Nuclear Reactor Laboratory

The MIT Nuclear Reactor Laboratory (NRL) operates a research reactor (MITR) that has been operational since the late 1950s. The 6 MW research reactor has a long and proud tradition of carrying out research and educational training in the forefront of fission engineering, materials studies, neutron physics, radiation effects in biology and medicine, geochemistry, and environmental studies. It is the second largest university research reactor in the US, and is the only research reactor located on the campus of a major research university that provides students with on-campus research experience working in radiation environments by conducting irradiations and doing post-irradiation examinations. A research reactor is an increasingly rare asset in the US and the NRL is highly valued by students as well as by their prospective employers in government and industry.

The NRL's primary mission is to provide faculty and students from MIT, as well as the national scientific and engineering community, with both a state-of-the-art reactor facility and the infrastructure to enable and support its use for research and other societal objectives. The highest priority is placed on operating the research reactor in a professional manner that ensures the safety of MIT, NRL staff and researchers, the public, and the environment. A secondary, but no less important, mission is to educate the general public about the benefits of maintaining a strong nuclear science program in the US. This is accomplished by providing tours and lectures that describe and clarify different nuclear science and technology programs.

For the past 57 years, the NRL has provided both a safe and reliable neutron source and the infrastructure to facilitate its use. During a long and distinguished history, the NRL has supported educational training and cutting-edge research in the areas of nuclear fission engineering, material science, radiation effects in biology and medicine, neutron physics, geochemistry, and environmental studies. As a result, many generations of undergraduate and graduate students have benefited from their association with the NRL. More important, it has proven itself to be a unique resource for assisting in the educational development of the next generation of nuclear engineers who will conceive, design, and manage the future of nuclear technology across the US and the globe.

Current research programs at the NRL are mostly centered on in-core experiments studying the properties of materials and fuels in a radiation environment that is remarkably similar to that of a nuclear power reactor. Other experimental facilities and instrumentation include radiochemistry laboratories, hot cells for dismantling or testing, a shielded hot box for handling and nondestructive testing of radioactive materials, nuclear detection equipment, delayed and prompt gamma activation analysis facilities, an inductively coupled plasma spectrometer, and a materials characterization laboratory.

Reactor Administration

The 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. These groups are Reactor Operations; Research, Development, and Utilization; Engineering; and Administration. David E. Moncton is the director of the NRL. The senior management team includes Thomas H. Newton, Lin-Wen Hu, John Bernard, Mary Young, and William McCarthy. This team works to sustain the NRL's long-standing record of safe operation, to maintain and improve upon the state-of-the-art reactor facility, and to provide an environment of support and excellence for researchers and students.

The NRL currently employs 41 individuals. The staff consists of six groups, including the previously mentioned senior staff. There are also six research staff, eight technical staff, 11 technical support staff, three academic staff, three administrative support staff, two technicians, and three part-time student operators. In general, NRL support staff, student employees, and technicians have specific responsibilities to a particular group.

Educational Impact

The MITR reactor has been and continues to be used extensively to support MIT's educational mission. Principal activities include:

- Use of the reactor for laboratory courses. The Physics Department conducts one of the Junior Laboratory's experiments using the reactor's neutron chopper facility. The Department of Nuclear Science and Engineering (NSE) either uses or has used the reactor as part of several subjects, including ones on reactor design and operation, radiation detection, and reactor dynamics.
- Performance of thesis research at all degree levels. Since the 1950s, cutting-edge research utilizing the MITR has been conducted by faculty, students, and scientists from MIT as well as other institutions. Students especially enjoy doing thesis work on the reactor because they have the opportunity to combine theoretical knowledge from the classroom with hands-on engineering. More than 200 BS, MS, and PhD theses have been completed by students who used the reactor for their research.
- Training of undergraduates to operate the reactor. More than 300 students have participated in the NRL's Reactor Operator Training Program. Every year, four to six undergraduates are hired to work part-time as licensed reactor operators. Individuals from all majors are welcome to apply. Selected students are placed in a rigorous training program that covers reactor systems, emergency planning, radiation health physics, and reactor dynamics. Students then take a two-day reactor operator (RO) license examination administered by the US Nuclear Regulatory Commission (NRC) and, if successful, are employed 10 to 15 hours per week to operate the reactor. Once they have a year of experience, they may take a second exam to obtain a senior reactor operator (SRO) license. Many student operators have told US that the experience of working at the MITR was one of the highlights of their time at MIT.
- Public outreach. The NRL offers tours of the facility together with an introductory lecture on the reactor for high-school students, local area colleges, and MIT parents, staff, and alumni.

