Nuclear Reactor Laboratory

The MIT Nuclear Reactor Laboratory (NRL) is an interdepartmental center that operates a high-performance 6 MW research reactor known as the MITR-II. It is the second largest university research reactor in the United States and the only one located on the campus of a major research university where students can be directly involved in the development and implementation of nuclear engineering experimental programs with neutron flux levels comparable to power reactors. For the past 55 years, the NRL has provided both a safe and reliable neutron source and the infrastructure to facilitate its use. During its 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 lab. More important, the lab has proven itself to be a unique resource for assisting in the educational development of the next generation of nuclear engineers—those who will conceive, design, and manage the future of nuclear technology across the US and the globe.

Facilities and Resources

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 highly professional manner that is safe for 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 United States. This is accomplished by providing tours and lectures that describe and clarify different nuclear science and technology programs.

The MITR-II is the second of two research reactors that have been operated by the NRL. 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 (NRC) 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. The next goal for the NRL is to convert the MITR-II's fuel from high-enriched uranium (HEU) to low-enriched uranium (LEU). Research funded under the Reduced Enrichment for Research and Test Reactors Program of the US Department of Energy (DOE) is now being conducted; this research will enable the MITR-II to meet this all-important, as well as highly anticipated, milestone.

The MITR-II, the major experimental facility of the NRL, is a heavy-water-reflected, light-water-cooled-and-moderated nuclear reactor that utilizes flat, plate-type, finned, aluminum-clad fuel elements. The average core power density is about 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 loops, and custom-designed irradiation facilities. The MITR-II generally operates 24 hours a day, seven days a week, except for planned outages for maintenance. The reactor 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 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 in the current environment. These groups are reactor operations; research, development, and utilization; engineering; and administration. David Moncton is the director of the NRL. He and Thomas Newton, Lin-Wen Hu, John Bernard, and Mary Young make up the NRL's senior management team. This leadership team works to sustain the NRL's long-standing record of safe operation, to continuously maintain and improve upon the state-of-the-art reactor facility, and to provide an environment of support and excellence for researchers and students.

The NRL currently employs 46 individuals. The staff consists of six groups, including the previously mentioned five senior staff. There are also six research staff, four technical staff, 11 technical support staff, four academic staff, three administrative support staff, two technicians, six part-time student operators, and three student trainees. In general, support staff, student employees, and technicians have specific responsibilities to a particular group.

Reactor Operations

The reactor operations group is led by Thomas Newton, director of reactor operations; Edward Lau, assistant director of reactor operations; and John Foster, reactor superintendent. 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 26 members of the group are licensed by the NRC and most hold a senior reactor operator (SRO) license. These licensed individuals perform reactor shift duties to support the 24/7 operating schedule. In addition, there is one full-time project mechanic to support reactor mechanical maintenance. Over the past year, reactor operations supported the following NRL research projects: advanced cladding irradiation, hydride-fueled irradiation, heated ICSA capsule irradiation, 4DH4 diffractometer, and 4DH1 student spectrometer.

As part of the NRL's continuous improvement program, a custom-made SAP-based job notification and occurrence reporting system was created by a team from Information Services and Technology. The system was successfully launched for routine use by all members of the NRL. Individuals can now log on and enter any unusual observations, which will be reviewed daily by NRL management for corrective actions, job assignments, and tracking of action status.

The MITR-II reactor completed its 55th year of operation (its 38th since the 1974–1975 upgrade and overhaul). Beginning in 1994, the reactor was put on a schedule of continuous operation to support major experiments and utilization. The reactor was nominally maintained at a full power of 5.5 MW or higher. Total energy output for FY2013 was 11,877 megawatt-hours. This translates to 2,013 hours of operation at full power.

