Nuclear Reactor Laboratory

The MIT Nuclear Reactor Laboratory (NRL) operates a research reactor (MITR) that has been operational since 1958. The reactor has completed 60 years of operation (43 years since the 1974–1975 upgrade and overhaul). The 6 megawatt (MW) research reactor has a long and proud tradition of enabling cutting-edge research and educational training in the areas 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. It is the only research reactor at a major research university that gives students on-campus opportunities to participate in power-reactor-relevant materials, fuel irradiations, and post-irradiation examinations. This is a rare asset in the US and 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 a state-of-the-art nuclear reactor facility and infrastructure and the technical expertise to support its use for research, development, education, and training. The highest priority is placed on operating the research reactor in a professional manner that is safe for MIT, NRL researchers and staff, 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.

Since 1958, NRL has provided both a safe and reliable neutron source and the infrastructure to facilitate its use. Many generations of undergraduate and graduate students have benefited from their association with NRL. More important, NRL has proven itself to be a unique resource for the educational development of the next generation of nuclear engineers—those who will conceive, design, and manage the future of nuclear technology.

Current research programs at NRL are mostly centered on irradiation tests of advanced materials and instrumentation in support of improved materials and fuels for current and next-generation power reactors. This effort is facilitated by a radiation environment in the MIT reactor core that is similar to that in light-water reactors (LWRs) that generate power. The NRL research staff's expertise (and that found in other research programs) have also led to expansion in reactor design, analysis, and benchmarking to support the development of fluoride salt-cooled high-temperature reactors (FHRs), the transient reactor test facility (TREAT) re-start, and neutron science. 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 gamma activation analysis facilities, an inductively coupled plasma spectrometer (ICP-OES), and a materials characterization laboratory.

Laboratory Administration

NRL's organizational structure comprises three groups that work as a team to meet short-term operational demands and long-term strategic challenges. These demands and challenges belong to developing a research program that will support both operating a nuclear research reactor in the current regulatory environment and current and future generations of nuclear reactor research. These groups are administration, reactor operations, and research and services.

David E. Moncton is the director of NRL. Lin-Wen Hu, director of research and services; John Bernard, compliance officer; Al Queirolo, director of operations; John Foster, deputy director of operations; Rose Rizzo, interim administrative officer; and William McCarthy, deputy director of the Office of Environmental Health and Safety, make up the remainder of NRL's senior management team. This leadership team works to sustain NRL's long-standing record of safe operation, maintain and improve upon the reactor facility, carry out research projects, design and conduct irradiation experiments, and provide an environment of support and excellence for researchers and students.

NRL currently employs 45 individuals. The staff consists of six groups, including the previously mentioned six senior staff members. There are eight research staff, seven technical staff, 11 technical support staff, four academic staff, two administrative support staff, two technicians, and six part-time student operators.

Educational Impact

The MIT reactor has been and continues to be used extensively to support MIT's research and educational missions. The principal activities that support education and training include:

- Use of the reactor for laboratory courses. The Department of Nuclear Science and Engineering (NSE) is a long-standing user of one of the neutron beam ports equipped with a time-of-flight neutron spectroscopy facility for its subject on radiation detection and measurement. This subject is required of all NSE juniors and is also taught to graduate students. Other NSE subjects incorporate MIT reactor experiments, including subjects on reactor design and operation and reactor dynamics. The Physics Department's so-called Junior Lab has also used the neutron time-of-flight facility for neutron spectrum and Bragg diffraction experiments. NRL's subcritical graphite pile has been licensed to re-start for teaching and research at both undergraduate and graduate levels. NRL staff members supported NSE faculty member Professor Kord Smith in this effort. Students will begin using the pile in academic year 2019.
- Performance of thesis research at all degree levels. Since the 1950s, cutting-edge research using the MIT reactor has been conducted by faculty, students, and researchers from MIT as well as other institutions. Students benefit from doing thesis work on the reactor because they have the opportunity to combine the theoretical knowledge that they have acquired in the classroom with hands-on engineering. As a result, more than 200 BS, MS, and PhD theses have been completed by students who used the reactor for their research. Some research topics included the design and construction of the in-core loops, performance of experiments using those loops, low enriched uranium (LEU) conversion of the MIT reactor, design and analysis of FHRs, development of new methodology for reactor safety analysis, design of the fission converter and characterization of its beam, biological effects and medical applications of radiation, digital closed-

loop control of the reactor, design and demonstration of novel neutron-focusing optics, demonstration of a polychromatic neutron diffractometer, and a variety of geochemical studies, including analysis of meteorites and air pollution sources.