Facilities and Resources

The MITR-II is the second of two research reactors that the NRL has operated. The original reactor (MITR-I) achieved criticality in 1958. It was shut down in 1973 to allow conversion to the MITR-II, which offered a higher neutron-flux level. On July 8, 1999, a formal application was submitted to the US Nuclear Regulatory Commission to relicense the reactor for an additional 20 years and to upgrade the power level from 5 MW to 6 MW; the license and upgrade permission were granted in 2010. A further goal for the NRL is to convert the MITR-II's fuel from high-enriched uranium (HEU) to low-enriched uranium (LEU).

The MITR-II, the major experimental facility of the NRL, is a heavy-water-reflected, light-water-cooled and light-water-moderated nuclear reactor that utilizes flat, plate-type, finned, aluminum-clad fuel elements. The average core power density is about 80 kW per liter. The maximum fast and thermal neutron fluxes available to experimenters are 1.2×10^{14} and 6×10^{13} neutrons/cm^2, respectively. Experimental facilities available at the research reactor include two medical irradiation rooms, beam ports, automatic transfer facilities (pneumatic tubes), and graphite-reflector irradiation facilities. In addition, three in-core positions are available for in-core sample assembly (ICSA), pressurized water loops, and custom-designed irradiation facilities. The reactor generally operates 24 hours a day, seven days a week, except for planned outages for maintenance. The MITR-II encompasses a number of inherent (i.e., passive) safety features, including negative reactivity temperature coefficients of both fuel and moderator, a negative void coefficient of reactivity, the location of the core within two concentric tanks, the use of anti-siphon valves to isolate the core from the effect of breaks in the coolant piping, a core-tank design that promotes natural circulation in the event of a loss-of-flow accident, and the presence of a full containment building. These features make it an exceptionally safe facility.

Reactor Operations

Leadership of the reactor operations group is provided by the director of reactor operations, Thomas Newton; the assistant director of reactor operations, Edward Lau; and the reactor superintendent, John Foster. The reactor operations group, the largest at the NRL, is responsible for supporting all laboratory activities, with priority given to operation and maintenance of the 6 MW research reactor. The group consists of full-time employees and part-time undergraduate students. Almost all of the members of the group are licensed by the NRC, and most hold a senior reactor operator's license. These licensed individuals perform reactor shift duties to support the reactor's operating schedule. In addition, there is one full-time project mechanic to support reactor mechanical maintenance. Reactor operations supported the following NRL research projects: advanced cladding irradiation (ACI-2), molten fluoride salt irradiations, high-temperature in-core sample assembly capsule irradiations, DH4 diffractometer, and 4DH1 student spectrometer.

The MITR-II completed its 57th year of operation (its 40th since the 1974–1975 upgrade and overhaul). During the year, the reactor has been nominally maintained at a full power of 5.5MW or higher. Total energy output from July 2014 to June 2015 was 26,591 megawatt-hours. This translates to 4,507 hours of operation at full power.

Major NRL maintenance and upgrade projects accomplished in FY2015 included:

- Auxiliary intake damper operating mechanisms were upgraded
- Leak in secondary piping was repaired
- Digital logbook was installed in the console
- Designed and built an isolated high-voltage power supply for channel #7
- Fan motor for air conditioning unit #1 was replaced by Facilities Department
- Replaced plenum blower #2
- Hydraulic system for the main airlock inner door was repaired
- GM tube for plenum particulate monitor #2 was replaced
- Spent fuel pool recirculating pump was replaced
- Proximity switches for control blades #1 and #2 were replaced
- Belt and shaft guards on the ventilation intake fan were installed by Facilities Department
- Manual reflector dump valve and handle were replaced on the console
- Core purge condensate system was installed
- Floor tiles were replaced in the main airlock
- Four security cameras were replaced
- Shield system pump was rebuilt
- Thermal overloads were replaced for the exhaust damper hydraulic pump
- Sewer pump electrical contactor was replaced
- Six-inch silicon tube was replaced
- Electrical safety guards, a new ladder, and fall protection were installed on the polar crane
- Replaced blade magnet and drive for shim blades #2 and #3
- 3 GV cooling jacket was removed and Mirion fission chamber installed
- MTS-1 and MTS-1A were replaced
- The fourth and final Mirion fission chamber was installed in 4IH4
- Secondary water radiation monitor flow switches were replaced
- New alarm system was installed to provide local and remote indication of weekend and intrusion alarm system status
- Parking lot pedestrian gate locking mechanism was repaired
- Channel #2 power supply was replaced
- Main airlock inner door hydraulics were rebuilt
- Auto-controller pre-amplifier circuit was repaired

Many other routine maintenance and preventive maintenance items were also scheduled and completed throughout the fiscal year for experiments and for reactor operations.