Major NRL maintenance and upgrade projects completed in FY2013 include:

- Several pinhole leaks in the secondary coolant system piping in the equipment room were repaired, and two spare flanges were installed in the cooling tower cleanup system.
- The multipoint temperature recorder in the control room was replaced with a digital paperless recorder.
- The two remaining faulty circuit breakers on motor control center one were replaced, and all of the circuit breakers on motor control center two were cleaned and inspected.
- The medical water shutter overflow probe was replaced.
- The fission converter tank was defueled.
- New xenon worth buildup and decay curves were developed.
- One of the plenum blowers was replaced.
- A pinhole leak in a 3 GV cooling line was repaired.
- Fan belts were replaced for all blowers and fans.
- The motors for primary coolant pump MM-1A and secondary coolant pump HM-A were replaced.
- The reactor's automatic regulating rod controller was replaced.
- The proximity switch for blade #6 was replaced.
- The fission converter tank's CO_2 purge line and helium blow down lines were replaced.
- A Bernoulli filter in the secondary coolant system was redesigned and rebuilt.
- The fission converter's annunciator panel on the reactor floor was replaced.
- The reactor staff coordinated with MIT Facilities and contractors to replace sprinkler heads for NW12 and the restricted area.
- The fission converter heat exchanger HE-5 was replaced.

- The blowout patch for the D_2O storage tank in the equipment room was replaced.
- The shaft seal for the main reflector system pump was replaced.
- Neutron transmission tests on three new shim blades for the 4DH4 diffractometer were completed.
- Shim blade #1 and its regulating rod were replaced.
- The operational amplifier that feeds the digital auto-controller was replaced.
- Reactor staff coordinated with MIT Facilities to replace the outdoor air-conditioning compressor for the control room.
- Reactor staff consolidated many detector signal cables from various port boxes in preparation for the installation of a new reactor safety system.

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

Student Reactor 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 (RO) 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. Students who have completed this training program have regularly reported that it was one of the high points of their MIT experience.

From July 2012 through June 2013, two sets of NRC examinations were administered at MIT: in September 2012, there were three candidates for the RO license and three candidates for an upgrade to the SRO license; in February 2013, there was one candidate for an SRO license and two candidates for an SRO upgrade. Two MIT students, one ex-Navy nuclear operator, and one Bachelor of Science in Electrical Engineering student from the Rensselaer Polytechnic Institute are applying for RO and SRO licenses and are in training for the next NRC examinations, scheduled for September 2013 and February 2014.

Reactor Engineering

Thomas Newton leads the reactor engineering group, whose activities include support and development of experiments such as the ICSA, the high-temperature irradiation facility, and advanced cladding irradiation. 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 also the principal investigator for the program to convert the reactor to LEU fuel. DOE's Global Threat Reduction Initiative (GTRI) has committed to converting all research reactors using HEU to LEU. Although a number of lower-power reactors have been converted under this program, the remaining five US reactors with higher power densities (the MITR-II, the University of Missouri Research Reactor, the National Institute of Standards and Technology Reactor, the High Flux Isotope Reactor at the Oak Ridge National Laboratory, and the Advanced Test Reactor at the Idaho National Laboratory [INL]) require the development of fuels with significantly higher densities. Such a fuel, a monolithic uranium-molybdenum fuel with a uranium density of about 16 g/cm^3, is under development and is undergoing qualification testing. The MITR-II is expected to be the first reactor in the world to use this fuel.

With continuing support from the GTRI program, 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. Burn-up 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 Idaho National Laboratory's Advanced Test Reactor National Scientific User Facility (ATR NSUF) 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 would exhibit high thermal efficiency as well as for hydrogen-production reactors. A related and equally important goal is to identify advanced fuels and materials that will enable both the extension of service and improved economic performance in the existing light-water reactor fleet. This collaboration is designed to increase user access to national reactor irradiations and testing capabilities. NSUF test spaces at ATR, MITR, and other facilities are made available at no cost to external users, whose projects are selected through a peer review process. The MITR will offer a portion of its test capability to NSUF experimenters. Lin-Wen Hu and Gordon Kohse jointly manage the NRL and ATR NSUF partnership.