- Training 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.
- Public outreach. NRL offers tours of the facility together with an introductory lecture on the reactor and nuclear technology for high-school students, local area colleges, and MIT parents and alumni. This past year, NRL hosted more than 100 tours for 1,228 participants. NRL staff members have also collaborated with other groups across MIT to provide educational outreach activities for local middle-school students.

Facilities and Resources

The MITR-II is the second of two research reactors that NRL has operated. The original reactor (MITR-I) achieved criticality in 1958. It was shut down in 1973 to allow extensive upgrading and 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 new license and power upgrade approval was granted in 2010. The MIT reactor has been designated as a partner facility of the US Department of Energy's Nuclear Science User Facilities (NSUF) since 2008 and serves a user base of researchers from other universities, national laboratories, and the nuclear industry. The MITR-II is one of five high-performance research reactors in the US that uses highly enriched uranium (HEU) fuel. A further goal for NRL is to convert the MITR-II's fuel from HEU to LEU when a new type of high-density LEU fuel is qualified.

The MITR-II, NRL's major experimental facility, 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/s, 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 controlled temperature inert gas irradiations, pressurized-water loops, and custom-designed irradiation facilities (including facilities for fuel irradiations). The reactor generally operates 24 hours a day, seven days a week, except for planned outages for maintenance. The MITR-II incorporates 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.

Post-irradiation Examination Facilities

The reactor containment building is equipped with an overhead polar crane with 20-ton and 3-ton hooks. The crane is used for installation and removal of in-core and other experiments; shielded transfer casks are also available. There are two hot cells in the reactor hall. The larger cell is generally used for handling and disassembling full-height in-core experiments. This cell is accessible for installation of custom fixtures required for particular experiments. The smaller cell has been used to handle small, high-activity components and fuel from in-core experiments. A collimated gamma scan facility can be installed in the small cell. The reactor spent fuel pool is also available for storage, handling, and packaging of irradiated experiments.

Laboratory space within the reactor exclusion area includes two standard fume hoods, a hood with a perchloric acid scrubber, and an inert-atmosphere, four-port glove box with furnace. A ventilated hot box with manipulators is available for specialized post-irradiation examination activities requiring more shielding than can be installed in the fume hoods. Standard metallurgical sample preparation (epoxy mounting, sectioning, and polishing) can be carried out on activated samples. Macro-photography, optical microscopy, and optical profilometry of irradiated specimens are also completed in this space. Other equipment used with radioactive materials in the exclusion area include a xenon-flash thermal diffusivity instrument, high-purity germanium gamma spectrometers, a liquid scintillation counter, and gaseous tritium and radiocarbon collection and measurement instruments.

Post-irradiation examination facilities continued to expand in the past year. Equipment purchased under a US Department of Energy (DOE) Nuclear Energy University Program (NEUP) general scientific infrastructure grant was installed in the reactor exclusion area. An additional grant was announced to Professor Koroush Shirvan of NSE for mechanical testing equipment. Also announced was a major grant to Gordon Kohse and Lance Snead (co-principal investigators) for replacement of the small in-containment hot cell with two modular cells. These new hot cells will expand NRL's post-irradiation examination capability.

Neutron Beam Experimental Facilities

NRL's web-enabled neutron time-of-flight spectrometer 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 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 upgrades to the hardware and software are planned, as are outreach efforts to broaden the user base of the facility outside MIT. Most significantly, the beam port components were removed during a recent outage and a corroded piece of cadmium shielding was found to have obstructed the beam. Cleaning and reassembly resulted in a very large increase in the thermal neutron intensity in the beam and consequently in much shorter acquisition times and better data statistics. Neutron diffraction experiments were found to be possible again at the higher beam intensity.