Student Operator Training Program

The reactor operations group trains up to six MIT undergraduates each year, typically starting in their freshman year, to obtain an NRC license to operate the MIT reactor. The training program is rigorous and covers reactor dynamics, radiation detection, radiation safety, and reactor systems. The level of instruction is comparable to that offered in undergraduate courses covering the same topics. On completion of the training program, students take a two-day examination administered by the NRC (one day written, one day oral). Successful candidates receive a reactor operator license and are employed part time. After the students gain experience, most are offered the opportunity to participate in a second training program that leads to a senior reactor operator license. This training program is an excellent educational opportunity for undergraduate students because it combines theoretical study with hands-on experience—squarely in the MIT tradition of graduating students who know how to design and build systems. In addition, students who receive the SRO license obtain management experience by serving as shift supervisors.

From July 2014 through June 2015, two sets of NRC examinations were administered at MIT. In September 2014 there was one candidate for the RO license; in February 2015 there were two candidates, one for an SRO license and one candidate retaking a section of the written exam for an RO license. One MIT research scientist and one ex-Navy nuclear operator are applying for SRO licenses and are training for the next NRC examinations, scheduled for October 2015.

Reactor Engineering

The reactor engineering group is led by Thomas Newton. This group's activities include support and development for experiments such as the ICSA, the high-temperature irradiation facility, and ACI-2s. This group also performs neutronic modeling of proposed experiments for evaluation of neutron fluxes, reactivity, and heat generation. Work with ex-core experiments, including upgrade and operation of a neutron diffractometer, has continued as well. Other activities of this group include engineering support of upgrades to reactor mechanical and instrumentation systems, supervising the management of fuel in the reactor and fission converter, and overseeing shipments of spent fuel. The group also offers other engineering services as needed.

Dr. Newton is the principal investigator for the program to convert the reactor to LEU fuel. MIT seeks to carry out the first conversion among the remaining five high-performance reactors in the US, adopting a special high-density LEU fuel that is currently undergoing qualification tests. Although the fuel development program, sponsored by the National Nuclear Security Administration, has experienced delays, the MITR-II remains a valuable reactor to provide the first demonstration of this important new fuel, which is critical to the mission of the Global Threat Reduction Initiative to eliminate weapons-grade HEU from civilian use worldwide.

With continuing support from the Global Threat Reduction Initiative, neutronic and thermal-hydraulic modeling tools for the MITR-II conversion study have been developed and benchmarked for both steady-state and transient conditions. These models are being used to compare the current HEU fuel with proposed LEU fuels. Burnup modeling tools using both Monte Carlo and diffusion theory methods have also been developed so that fuel life, reactivity, neutron fluxes, and power peaking can be evaluated over time. Such models are being used to determine core performance and to develop a fuel management strategy that will reduce power peaking in the LEU core while meeting experimental as well as fuel supply needs.

Feasibility studies have shown that this LEU fuel can be used in the MIT reactor, although without an increase in reactor power it could come at a significant penalty in neutron flux to in-core and ex-core experimental facilities. These studies have also shown that the reactor could operate using LEU fuel at or near 7 MW without significant changes to the reactor infrastructure, which would allow all experiments to operate with the same or greater neutron fluxes present in the current HEU core at 6 MW.

Reactor Research Facilities and Services

Partnership with Idaho National Laboratory

The NRL is in a partnership with the Nuclear Science User Facilities (NSUF) of the Idaho National Laboratory (INL) to perform advanced nuclear fuel, materials, and instrumentation irradiation experiments that are crucial to future-generation reactors. High-temperature and radiation-resistant materials are needed for advanced high-temperature reactor designs that enable high power conversion efficiency as well as for hydrogen-production reactors. A related and equally important goal is to study advanced fuels and materials that will enable both the extension of service and improved economic performance in the existing light-water reactor (LWR) fleet. This collaboration is designed to increase user access to national reactor irradiations and testing capabilities. NSUF test spaces at Advanced Test Reactor (ATR), MITR-II, and other facilities are made available at no cost to external users, whose projects are selected through a peer review process. MIT will offer a portion of MITR-II’s test capability to NSUF experimenters. Lin-Wen Hu and Gordon E. Kohse jointly manage the NRL partnership with the NSUF.