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 offers a unique technical capability that involves the design and use of in-core loops that replicate pressurized water reactor (PWR) and boiling water reactor (BWR) 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 DOE and the nuclear industry in next-generation nuclear power systems—many 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 is the university reactor best suited for carrying out such basic studies because of its relatively high power density (similar to that of a light-water reactor), its capability to control chemistry and thermal conditions to reflect prototypic conditions, its easy-access geometric configuration, and its in-core space for up to three independent irradiation tests.

Post-irradiation Examination Facility

The MITR-II is equipped with post-irradiation examination 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 reactor-containment facilities, 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.

Reactor Thermal Hydraulics Laboratory

The Reactor Thermal Hydraulics Laboratory is supported jointly by MIT's Department of Nuclear Science and Engineering (NSE) and the NRL. Several flow loops and experimental facilities have been designed and built for research projects in heat transfer and two-phase flow research and for teaching at both the undergraduate and graduate levels. Experimental facilities and advanced instrumentation were constructed or acquired with funding support from industry sponsors including AREVA, the Electric Power Research Institute, ABB, the Idaho National Laboratory, the DOE Nuclear Education and Engineering Research Program, the DOE Innovations in Nuclear Infrastructure and Education Program, Saudi Arabia's King Abdulaziz City of Science and Technology, and the Argonne National Laboratory. The facilities can be described briefly as follows.

- Single-phase heat transfer loops: These are forced convection loops designed and constructed by MIT students and staff to investigate nanofluid heat transfer and pressure drop characteristics in laminar and turbulent flow regimes.
- Critical heat flux (CHF) loop: The CHF facility obtains flow CHF data for different types of nanofluids.
- Onset of nucleate boiling loop: This facility was designed and built to support the LEU fuel assembly design of the MITR. The heated test section is a full-scale rectangular coolant channel of MITR fuel with prototypic heat flux.
- Pool boiling facility: This apparatus is designed to understand the fundamental CHF mechanism. The facility is equipped with a thin indium-tin-oxide heater deposited over a sapphire substrate to provide a direct bottom-up view of the boiling phenomena on the heater surface and with an optical probe for measuring bubble size distribution.

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 semester of 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 the Oak Ridge National Laboratory and includes the participation of a graduate student, an undergraduate student, and professor Benoit Forget of NSE. Researchers from INL used the facility for testing neutron detectors that are under development.

Neutron-Scattering Facility

Neutron scattering refers to 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 each year. New facilities such as the Spallation Neutron Source at the 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 Professor Moncton and with the assistance of research scientist Boris Khaykovich, a major restructuring of 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 with polarizing capabilities and a neutron optics test station.

Dr. Khaykovich uses the neutron optics test station in a DOE-funded neutron optics research program whose goal is to develop specialized neutron-focusing optics for scattering and imaging applications.

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, and this instrument 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. Inductively coupled plasma atomic emission spectroscopy is also available at the NRL. The Nuclear Reactor Lab'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 (UROP) 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 Laboratory
- Activation of ocean sediments for the Woods Hole Oceanographic Institute
- Activation of Teflon, Si photodiode, and NAA standards for the University of Alabama
- Activation and NAA of zinc oxide, cerium oxide, and barium sulfate nanoparticle samples for animal tracer studies at the Harvard School of Public Health
- Activation and NAA of FLiNaK and FLiBe 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 Pennsylvania State University ATR NSUF experiment
- Activation and NAA of various materials for a detailed flux study at 5.9 MW with a range of blade positions in the 1PH1, 2PH1, and 3GV6 irradiation facilities
- 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)
- Neutron transmutation doping of germanium wafers for both the Lawrence Berkeley National Laboratory and the National Institute for Nuclear Physics and subsequent use of the wafers for further neutrino detector research at Lawrence Berkeley National Lab

Research Programs

In-Core Loops

The MITR's experimental capability in regard to in-core loops is unique among US university research reactors. Factors that have made the 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 Nuclear Energy University Program, Innovations in Nuclear Infrastructure and Education Program, and other programs
- The continuing collaboration with ATR NSUF, which is to the benefit of both INL and the NRL

As a result, the demand for the NRL's MITR experimental facilities has increased because of the lower cost of using the MITR relative to national laboratory facilities, as well as the quick turnaround in experiment design and execution and the excellent track record of recent experiments.