The MIT reactor is home to a triple-axis diffractometer and a neutron-imaging facility. The imaging facility can be used to study the structure of materials and structural changes caused by irradiation, in support of the in-core irradiation program at the MIT reactor, MIT faculty work, and outside users requiring access to neutron diffraction or imaging. The diffractometer is a standard triple-axis diffractometer equipped with graphite monochromator and analyzer and helium-3 detectors. The instrument is used in the ongoing collaboration with Idaho National Laboratory (INL) for studies of novel nuclear fuel. The diffractometer is being upgraded to allow measurements of irradiated materials, such as those irradiated in the core of the MITR and other samples of interest to NSUF users. The neutron-imaging facility at the same beam port is equipped with the necessary beam-forming apertures and a scintillator-based imaging detector. The facility has most recently supported MIT research.

Research and Services

Lin-Wen Hu and Gordon Kohse are the director and deputy director, respectively, of the Research and Services Division within NRL. This division consists of four groups: reactor experiments, reactor physics analysis, neutron beam applications, and neutron activation and elemental analysis. Research staff members in the division lead a wide range of research projects and perform service irradiations. They have developed a robust program to facilitate the advancement of nuclear technology in collaboration with MIT faculty, researchers, and students, as well as those outside NRL, in their use of the MITR and its irradiation facilities. Tasks undertaken by this division include:

- Performing research in the area of irradiation effects on advanced materials and fuel;
- Conducting research projects in advanced reactor technology, reactor physics analysis, and neutron science;
- Mentoring undergraduate and graduate students in thesis research;
- Providing researchers with a service-based infrastructure that uses 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 students in the Undergraduate Research Opportunities Program, and offering laboratory courses for professionals, undergraduates, and advanced secondary school students;
- Expanding the user base of the MITR's experimental facilities; and
- Contributing to modeling and development of test reactors and small modular reactors by leveraging NRL research staff's expertise in reactor design, instrumentation, and safety analysis.

Reactor Experiments

David Carpenter is the leader of the reactor experiments group. NRL has a strong in-core experimental program that supports research in advanced materials and fuels and innovative instruments that are necessary for both existing and advanced power reactors. The MIT 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 as well as specialized facilities capable of reaching very high temperatures and containing exotic compounds. With rekindled interest on the part of DOE and the nuclear industry in next-generation nuclear power systems using novel materials and advanced forms of fuel, there is a critical need for such facilities to test materials' and fuels' behavior in a variety of radiation environments. The MIT reactor is the university reactor best suited for carrying out both basic and integrated studies because of its relatively high power density (similar to that of an LWR), its capability to control chemistry and temperature to reflect prototypic conditions, its easy-access geometric configuration, its in-core space for up to three independent irradiation tests, and the proven ability of the MITR staff to design and execute proof-of-concept experiments more quickly and cost-effectively than at other research reactors. Close collaboration with national laboratories, universities, and domestic and international organizations have put the reactor experiments program at the forefront of research on recent advances such as MAX-phase or glassy iron-based materials, radiation-resistant fiber optics, fluoride salts, and silicon carbide composite cladding for commercial reactor use. The in-core irradiation program also supports the development of irradiation-hardened instrumentation to enhance data collection from research irradiations and to develop sensors for application in operating plants.

Reactor Physics Analysis

Kaichao Sun leads the reactor physics analysis group. This group has two main activities: technical support for MIT reactor operation and experiments, and cutting-edge research in advanced reactor concepts and innovative test reactor design.

Technical support for the MIT reactor's routine operation and research and development consists of the fuel management program and corresponding code development, the LEU conversion program, criticality safety analysis, and neutronics and thermal analysis for safety evaluation of reactor experiments. Two major achievements in academic year 2018 included the submission of the preliminary safety analysis report to the US NRC for the MIT reactor LEU conversion and technical support for re-starting the MIT graphite exponential pile.