In-core Loops and Capsule Irradiation Facilities

The NRL has a strong in-core experimental program that supports research in advanced materials and fuels that are necessary for both existing and advanced power reactors. The MITR-II reactor offers a unique technical capability that involves the design and use of in-core loops that replicate pressurized-water reactor and boiling-water reactor conditions to study the behavior of advanced materials and to perform scoping studies of advanced nuclear fuel. With rekindled national interest on the part of the US Department of Energy (DOE) and the nuclear industry in next-generation nuclear power systems, many of which are intended to use novel materials and advanced forms of fuel, facilities are needed to test material and fuel behavior in a variety of radiation environments. The MITR-II is the university reactor best suited for carrying out such basic studies because of its relatively high power density (similar to that of a LWR), its capability to control chemistry and thermal conditions to reflect prototypic conditions, its easy-access geometric configuration, its in-core space for up to three independent irradiation tests, and the proven capability of the reactor staff to design and execute proof-of-concept experiments more quickly than at other research reactors.

Post-irradiation Examination Facility

The MITR-II is equipped with post-irradiation examination (PIE) facilities that include 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- and 20-ton capacities, and several transfer casks. One of the hot cells is currently equipped to disassemble and reassemble in-core water loop sample trains; the hot box is set up to perform similar tasks for ICSA capsules. In addition to these facilities in reactor containment, an exclusion-area laboratory is equipped for irradiated sample mechanical tests (tube specimens and miniature four-point bend test bars) and for irradiated sample sectioning and polishing.

Neutron Spectrometer Experimental Facility

The web-enabled time-of-flight experimental facility can be operated locally or remotely over the Internet using MIT's iLabs server architecture. Hardware and software upgrades made during previous years improved reliability and supported a heavy schedule of student experiments in both the fall and spring terms. The longer data collection times that are feasible with remote operation have both markedly improved the data quality available to students and greatly enhanced the educational value of the experiments conducted. Continued incremental improvements to the hardware and software are planned, together with outreach efforts to broaden the user base of the facility outside MIT. The US Military Academy at West Point ran experiments on the facility using iLabs as part of its physics and nuclear engineering instrumentation laboratory course during the fall semesters of 2011 and 2012. In addition to the educational use, the time-of-flight beam is in use as part of a research program to measure neutron capture cross sections for copper isotopes. This program has funding from Oak Ridge National Laboratory and the participation of a graduate and undergraduate student and professor Benoit Forget of NSE. Researchers from the INL used the facility for testing neutron detectors that are under development.

Neutron-scattering Facility

Neutron scattering is a powerful suite of scientific tools for studying the structure and dynamics of matter. National neutron scattering facilities are multimillion-dollar installations serving hundreds of scientists per year. New facilities, such as the Spallation Neutron Source at Oak Ridge National Laboratory, are being built around the globe. MIT has a long tradition of leadership in neutron science, extending back to professor Clifford Shull, who shared a Nobel Prize for pioneering neutron scattering techniques. Several years ago, under the direction of David Moncton and with the assistance of research scientist Boris Khaykovich, a major restructuring of the NRL's neutron scattering program was initiated with the following goals:

- 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 new instruments for future installation at the Spallation Neutron Source
- Establishment of a facility designed to allow users from outside MIT to conduct early phases of some experiments more quickly than at large facilities, and to test and develop new neutron optics components

Currently, several groups at MIT are utilizing neutron scattering methods, as well as developing novel neutron sources, devices, and applications. The NRL's neutron-scattering instruments include a neutron diffractometer and a neutron optics test station.

Dr. Khaykovich conducts a DOE–funded neutron optics research program whose goals are to develop specialized neutron-focusing optics for scattering and imaging applications, demonstrate improved magnetic imaging with polarized neutrons, and develop novel technology for manufacturing neutron guides.

Environmental Research and Radiochemistry

The NRL's environmental research and radiochemistry laboratories are equipped for both prompt and delayed gamma neutron activation analysis (NAA). A prompt gamma spectrometer was built as part of the boron neutron capture therapy program to measure the boron content in the blood and tissue of patients and experimental animals; this is now available to other users. With respect to delayed NAA, the MITR-II is equipped with two pneumatic tubes that are commonly used for NAA, primarily for analysis of trace metals. One offers a thermal flux of 5.7×10^{13} and the other offers a thermal flux of 7.2×10^{12}. Several of the tubes are automated so that samples can either be ejected to a hot cell within the reactor containment or be 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 can be rotated. An inductively coupled plasma-atomic emission spectrometer is also available at the NRL. The NRL's NAA laboratory is equipped with three high-purity germanium systems with Genie 2000 software. The NRL makes its NAA facilities and expertise available to industry, other universities, private and governmental laboratories, and hospitals. Research- and service-oriented collaborations were continued with several MIT research laboratories as well as with other educational and research institutions.