The past year has been very labor intensive for Dr. Hu's group, which includes several research scientists, postdocs, graduate students, and UROP students. They work closely with the experimenters, the MIT Reactor Radiation Protection Program, and the MIT Reactor Safeguards Committee to ensure that all necessary safety protocols and approvals are in place before any experiments are started. Some of the research projects and experiments scheduled for the upcoming year are listed below.

Silicon Carbide Composite Channel Box Project

In a boiling water reactor, 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 Fukushima accident has greatly increased interest in finding in-core materials that do not exhibit this behavior. SiC composites are a candidate for both fuel cladding and channel box applications.

The Electric Power Research Institute is leading a major program to develop the necessary design and physical property data to permit a demonstration test of a SiC composite channel box in an operating reactor. The NRL's work focuses on the irradiation creep and in-reactor corrosion behavior of samples of SiC composite extracted from a previously constructed, reduced-scale channel box. Samples will be irradiated in the MITR in-core water loop at 280° C and approximately 100 bar in BWR coolant chemistry conditions. In addition to the channel box samples, SiC composite tube samples being evaluated for control rod guide tubes will be irradiated and their corrosion behavior evaluated. Some of the samples will be exposed to flowing coolant for corrosion evaluation. Irradiation creep samples will be irradiated in fixtures that establish a known strain. Measuring permanent deformation of the samples after irradiation will allow the in-core creep rate to be determined. These irradiations will be conducted in the MITR.

This research is funded by DOE's Nuclear Engineering Enabling Technology program. Irradiation will begin in August 2013 and last for 160 full-power days with several interim examinations.

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. The effort involves changes in both the fuel meat and the cladding; the NRL will conduct irradiation testing of candidate cladding materials. The primary replacement clad candidate is multi-layer SiC (SiC composite tubing that is an evolution from tubing previously tested in the MITR). Large-scale manufacture and bonding of this tubing may be an obstacle to near-term commercial deployment, so alternate clad concepts based on Zircaloy tubes coated with MAX phases or glassy iron-based materials will also be tested. The tube samples will be irradiated in the MITR water loop at 280° C and approximately 100 bar in PWR coolant chemistry. The primary post-irradiation evaluation (PIE) will focus on sample weight loss, but dimensional changes, surface morphology, and mechanical property evaluation by burst testing will also be explored. In a complementary project under this program, professor Mujid Kazimi and Dr. Thomas McKrell of NSE will be evaluating the behavior of the tube samples in out-of-pile high-temperature steam tests.

This research is also funded by DOE's Nuclear Engineering Enabling Technology program. Irradiation is scheduled to start in April 2014, after completion of the channel box experiment, and will last for 230 full-power days with several interim examinations.

Ultrasonic Transducer 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 DOE's Office of Nuclear Energy research programs has been investigating ultrasonic transducers for both under sodium viewing and in-service inspection measurements near the core.

The Advanced Test Reactor National Scientific User Facility has funded an ultrasonic transducer research program to select candidate sensor materials, perform high-temperature irradiation tests in the MITR, and conduct post-irradiation evaluations. The instrumented lead test will provide real-time data related to magnetostrictive and piezoelectric transducer survivability during irradiation tests. NRL staff members have worked with INL staff, researchers from Pennsylvania State University, and other collaborators in experiment assembly design since March 2013. Irradiation testing will be performed in the ICSA in an inert gas environment up to 400° C. Irradiation is scheduled to start in November 2013 and will last for 250 full-power days with subsequent PIE.

Materials and Fluoride Salt Irradiation

MIT, the University of Wisconsin, and the University of California, Berkeley, 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 above 1,650° C), liquid salts developed for molten salt reactors (boiling point above 1,400° 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 wherein catastrophic accidents, such as the Fukushima accident, would not be credible because the FHR fuel and coolant combination may allow decay heat to conduct 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 fluoride salt (FliBe) and reactor fuel/materials in a radiation environment. Salts and materials will be irradiated at a temperature of 700° C in the MITR to determine the suitability of the fuel cladding and structural materials. The tests have multiple goals; however, the primary goals are evaluation of whether salt coolants may attack the fuel cladding system (SiC in graphite matrix) or other components via radiation-enhanced corrosion and verification of models for tritium generation and transport.