Primary research activities in academic year 2018 included:

- Evaluation of an integrated demonstration option of constructing and operating a subcritical facility with 700°C salt circulating through multiple full-width partial-height fuel assemblies adjacent to the MITR biological shield;
- Expanding the operating envelope for the advanced test reactor, attracting new high power density fuel experiments, which are currently limited by the existing safety basis;
- Technical investigation toward licensing a pebble-bed fluoride-salt-cooled high-temperature test reactor; and
- Designing, and eventually executing, reactor transient tests at the MIT reactor and the INL's TREAT facility in support of advanced instrumentation development.

Neutron Beam Applications

Boris Khaykovich is the group leader for neutron beam applications. 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 of the MIT Physics Department, 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 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 neutron-scattering facility to support development of new neutron optics components designed to allow users from outside MIT to conduct early phases of some experiments more quickly than at large facilities
- Establishment of a neutron optics test station to test and develop new neutron optics components
- Use of expertise established for neutron beam applications to support development of experimental methods for exploiting compact x-ray sources

Neutron Activation and Elemental Analysis

Michael Ames is the group leader for neutron activation and elemental analysis. NRL has several facilities that are used for trace elemental analysis and for the production and analysis of radioisotopes. The primary analytical method employed is neutron activation analysis (NAA), which first uses neutrons from the reactor to create radioactive isotopes in sample materials. Then gamma spectroscopy is performed on the activated samples to quantify the material's original elemental composition. The MIT reactor is equipped with two pneumatic systems used to transport samples to locations near the reactor core where the thermal neutron fluxes are up to 5.6×10^{13} n/cm^2-s. A third, manual facility is also available in which a large number of samples can be irradiated simultaneously in a thermal neutron flux up to 1.2×10^{13} n/cm^2-s. NRL's NAA laboratory is equipped with high-purity germanium gamma detectors and Canberra's Genie 2000 software for gamma spectroscopy. The two components of NAA can also be applied separately to produce radionuclides in a variety of forms for use as tracers in physical, chemical, and biological fate and transport studies; induce neutron damage in sample materials; and detect, identify, and measure the presence of radioactivity in natural or manmade materials. This analytical method is often used to detect and quantify trace elements that are difficult to measure by other means but that are of particular interest in nuclear systems. NAA is performed on materials that are part of planned in-core experiments so that the materials' in-core behavior and post-irradiation dose levels can be predicted.

The NAA facilities have been used in research- and service-oriented collaborations with several MIT laboratories as well as with other educational and research institutions. NRL makes these facilities and technical expertise in these areas available to researchers from MIT, other universities, private and governmental laboratories, industry, and hospitals.

Research Programs

The major emphasis of the Research and Services Division is on in-core experiments that support current and next-generation nuclear power reactor technology development. Several of these programs have related elements that take advantage of the expertise in the reactor physics analysis, neutron beam applications, and neutron activation and elemental analysis groups. However, there are research programs, such as the LEU conversion project, that do not involve any experimental reactor activity. Following a general overview of the in-core experimental program, all of NRL's ongoing research programs are briefly described below.

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 MIT reactor was designated as the first partner facility of NSUF and has played a key role in performing various NSUF-funded irradiation experiments since 2008. The capability of the NRL staff to design and 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 will remain, an essential national capability. NRL's unique expertise and capabilities have established its reputation for rapidly demonstrating the survivability of new sensors and instrumentation components, and for developing rigs for irradiation testing. In addition, it is anticipated that several recently launched, privately funded, advanced reactor development initiatives will seek support from NRL to study their chosen materials and fuels. There are also international efforts in need of the MITR's capabilities. For example, the program on FHRs has attracted substantial support from a larger Chinese development program. Other factors that have made NRL's in-core program successful include:

- The high neutron flux, flexible core design, and 24-hours-a-day, 7-days-a-week 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 NEUP and other programs; and
- The continuing collaboration with the NSUF, which is to the benefit of both INL and NRL.

The demand for NRL's MITR experimental facilities has increased because the cost of using the MITR is lower than that of national laboratory facilities. Also, NRL provides quick turn-around in experiment design and execution, and the track record of recent experiments is excellent.