Reactor Research, Development, and Utilization

Lin-Wen Hu is the associate director of the research, development, and utilization group. She and her staff have developed a robust program that assists MIT faculty, researchers, and students, as well as those outside the NRL, in their use of the reactor and its irradiation facilities. Tasks undertaken by this group include:

- Supporting research in the area of advanced materials and fuel research
- Providing researchers with a service-based infrastructure that utilizes the MITR-II for trace element analysis, isotope production, and irradiation services
- Supporting an outreach program to the educational community to encourage understanding of nuclear energy and its applications
- Supporting MIT's educational missions by providing Independent Activities Period lectures, hosting Undergraduate Research Opportunities Program students, and offering laboratory courses for professionals, undergraduates, and advanced secondary school students
- Expanding the user base for underutilized experimental facilities

Irradiations and experiments conducted during this reporting period include the following:

- Activation of gold-198 seeds for brachytherapy
- Activation of uranium foils for detector calibration at the Los Alamos National Laboratories
- Activation and NAA of fusion laminate samples for neutron damage study for Composite Technology Development Inc.
- Activation of ocean sediments for the Woods Hole Oceanographic Institute
- Activation of ocean sediments for the University of British Columbia
- Activation of silicon photodiodes and NAA standards for the University of Alabama
- Activation of germanium targets for neutron damage study at MIT Materials Processing Center
- Activation and NAA of FLiBe [mixed lithium fluoride (LiF) and beryllium fluoride (BeF_2)] salt crystals in conjunction with the MIT portion of the Liquid Salt Reactor Project
- Activation and NAA of various sample materials and structural components for the INL crack growth irradiation experiment
- Experiments in reactor building by the Physics Department to determine background neutron flux for a possible reactor neutrino detection experiment
- Experiments at the 4DH1 radial beam port facility by MIT undergraduate and graduate students, including measurements of leakage in the neutron energy spectrum to determine reactor temperature, measurements of neutron wavelength and time of flight, and measurements of attenuation coefficients for eight shielding materials
- Use of the reactor for training MIT student reactor operators and for NSE classes (22.06 Engineering of Nuclear Systems, 22.09 Principles of Nuclear Radiation Measurement and Protection, 22.921 Nuclear Power Plant Dynamics and Control, and the reactor technology course for nuclear power executives) and the Physics Department (8.13 Junior Laboratory)

Research Programs

In-Core Experiments

The NRL's in-core experimental program has been seamlessly integrated into various US industry- and government-funded programs, such as the NSUF Program, the Accident Tolerant Fuel Program, the Advanced Reactor Program, and other DOE Office of Nuclear Energy initiatives. The proven capability of the NRL staff to design and successfully execute complex proof-of-concept experiments and to deploy in-core loops for studying both LWR and non-LWR coolants and materials at high temperatures is and will remain an essential national capability. The NRL's unique expertise and capabilities have established its reputation to rapidly demonstrate the survivability of new sensors and instrumentation components, and to develop rigs for irradiation testing. In addition, it is anticipated that several recently launched, privately funded advanced reactor development initiatives will seek support from the NRL to study their chosen materials and fuels. There are also international efforts in need of the capabilities of the MITR-II. For example, the program on fluoride-salt-cooled high-temperature reactors has attracted substantial support from a larger Chinese development program in this area.

Factors that have made NRL's in-core program a success include:

- The high neutron flux, flexible core design, and 24/7 operating schedule of the MITR
- The expertise of NRL staff research scientists and engineers with the assistance of MIT undergraduate and graduate students
- Recent upgrades to the infrastructure of the MITR as a result of the US Department of Energy's Nuclear Energy University Program (and other programs)
- The continuing collaboration with the ATR-NSUF, which is to the benefit of both the Idaho National Laboratory and the Nuclear Reactor Laboratory

The demand for the NRL's MITR experimental facilities has increased because the cost of using the MITR is lower than that of national laboratory facilities, we provide quick turn-around in experiment design and execution, and the track record of recent experiments is excellent. Dr. Hu's group, which includes several research scientists, post-doctoral associates, graduate students, and students from the Undergraduate Research Opportunities Program continue to design and implement new in-core experiments in addition to continuing operation on existing facilities. They work closely with the experimenters, MIT Reactor Radiation Protection, and the MIT Reactor Safeguards Committee to ensure that all necessary safety protocols and approvals are in place before any experiments are started. Descriptions of experiments that were installed and operated during the past year follow.

