactor Engineering

Dr. Thomas H. Newton is the associate director of reactor engineering at NRL. This group's activities include experimental support and development for in-core sample assembly, nanofluids, the HTIF, advanced clad irradiation, irradiation of fusion insulation materials, and neutronic modeling of proposed experiments. In addition, Dr. Newton is the principal investigator for two research projects funded by Argonne National Laboratory that will eventually enable the MITR (along with the other research reactors within the high-powered reactor group (University of Missouri Research Reactor Center, 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 design of the LEU fuel and core for future use in the MITR, are of 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 obtained from NIST last fall. Other activities of the group include supervision of the management of fuel in the reactor and fission converter and oversight of shipments of spent fuel, as well as other engineering services such as the revamping of pressure test measurements and calculations.

Research Programs and Facilities

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. The 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. The 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 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, the MITR 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 being 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.

The following is a list of activities and in-core loop and materials studies conducted during this reporting period.

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 the 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 the Rhode Island Nuclear Science Center, the University of Massachusetts-Lowell, and the Rensselaer Polytechnical Institute). Procurement and installation of the equipment are ongoing, as is an upgrade of the MITR's existing hot cells, which are used to support in-core experiments. The combination of the AMTF and MITR will be ideal for carrying out the more basic components of research on materials in a radiation environment. As mentioned, the MITR offers good geometric access and space for up to three independent irradiation tests, it has a sufficiently high in-core flux to simulate accurately the radiation environment in PWR/BWR power reactors, and it has the ability to control chemistry and thermal fields to reflect prototypic conditions.

High Temperature Irradiation Facility: This project is directed by Professor Ronald Ballinger, Professor Mujid Kazimi, and Dr. Gordon Kohse. The HTIF was designed to provide an environment appropriate for test irradiations of high-temperature, gas-cooled reactor materials, and in November 2005 this in-core loop was installed in the MITR. A demonstration test was performed with temperatures up to 1,600 °C. A variety of materials relevant to high-temperature gas reactor design, including SiC, AGR matrix graphite, and nonfueled coated particles, were irradiated. Development and in-pile testing of high-temperature-resistant materials are essential for the Gen-IV reactor programs. The HTIF will be a valuable test facility for research on high-temperature-resistant materials.

SiC Duplex Advanced Clad Irradiation: This project, directed by Dr. Gordon Kohse and Professor Mujid Kazimi, 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 terms of both improved safety margin and higher burnup. Irradiation testing in prototypical PWR and BWR coolant conditions began in May 2006 and continued until the end of the year. PIE is then planned to measure weight loss, thermal conductivity changes, mechanical property tests, and scanning electron microscopy. The irradiation testing and some of the PIE are being conducted at NRL with the MITR's in-core loop facilities and hot cells.

High-Performance Fuel Design for Next-Generation PWRs: This project is directed by Professor Mujid Kazimi, Professor Pavel Hejzlar, and Dr. Gordon Kohse. In February 2004, a new type of in-core experiment was carried out in the MIT research reactor to test performance of innovative annular fuel designs as a part of the Gen-IV power reactor research effort by NSE. 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 heat temperature will 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. The specimens are awaiting movement to the reactor floor hot cell for PIE prior to transfer to the Idaho National Laboratory. This is the first irradiation of a fueled test capsule at the MIT reactor and one of very few undertaken at any university reactor.

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 directed by Thomas Newton, was used to test fusion magnet insulation materials for suitability in simulated fusion radiation environments. A water-cooled lead shield was developed to lower the reactor gamma component and provide a cooled environment for the sample irradiations.

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 looking ahead in order to meet future challenges. One particular challenge that needs to be addressed is the reliance of the United States on fossil fuels. Currently, only 20 percent of the country's energy resources are provided by nuclear power. The proposed Generation-IV (Gen-IV) Program 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. NRL is uniquely qualified to be a key contributor to the design and performance of experiments evaluating the advanced materials and fuels needed for Gen-IV reactors.

Neutron Capture Therapy Program

Directed by Professor Otto K. Harling, 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 a high-performance irradiation facility for NCT-related research utilizing the MITR. Upgrades to this facility have been supported by DOE. A high-intensity and high-purity thermal neutron beam is now available at the MITR. This facility was designed to:

- Provide physical and computational dosimetry associated with experimental (and clinical) studies
- Analyze bulk and microscopic boron distributions in tissue specimens
- Maintain a working cell culture laboratory
- Assist with designing and performing animal or cell culture experiments (as well as clinical trials)

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 percent.