Westinghouse Accident Tolerant Fuel Project

The Fukushima accident created very strong interest in finding alternatives to the currently used Zircaloy™ fuel cladding. This interest is driven by the problematic behavior of Zircaloy in high-temperature steam, where rapid reactions can occur with the 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 itself and the cladding. NRL's contribution is to irradiation test candidate cladding materials and associated end plug sealing methods. A leading replacement cladding candidate is multi-layer silicon carbide/silicon carbide composite tubing, with or without engineered coatings to enhance corrosion resistance. Large-scale manufacture and bonding of this tubing may be an obstacle to near-term commercial deployment, so alternative cladding concepts based on Zircaloy tubes coated with MAX-phases or glassy iron-based materials are also being considered, together with hybrid concepts involving composite layers in conjunction with metal alloy tubing.

The final five-year phase of the accident-tolerant fuel project is currently underway, with the goal of producing a lead test assembly for testing in an operating pressurized-water reactor. Under this program, irradiations of optimized fuel cladding were performed in the MITR water loop from August 2017 through July 2018. In a related effort, accident-tolerant fuel cladding samples from Oak Ridge National Laboratory were exposed at LWR temperatures in an inert gas environment in-core from October to December 2016. The same set of samples was then exposed in the water loop from January through June 2017. The water loop irradiation was shared with additional accident-tolerant cladding samples from Ceramic Tubular Products, Inc., under first-round funding from a DOE initiative—the Gateway for Accelerated Innovation in Nuclear Program.

NSUF In-core Sensors Irradiation Test (ULTRA)

Current generation LWRs 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 (DOE-NE) 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. Work supported by several of DOE-NE's research programs has been investigating ultrasonic transducers for both under sodium viewing and in-service inspection measurements near reactor cores.

NRL has performed two approximately year-long irradiations to support this program. The first irradiation tested ultrasonic transducers with readout in real time; post-irradiation examination of the sensors and their components was completed in FY2016. A second in-core instrumentation test was installed in the reactor in April 2017. In addition to a second generation of ultrasonic transducers, this test contained fiber-optic temperature sensors from researchers at the University of Pittsburgh and from the French Centre d'Energie Atomique, and novel optical glasses from AFO Research. All of the instruments were read in real time, allowing inter-comparisons among the advanced sensors and benchmarking against well-characterized thermocouples. The ultrasonic and fiber-optic sensors have the potential to provide temperature data over a range of locations from a single sensor. They can also be used to investigate other parameters such as mechanical strain, pressure, and gas composition. The irradiation was completed in March 2018 and was successfully disassembled in the NRL hot cells after post-irradiation testing of the sensors. The glass specimens have been examined in an NRL hot lab and will next be sent to INL for further analysis.

FHR 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 a path forward to a test reactor and ultimately a commercial FHR. The second of two three-year projects funded by the DOE NEUP is currently underway, with MIT in the leadership role. 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 greater than 1650°C), liquid salts developed for molten salt reactors (boiling point greater than 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 at which catastrophic accidents, such as the Fukushima accident, would not be credible. 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 fluoride salt (a mixture of lithium fluoride and beryllium fluoride known as flibe) and reactor fuel and materials in a radiation environment. Testing in the MIT reactor addresses this concern and is also intended to help verify models for tritium generation and transport.

The third in a series of flibe salt irradiation tests was operated in the reactor core for 950 hours in November and December 2016. This test contained graphite and carbon/carbon composite samples from US and Chinese sources, the latter with funding from the Chinese Academy of Sciences. This irradiation incorporated improvements made on the basis of two earlier irradiations, including an electrical heater to maintain minimum temperatures to prevent gamma-irradiation-driven release of free fluorine from the flibe during any unplanned reactor shutdowns. As with the earlier flibe irradiations, tritium and short half-life irradiation products were monitored during the run. Post-irradiation examinations are continuing for samples from three successful in-core flibe irradiations at 750°C. This includes analysis of radioactive samples with new instruments, such as a dedicated scanning electron microscope at NRL in collaboration with INL. Recently, an additional irradiation test was carried out in a graphite vertical position outside the reactor core. This experiment was designed to study the transport of tritium through materials with and without the presence of flibe, and to test the performance of a tritium barrier coating under various conditions. The experiment was operated successfully during April 2018. The analysis of the tritium permeation results and changes to the barrier coating microstructure will continue.