EPRI Silicon Carbide Composite Channel Box Project

In a boiling water reactor (BWR), a "channel box" is a duct surrounding the fuel bundles that is used to maintain radial isolation of the coolant flow. Channel boxes in current BWRs are made of Zircaloy™ and are subject to two major problems. First, near the end of life of a fuel assembly, the channel box can exhibit severe bowing due to fast neutron flux gradients and possible shadow corrosion effects. This can lead to unpredictable water gaps and problems with control rod insertion. In severe accident conditions with exposure to high temperature steam, Zircaloy™ reacts rapidly and generates hydrogen and additional heat. The accident at the nuclear plant in Fukushima, Japan, has greatly increased interest in finding in-core materials that do not exhibit this behavior. Silicon carbide (SiC) composites are a candidate for both fuel cladding and channel box applications.

As reported previously, initial samples produced under funding from the Electric Power Research Institute (EPRI) experienced very high corrosion rates under irradiation in BWR conditions in the MITR. One of the materials was subsequently irradiated in water coolant with much lower oxygen concentrations with no observable weight loss over a six-month exposure. The EPRI is continuing efforts to develop a coating that can protect the SiC/SiC composite materials from oxygenated coolant and another round of irradiations is planned if these efforts succeed.

Westinghouse Accident Tolerant Fuel Project

The Fukushima accident has created very strong interest in finding alternatives to the currently used Zircaloy™ alloy for fuel cladding. This interest is driven by the problematic behavior of Zircaloy™ in high-temperature steam, where rapid reactions can occur with generation of hydrogen and heat, compromising the ability of the cladding to maintain a "coolable geometry" for the fuel pins.

Westinghouse is leading a multi-institutional effort to design and demonstrate an advanced fuel concept with improved post-accident behavior that can be rapidly commercialized. This research is funded by the DOE Nuclear Engineering Enabling Technology Program. The effort involves changes to both the fuel meat and the cladding, with the NRL's contribution being to irradiation test candidate cladding materials. The primary replacement candidate is multi-layer SiC/SiC composite tubing, which is an evolution from tubing previously tested in the MITR-II. Large-scale manufacture and bonding of this tubing may be an obstacle to near-term commercial deployment, so alternate cladding concepts based on Zircaloy™ tubes coated with MAX-phases or glassy iron-based materials will also be tested. A two-stage irradiation of SiC/SiC composite clad materials was carried out from April 2014 through May 2015, with some samples removed and replaced with others at approximately the mid-way point. The replacement samples included end plugs to test clad tube sealing methodology. Post-irradiation examination is under way on these samples, with preliminary examinations indicating that the seal methodology may have adequate performance at the exposure levels achieved.

At the interim sample changeout, the coupon specimens were replaced with samples produced by three-dimensional (3D) printing. This material is being investigated for application in 3D printed fuel spacer grids that could be designed to have very low pressure drops and favorable vibration characteristics. These samples were removed at the conclusion of the irradiation and are being shipped to a Westinghouse hot cell facility for mechanical testing. This may well be the first exposure of 3D printed metal materials in a nuclear reactor environment.

A second phase of the accident tolerant fuel test has been funded by DOE and the MITR-II will continue to the main test bed for irradiation of candidate fuel cladding materials. Further tests of SiC/SiC composites are planned, together with the hybrid coated Zircaloy™ tubes discussed above. The test is expected to start in November 2015 and continue for approximately one year of exposure.

NSUF Ultrasonic Transducers Irradiation Test

Current-generation light water reactors and advanced nuclear reactors have harsh environments in and near the reactor core that can severely challenge materials performance and limit their operational life. As a result, several DOE Office of Nuclear Energy research programs require that the long-duration radiation performance of fuel and materials be demonstrated. Such demonstrations require enhanced instrumentation to detect microstructural changes under irradiation conditions with unprecedented accuracy and resolution. Recent work supported by several of the Office of Nuclear Energy's research programs has been investigating ultrasonic transducers for both under-sodium viewing and in-service inspection measurements near the core.

The NSUF sponsored an ultrasonic transducer research program to select candidate sensor materials, perform high-temperature irradiation tests in the MITR, and conduct post-irradiation evaluation. The irradiation is an instrumented lead test providing real-time data from two magnetostrictive and four piezoelectric transducers during the irradiation exposure. The test was completed in May 2015 after operating from January 2014 with accumulation of a fast neutron fluence of about 3×10^{21} n/cm^2 ($E > 0.1$ MeV) at temperatures of up to 450°C. Both the magnetostrictive sensors and one of the piezoelectric sensors were still producing useful signals at the end of the test.

Additional testing was performed in a reactor floor hot cell after removal of the test from the reactor, with the participation of researchers from Pennsylvania State University and INL. During PIE, "drop-in" samples of the active materials (not made up into operating sensors) were characterized. This irradiation and PIE program is now completed. The data obtained is an important contribution to understanding the evolution of ultrasonic transducer materials under high-temperature and high-dose operation. It will help establish the potential for useful in-core sensors based on this technology.