The first in-core irradiation will be a capsule irradiation consisting of FLiBe salt, SiC, nuclear-grade graphite, Hastelloy N, and other metal alloy samples. The design of this experiment is complete, and it is scheduled for insertion in September 2013 for 42 full-power days. Another salt/materials irradiation in a larger, natural convection capsule is planned for next year, pending the PIE results of the first capsule irradiation.

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 lead to significant, even transformative, improvements in rate-limited neutron methods and enable new science. An NRL group led by Professor Moncton and Dr. Khaykovich recently advanced a class of such tools: 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 Ni using existing technology. The benefits of such optics are their capacity for high-fidelity achromatic imaging and the possibility of coaxial nesting of multiple mirrors for increased throughput. As a result of this combination of high throughput and high fidelity, these optics are capable of transforming neutron imaging and scattering instruments from pinhole cameras into microscopes in the cold to thermal energy range.

Accelerator Research and Development for X-Ray Light Sources

Compact X-Ray Free Electron Laser

As part of a collaboration involving the Research Laboratory of Electronics, Deutsches Elektronen-Synchrotron (DESY) Hamburg, and the SLAC National Accelerator Laboratory, NRL principal research scientist William Graves is constructing a compact x-ray free electron laser by at the Bates Lab with funding from the Defense Advanced Research Projects Agency. The device will consist of an electron beam accelerated in a one-meter-long x-band RF linac that collides with a high-power laser to produce x-rays via inverse Compton scattering. The electrons are generated by a nanostructured array cathode, resulting in an array of electron beamlets that can be manipulated to produce an electron beam with coherent modulation at x-ray wavelength. The predicted output radiation at a 1 keV photon energy level is 10 nJ or 6×10^8 photons per shot, and the output is fully coherent in all dimensions, a result of the dominant mode growth from the free electron laser instability and the longitudinal coherence imposed by the electron beam nanostructure. This output is several orders of magnitude higher than incoherent inverse Compton scattering and occupies a much smaller phase space volume, reaching peak brilliance of 10^{27} and average brilliance of 10^{17} photons/(mm^2 $mrad^2$ 0.1% sec). The device is much smaller and less expensive than traditional x-ray free electron lasers requiring multi-GeV electron energy.

Superconducting Accelerator Research and Development for Coherent Light Sources

A compact superconducting radio frequency (SRF) accelerator is an ideal electron source for very high average power compact light sources based on inverse Compton scattering. Dr. Graves is currently participating in SRF research and development with the Jefferson Lab (JLab) to develop such a device based on an MIT-proposed design. The JLab research and development program focuses on optimizing SRF cavities for 4 Kelvin operation rather than the more common 2 Kelvin operation. The higher operating temperature allows a much simpler and less expensive cryogenic system, which is the major cost driver for a compact SRF accelerator. However, the higher temperature necessitates significant design changes in the accelerating structures. Power deposition at radio frequencies in the cavities is dominated by BCS losses at the higher operating temperature; thus, the RF must be scaled to lower frequency (400 MHz as opposed to 1,500 MHz), resulting in large cavities. Multiple cavity geometries including transverse electromagnetic mode spoke structures and conventional transverse magnetic mode elliptical cavities are under study. MIT's role is to study electron beam dynamics and model x-ray output for the various SRF cavity structures to ensure that overall compact light source performance goals can be met. Prototype cavities are under construction at JLab.

Safety and Security

Operational Safety

The NRC's Office of Nuclear Reactor Regulation has oversight responsibility for program management, inspections, and operator licensing of 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 safeguard committee. The committee—whose members are from both MIT and industry—is ultimately responsible for overseeing all nuclear safety issues related to the reactor and ensuring that reactor operations are 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 the 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 committee guidelines. An EHS officer (James Rowlings from the safety program) serves as EHS lead contact with the NRL under the office's organizational structure.