NRL staff also initiated two research projects to accelerate the FHR technology demonstration: design of a transportable FHR and design of a subcritical facility at MITR to support testing of a variety of flibe salt fuel and materials technologies. In the facility, 700°C salt would circulate through multiple full-width, partial-height, fuel assemblies operating with a power density of up to 30% of a reference FHR. The neutronics feasibility study was published in a peer-reviewed journal. Recent research activities focus on the detailed thermal-hydraulics design of the subcritical facility for both nominal (forced convection) and loss-of-primary-flow (natural convection or fully drained) conditions. In particular, installing heat pipes to the periphery of the active zone has shown satisfactory performance as a backup secondary heat removal system that ensures a sufficient thermal-hydraulic safety margin without affecting routine reactor operation. Optimization of the heat pipe arrangement is being studied.

Transient Reactor Test Facility Re-Start Support

The TREAT, located at INL, has been used to study light-water, lead-cooled, and sodium-cooled fast reactor fuel under a variety of very high-power transient conditions. After decades of inactivity, it resumed transient operation in early 2018. Members of the NRL Research and Services division are part of a DOE-funded integrated research project to assist in the re-start process. Research and Services researchers have been working with INL staff and other stakeholders to support the improvement of the reactor's instrumentation with **quantitative analysis and experimental data. This effort includes developing a modern instrumentation plan for TREAT and designing and operating a test instrumentation facility. During FY2018, in-core MITR irradiation tests at low power were carried out on a set of neutron and gamma detectors in reactor maneuvers carefully designed to mimic TREAT conditions. These sensors were then sent from NRL to TREAT and installed in the center of the TREAT core; this represents the first outside user experiment in TREAT since its re-start. Over three weeks, NRL Research and Services staff, INL instrumentation development staff, and TREAT operations staff took these sensors through a series of tests, first replicating the MITR procedures, then expanding into transients that only TREAT is capable of performing. First-of-a-kind data was successfully gathered during these tests and will be analyzed by NRL staff to understand the sensor and reactor performance versus available computational models. This project also successfully established new practical protocols for university participation in TREAT experimental operations, radioactive and fissile material handling between NRL and TREAT, and sharing of TREAT reactor data.

Low Enrichment Uranium Conversion Program

The goal of this research program is to convert the MITR from HEU to LEU fuel. NRL staff members seek to carry out the first conversion among the remaining five high-performance reactors in the US, adopting a special high-density LEU fuel currently undergoing qualification tests. Although the fuel development program sponsored by the National Nuclear Security Administration has experienced delays, the MITR remains a valuable reactor to provide the first demonstration of this important new fuel, which is critical to the mission to eliminate weapons-grade HEU from civilian use worldwide. A major objective of MITR's LEU conversion is to maintain the HEU core performance. A power uprate to 7 MW has been determined from a previous feasibility study.

After development of a new low enriched uranium fuel, alloyed with10 weight percent molybdenum (U-10Mo), and of a monolithic fuel design with graded fuel meat thickness, LEU conversion impacts on in-core experiments and accident analysis were completed. During FY2017, the nuclear and thermal-hydraulic design has been evaluated and confirmed to meet operation safety. A preliminary safety analysis report for LEU fuel conversion was completed and submitted to the US NRC in FY2018. Transition cycles to reach an equilibrium core using the new LEU fuel design are ongoing as part of the start-up plan. Work on detailed MITR LEU fuel specifications and fabrication tolerances will begin in collaboration with the reactor conversion and fuel fabrication pillars of the reduced enrichment research and test reactors program. In addition to the U-10Mo plate-type fuel study, another feasibility study for converting the MITR was completed using uranium-zirconium-hydride rod-type fuel. It was concluded that such an option is not feasible because of a limited safety margin.