A follow-up test including both ultrasonic sensors and other advanced in-core instrumentation is under discussion with INL and the NSUF.

Fluoride High-Temperature Materials and Fluoride Salt Irradiation

MIT, the University of California at Berkeley, and the University of Wisconsin initiated a cooperative integrated research project to develop the path forward to a test reactor and ultimately a commercial fluoride-salt-cooled high-temperature reactor (FHR). The three-year project is funded by the DOE Nuclear Energy University Program and is led by MIT.

The FHR is a new reactor concept that combines high-temperature graphite-matrix coated particle fuel developed for high-temperature gas-cooled reactors (fuel failure temperature > 1650°C), liquid salts developed for the molten salt reactors (boiling point > 1400°C), safety systems originating from sodium fast reactors, and Brayton power cycle technology. This combination of existing technologies may enable the development of a large power reactor where catastrophic accidents, such as the Fukushima accident, would not be credible, because the FHR fuel and coolant combination may allow decay heat to be conducted to the environment without massive fuel failure even with large-scale structural and system failures. One of the major technical challenges is the corrosion behavior of the fluoride salt FLiBe [mixed lithium fluoride (LiF) and beryllium fluoride (BeF_2)] and reactor fuel and materials in a radiation environment. Testing in the MITR addresses this concern and is also intended to help verify models for tritium generation and transport.

Two irradiations of FLiBe salt have been completed. The first, as previously reported, was a capsule irradiation consisting of FLiBe salt, SiC, nuclear grade graphite, Hastelloy-N, and other metal alloy samples. The experiment was installed in the reactor in mid-September 2013 and ran continuously for a thousand hours, with temperature controlled at 700 ± 3°C. PIE has been performed to assess the corrosion behavior of the samples exposed. Additional PIE will analyze the content and distribution of tritium in the graphite parts. The second irradiation had a larger FLiBe salt volume and was operated in the reactor during July and August 2014. Problems arose in this irradiation when an unscheduled reactor shutdown resulted in cooling of the salt with continued exposure to high gamma fluxes. This led to evolution of fluorine gas from low-temperature radiolysis of the salt, damaging the gas outlet system and requiring shutdown and removal of the experiment. Some exposure was achieved, however, and PIE will be undertaken on the samples and graphite parts. The irradiation also provided valuable technical insights that will inform the design of future irradiation experiments.

A variety of FHR work will continue in the upcoming year. Renewed funding from DOE will be used for irradiations primarily aimed at understanding tritium evolution and transport and behavior of short-lived, gaseous, radioactive species generated in the salt under neutron irradiation. Under additional funding from the Chinese Academy of Sciences, investigation of gaseous radioactive species transport and low fluence corrosion behavior of a variety of materials will continue.

Neutron Scattering Optics

Modern optical instruments for visible and synchrotron light use a variety of focusing devices, such as lenses, Fresnel zone plates, and mirrors. These devices help increase the signal rate, resolution, or both. Were such powerful optical tools available for neutron scattering, they might bring significant, even transformative, improvements to ratelimited neutron methods and enable new science. The NRL group, led by Professor Moncton and Dr. Khaykovich, recently advanced such a tool: grazingincidence mirrors based on full figures of revolution, often referred to as Wolter mirrors. Neutron imaging and small-angle scattering with the help of the novel mirrors have been analyzed and demonstrated. Computer simulations predict that it might be possible to increase the signal rate of existing instruments by a factor of 50 or more, if optimized mirrors are used. Such mirrors can be made of nickel using existing technology. The benefits of such optics are their ability for highfidelity achromatic imaging and the possibility of coaxial nesting of multiple mirrors for increased throughput. The combination of the high throughput and high fidelity makes this optics capable of transforming neutron imaging and scattering instruments from pinhole cameras into microscopes in the cold to thermal energy range.

Operational Safety

The NRC's Office of Nuclear Reactor Regulation has oversight responsibility for program management, inspections, and operator licensing for all test and research reactors, including the MITR-II. Many years ago, MIT established its own means of ensuring safe operation of the nuclear reactor by appointing independent experts to a Reactor Safeguards Committee. The 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 policies as well as with NRC rules, operating procedures, and licensing requirements. 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 commitment and continuous training provided by the NRL's management team. An environment of cooperation and attention to detail among reactor employees and experimenters regarding all reactor safety matters is essential. Because 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 seen in the results of NRC inspections.