This project is making extensive use of the reactor's fission converter facility, the prompt gamma facility, and the thermal neutron beam facility for drug testing and characterization using cell culture, tissues, and lab mice. Construction of the fission converter facility was funded by DOE and completed by NRL staff in autumn 2000. Major peripheral equipment installation was completed in FY2001. In FY2002 and FY2003, it was used primarily for beam and drug studies by national and international groups. Many of the beam and drug studies were performed as preparation for Boron Neutron Capture Therapy (BNCT) group clinical trials. The clinical trials at MIT were a collaborative effort with the Beth Israel–Deaconess Medical Center, which is affiliated with the Harvard Medical School.

As part of the BNCT project, the epithermal neutron beam at the reactor basement's original medical facility was converted into a thermal beam during FY2002. In FY2003, Ricorad shielding was installed along the thermal beam medical room's inner wall adjacent to the reactor's equipment room in order to minimize radiation interference in the thermal beam room during operation of the fission converter facility. Construction of a full-sized control console away from the outer wall of the thermal beam facility was completed, replacing the original beam control panel. In FY2004 and FY2005, new lighting and wall surfaces and a new floor were installed inside the medical room. In FY2005, additional Ricorad shielding was installed along the medical room's inner wall, and then the final inner wall surface was mounted in place. Extensive instrumentation rewiring for shutter operation from the new control console was also completed in FY2005.

The 10 spent elements making up the subcritical neutron source for the FCB were replaced with slightly burned MITR fuel in FY2006. An 11th element was also accommodated within the existing grid by slight modifications to this element that were allowed within the fuel specifications. Refueling the FCB has increased the available epithermal neutron flux at the patient position by 20 percent. Shielding on the reactor top was also improved to allow better access to the FCB fuel tank and simplify maintenance of nearby reactor-related equipment.

Innovations in Nuclear Infrastructure and Education Program

The Department of Energy 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.

This program, now in its fourth year, has led to renewed interest in utilization of the MITR. INIE has supported numerous research initiatives conducted by NSE faculty members and researchers. Funds received during the fourth year of INIE were used for upgrades to the NCT user facility; design and construction of the PIE facility for in-core irradiations of advanced fuels and materials, which will ultimately support research for the next generation of power plant initiatives; funding for equipment in support of phase contrast imaging research; and funding for two MIT graduate students conducting research in the areas of neutron interferometry and NCT.

NCT User Center: INIE provided funds to establish the NCT User Center. It is the only such facility in the United States and is essential for a viable research and clinical program in NCT. The center is made up of several state-of-the-art neutron facilities for NCT research that have been developed and are in operation at the MITR. They include:

- The epithermal neutron irradiation facility (FCB), which is licensed by NRC. It has an intensity of ~$5x10^9$n/cm^2-s with low inherent beam contamination that approaches the theoretical optimum. If the FCB is used at maximum intensity, tissue tolerance can be reached in less than 10 minutes. With current capture compounds, the high beam purity results in a useful treatment depth of ~9 cm. Therefore, the FCB is well suited to treating deep-seated cancers. The FCB is currently the only operating US epithermal neutron beam that 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, low-contamination thermal neutron beam. This facility has its own medical irradiation room separate from the FCB's irradiation room. The thermal neutron facility is well suited for small animal studies and for clinical studies of NCT in which tumors are less than ~4 cm deep. There is currently no other comparable facility for thermal neutron irradiations in the United States.
- 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 (ICP-AES) and an 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. High-resolution quantitative track etch autoradiography developed in the joint Harvard-MIT program permits 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.

INIE funds supported the following upgrades during the past year:

- Installation of improved shielding above the FCB fuel tank to facilitate access
- Purchase of a new ICP-AES machine (partially funded by INIE)
- Implementation of high-resolution quantitative autoradiography to determine the inhomogeneous uptake of boronated liposomes in EMT-6 tumors (murine)

Investigation of Nanofluids for Nuclear Applications: Dr. Lin-Wen Hu and Professor Jacapo 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 depend on nanoparticle loading, material, and shape in ways that are not yet clear. 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 collaborative NRL-NSE 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, and plasma diverters. The program comprises the following activities, currently sponsored by the Idaho National Laboratory, NRC, AREVA/Framatome, and INIE.

- Construction of two out-of-pile loops to investigate nanofluid 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 application evaluations: subchannel, safety, and neutronic analyses of PWRs with nanofluid coolant

Coherent Imaging via Neutron Interferometry: This project, directed by Professor David Cory in collaboration with NIST, involves a reciprocal space approach to coherent imaging via a three-blade neutron interferometer. The new approach promises improved contrast and a resolution independent of the spatial resolution of the detector. This work has been extended to using a three-blade interferometer to create a neutron beam that is a coherent superposition of two beams separated by a controllable distance limited by the coherence length of the interferometer (about 500 Å in this case). This spatially separated coherent beam will enable a new class of coherent scattering and holds great promise for future neutron scattering studies in condensed matter.