The NRL has a robust As-Low-as-Reasonably-Achievable (ALARA) program. ALARA-related policies, procedures, and metrics have resulted in improvements in the reactor facility's day-to-day safety and efficiency.

The new rooftop environmental monitors are fully functioning and integrated with the NRL's electronic reactor monitoring display. These monitors 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

The reactor's security system was overhauled in two phases, with funding provided by DOE's National Nuclear Security Administration (NNSA); phase 1 was completed in FY2010 and phase 2 in FY2011. Funding for the new system's maintenance and warranty, also provided by NNSA, expired in November 2012. A funding extension of one year was successfully obtained, with a new expiration date of December 2013. The system maintenance and warranty includes quarterly system-wide tests, with the coordination of the MIT Police, the MIT Security and Emergency Management Office, and Siemens Building Technologies. Assistant director Lau prepared detailed reports on each quarterly test and sent them to NNSA for review. These reports were also reviewed by the NRC during its security inspections. Additionally, NNSA continued to conduct its own annual site walk-through and assessment.

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 MIT Reactor Safeguards Committee.

Edward Lau coordinated with NNSA to review a phase 3 upgrade proposal, with one site visit in FY2013 by NNSA officials. The site review was favorable, and NNSA is finalizing its recommendations. The phase 3 upgrade will include enhancements to the western perimeter of NW12 and enhanced communications with MIT Police headquarters. Additionally, assistant director Lau coordinated a voluntary cyber-security assessment visit by a team of NRC experts. A preliminary report specific to MIT has been received and was reviewed by the MIT Reactor Safeguards Committee.

Compact High Average Power Laser Concept

Dr. Graves and Emilio Nanni, a postdoc working in Dr. Graves' research group, are currently exploring the development of a Compact High Average Power (CHAP) laser for the Office of Naval Research (ONR). Recent advances in technology enable a new approach to a megawatt-class free electron laser (FEL) that is much smaller, less complex, and more efficient than conventional high power FELs. These technology advances include nanopatterned cathodes combined with advanced electron beam optics that enable continuously tunable single-mode FEL output. They also include the development of high power terahertz generation and resonant terahertz undulator structures that lower the required electron beam energy and result in undulators only a few centimeters in length. The entire assembly will be less than 8 meters long, producing a CHAP laser with very high output power. The low electron energy of the new concept not only reduces cost, size, and power requirements but also reduces or removes the need for bulky neutron shielding and complex energy recovery systems. The electron gun and accelerator are superconducting RF cavities that operate at 4 Kelvin for low wall plug power. Each of the key technologies is currently in development and could be rapidly combined into a working FEL prototype. The CHAP concept for a low-cost and powerful FEL is still in a conceptual phase, and, depending on ONR's interest, future steps could include simulation studies, identification of technical risks, and experiments at MIT demonstrating the concept.

Professional Activities in Support of Mission

The NRL maintains a very close working relationship with the National Organization of Test, Research, and Training Reactors whose primary mission is education, fundamental and applied research, application of technology in areas of national concern, and improving US technological competitiveness around the world.

Awards and Recognition

David Moncton was a co-recipient of the 2013 Advanced Photon Source Arthur H. Compton Award along with Michael D. Boreland, Louis Emery, and John N. Galayda; they were recognized for their outstanding contributions to the development of the "top-up" mode at the Advanced Photon Source. Professor Moncton was instrumental in initiating the top-up mode at the facility, which was the first light source to use this technology. Top-up operation is now standard for many light sources around the world.

In addition, Lin-wen Hu's presentation at the Nuclear Thermal-Hydraulics, Operation and Safety Conference in September 2012 won the Best Paper Award (with co-authors Greg Dewitt, Tom McKrell, and Jacopo Buongiorno of NSE).

The NRL is also pleased to report that Edward Block was the recipient of an Infinite Mile Award in 2013 in recognition of his long-term expertise in engineering and information system design.

David E. Moncton
Director