Reactor Radiation Protection

Radiation protection coverage is provided by the Reactor Radiation Protection Program of MIT's Environment, Health, and Safety Office (EHS). Although this is a separate organization within MIT, it is very responsive to the NRL management team. Personnel include a deputy director for EHS who serves as the reactor radiation protection officer (William McCarthy) and two EHS officers, one technician, and a part-time administrative support staff member. Routine activities include, but are not limited to, radiation and contamination surveillance, experimental review and approval, training, effluent and environmental monitoring, internal and external dosimetry programs, radioactive waste management, emergency preparedness, and ensuring that all exposures at the NRL are as low as reasonably achievable in accordance with applicable regulations and Institute committees. An EHS officer (James Rowlings from the safety program) serves as EHS lead contact to the NRL under the EHS management system organizational structure.

The NRL has a robust as-low-as-reasonably-achievable (ALARA) program. ALARA-related policies, procedures, and metrics have resulted in improvements to the facility's day-to-day safety and efficiency.

Rooftop environmental monitors are fully functioning and integrated with the NRL's electronic reactor monitoring display. These have replaced the old system, which used the MIT telephone lines and was at risk of the infrastructure becoming obsolete. The new technology uses the MIT network as well as a wireless system as a backup in case the network goes down.

Security

In FY2009 and FY2011, Edward Lau oversaw the upgrade of the reactor's security system, funded by DOE's National Nuclear Security Administration (NNSA). Through December 2013, NNSA provided funding for the system's maintenance and warranty, including quarterly system-wide tests, with the coordination of MIT Police, the MIT Security and Emergency Management Office (SEMO), and Siemens Building Technologies. Lau prepared reports on each quarterly test for documentation purposes, for NNSA review, and for NRC security inspections.

In March 2014, SEMO assumed responsibility for repair and maintenance of the security system. All repair and maintenance tasks have been tracked via the service request system of the MIT Facilities Department. The reactor's security hardware has been properly maintained and continues to meet all NRC regulatory requirements.

The camera system, one of the key security components, includes recording capability and operates continuously. It is now six years old and has experienced the expected aging seen in similar systems. It is also an older style compared to other camera systems on the MIT campus. In February 2015, after several rounds of site evaluation visits, SEMO, Information Systems and Technology, and Reactor Operations jointly presented a plan to the MIT Reactor Safeguards Committee (MITRSC) for upgrade of the reactor camera system using high-resolution digital Internet protocol cameras, which are compatible with similar technology that is replacing existing cameras all over campus. Most importantly, the new technology will improve communication with MIT Police for enhanced emergency response. The MITRSC approved a phased approach for the project, beginning with cameras that cover the site perimeter. The upgrade also includes remote and independent storage of camera data. Cybersecurity was an important factor during consideration of the project. Replacement work is expected to begin in autumn 2015.

In FY2013, the reactor's security plan was upgraded to reflect current practices and new protocols as a result of the hardware upgrades. The revised security plan was reviewed and approved by the MITRSC and subsequently accepted by the NRC. In FY2014 the security plan was again updated to modify MIT Police patrol protocols. This modification was also approved by MITRSC, and then by the NRC in May 2014 as a license amendment. In February 2015, NRC conducted a four-day security inspection and concluded reactor security was satisfactory and in full compliance with regulations.

In FY2013, Edward Lau coordinated with NRC for a voluntary cybersecurity-assessment visit by a team of NRC experts. A final report showing a negligible cybersecurity threat to reactor security and reactor operation has been presented to the MITRSC. A second round of assessments, with a renewed focus based on recent cybersecurity threats, is planned.

Appointments, Awards, and Events

During the past several months, Lin-Wen Hu has been a member of a review committee appointed by the National Academy of Sciences to study the state of molybdenum-99 production and utilization and progress toward eliminating the use of highly enriched uranium. The NRL is also pleased to report that David Carpenter, group leader in reactor experiments, was the recipient of an Infinite Award Mile in 2015.

The NRL has added two additional technical support staff, Timothy Leurini and M. Craig Parr, along with two new academic staff, Jingquan Liu (visiting scholar) and Guigiu Zheng (postdoctoral associate).

The NRL maintains a very close working relationship with the National Organization of Test, Research, and Training Reactors (TRTR). The TRTR's primary mission is education, fundamental and applied research, application of technology in areas of national concern, and improving US technological competitiveness around the world. The NRL will be hosting, and is coordinating, the 2015 TRTR Conference, which will be held at the Ocean Edge Resort in Brewster, MA. This conference is in collaboration with the International Atomic Energy Agency, which will be providing workshop sessions on managing aging issues for nuclear power plants.

David E. Moncton
Director