Phase Contrast Imaging: This project is directed by Dr. Richard Lanza. Phase contrast imaging uses the wave properties of neutrons to greatly increase spatial resolution and contrast in materials imaging. A beamline and detector system for implementing this technique was installed at the MIT Nuclear Reactor Lab. A new approach is now being examined that can lead to phase tomographic imaging, which would enable us to produce three-dimensional images of materials that cannot be distinguished by their density and absorption.

In-Core Loops: This portion of the MITR INIE program involves the design and construction of a 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 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.

Environmental Research and Radiochemistry

Dr. Lin-Wen Hu has taken on the role of overseeing operation of NRL's environmental research and radiochemistry laboratories. The 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, the MITR 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 8 $x10^{12}$. 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.

The NRL NAA laboratory has 2 Hp(GeLi) detector systems with Genie 2000 software. One new detector was 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, the California Institute of Technology, Tufts University, the University of Connecticut, and the Woods Hole Oceanographic Institute.

The following list represents some of the ongoing research activities conducted at NRL involving neutron activation analysis:

- Environmental biomonitoring of chromium and arsenic in shallow groundwater utilizing NAA and secondary mass spectrometry in order to discriminate between groundwater and 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 utilizing tree-ring chemistry. The 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 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 ALS as compared with 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 mercury contamination, which is severely neurotoxic, particularly to fetal development during the gestational period. This demonstration is a hands-on exercise that serves as an educational tool underscoring the Food and Drug Administration's warning against fish consumption by pregnant women. This exercise is being conducted by Lin-Wen Hu.
- Sn-112 samples were irradiated with the goal of investigating the response characteristics of various detectors of electrons in the several hundred KeV energy range; also, angular correlations in the neutron decay process were measured. The main result was an essential improvement in the characteristics of detectors with plastic scintillators and liquid scintillators. This work was done to support an experiment designed to determine the precise measurement of electron-antineutrino angular correlation in free neutron decay; the experiment was conducted by Professor Boris Yerozolimski of Harvard University's High Energy Physics Laboratory in collaboration with other scientists from NIST, Tulane University, Indiana University, and Hamilton College.

New Research Initiatives

Neutron Spectrometer Experimental Facility

NRL is designing and constructing a web-enabled neutron spectrometer experimental facility. Currently the neutron spectrometer is a nonautomated facility installed in the MITR's 4DH1 beam port. While this facility has been enhancing MIT undergraduate curriculums for the last 20 years, it is limited in that it is accessible only on-site. In collaboration with MIT's iCampus program, NRL plans to debut the first online, interactive, real-time neutron-based experiment this winter. Using a combination of LabVIEW software and a prototype iCampus-developed architecture, NRL will be able to provide educational opportunities to both US students and international students who do not have the benefit of an on-site nuclear reactor or other neutron source.

Neutron Scattering

Neutron scattering, although having a long and distinguished history at NRL, has not been actively pursued since the retirement of Professor Cliff Shull. However, a revitalization of NRL's neutron scattering program has begun under the direction of Professor David Moncton with the assistance of Dr. Boris Khaykovich. They have received funding from the National Science Foundation 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 scales. A powerful new neutron facility, the Spallation Neutron Source (SNS), is currently under construction at the Oak Ridge National Laboratory, and it 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 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 NRL's outstanding safety and operating record, which is evidenced by the results of NRC inspections. These results are shown in the table below.

Table 1. MITR Inspection Record, 2001–2005

Inspection Date	Inspection Type	Result
01/22/01	Inspection on reactor operations/ requalification/safeguards	No deficiencies
06/25/01	Inspection on RRPO[a]	No deficiencies
10/28/01	Inspection on RRPO/security	No deficiencies
09/04/01	Licensing exams	3 ROs[b] + 2 SROs[c], 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 1 RO, who passed a subsequent makeup exam, and 1 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 2 ROs, 1 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
09/06/05	Licensing exams	6 ROs + 6 SROs, all passed
11/14/05	Inspection on RRPO/reactor operations	No deficiencies

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

Modern approaches to safety combine personal expertise and strong training with a methodology for continuous improvement. NRL will soon be implementing a continuous improvement program with three major goals: (1) reducing unplanned shutdowns, (2) minimizing environmental releases, and (3) limiting personnel exposures as per the "as low as reasonably achievable" principle. The program, which will be computer based, will 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.

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 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 the following: 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.

David E. Moncton
Director

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