Neutron Optics Research Program

The neutron beam applications group conducts neutron optics research with the goals of developing specialized neutron-focusing optics for scattering and imaging applications, demonstrating improved magnetic imaging with polarized neutrons, and developing novel technology for manufacturing neutron guides. These programs are funded by DOE, the US Department of Commerce, and INL. A DOE Small Business Innovation Research–funded collaboration with a small company (Dawn Research, Inc.) resulted in the demonstration of sections of neutron guides that could be used in future neutron-scattering facilities. A DOE Small Business Technology Transfer–funded project with a small company, Electroformed Nickel, Inc., resulted in the demonstration of axisymmetric optics. The Department of Commerce–funded collaborative project with the National Institute of Standards and Technology resulted in the demonstration of novel modes of neutron imaging, such as a polarized neutron microscope and a focusing neutron interferometer for spatially resolved small-angle scattering. The polarized neutron microscope was used to study modern quantum magnets, including under cryogenic temperatures and pressure, to study spatial inhomogeneities of the phase transition. The collaborative project with INL could revolutionize the current way of neutron imaging spent nuclear fuel and significantly improve post-irradiation examination capabilities. A design of the focusing mirrors for the INL neutron-imaging facility has been submitted for publication. The use of this design could transform this facility into a fully automatic digital imaging and tomography facility while increasing the signal rate of the facility by a factor of 10.

Nuclear Reactor Laboratory Seed Program

In fall 2017, Lin-wen Hu established the NRL Seed Program as a means of cultivating new MIT research areas and of obtaining preliminary data to help pursue externally funded research proposals. The NRL Seed Program provides MIT faculty and research staff with no-cost access to MITR irradiation, post-irradiation evaluation services, neutron activation analysis and gamma spectroscopy capabilities, and materials characterization instruments with support for irradiated materials. Researchers are asked to submit a synopsis of their proposed research. Four categories of experiments are considered: small-scale dedicated irradiation experiments, shared use in-core experiments, neutron beams and instruments, and materials characterization and post-irradiation evaluation.

Six proposals were selected from those submitted by researchers in various academic departments. The first proposals that received awards in fall 2017 were submitted by Anu Agarwal, principal research scientist, Microphotonics Center, together with J. J. Hu, associate professor, Department of Materials Science and Engineering; Matteo Bucci, assistant professor, NSE; and Michael Short, assistant professor, NSE. The most recent awards, in spring 2018, went to proposals submitted by D. Cem Tasan, assistant professor in the Department of Materials Science and Engineering; Mingda Li, NSE; and David McGee, associate professor in the Department of Earth, Atmospheric, and Planetary Sciences.

Services

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

- Activation of gold-198 seeds for brachytherapy
- Activation of uranium foils for detector calibration at Los Alamos National Laboratories and Ciambrone Laboratory at Patrick Air Force Base
- Activation of fusion laminate samples to study radiation damage effects for composite technology development
- Activation of silicon, sapphire, and Teflon™ samples along with NAA standards for the University of Alabama
- Activation of metallic single-crystal samples for an NSE displacements per atom study
- Neutron activation of silicon wafers to study radiation-induced photonic defects for the MIT Materials Processing Center
- Activations of europium sample for the Junior Physics Laboratory
- Neutron radiography of mineral samples for the Department of Earth, Atmospheric, and Planetary Sciences
- Neutron radiography of boiling water through a sapphire window for NSE
- Activation and NAA of flux wires to support the low power steady-state and transient tests for the TREAT core instrumentation experiment
- Activation and NAA of saline solution samples for confirmation of trace element concentrations for MIT's Center for Environmental Health and Sciences
- Activation and NAA of epoxy samples for NSE
- Activation and NAA of FLiBe salt samples, carbon composite, and silicon carbode materials for the Shanghai Institute of Applied Physics in support of the FHRs research project
- Activation and NAA of various sample materials and structural components for the Westinghouse accident-tolerant fuel experiment
- Activation of uranium and plutonium targets for detailed fission product yield measurements in the thermal neutron beam facility for Los Alamos National Laboratories

- 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 to train MIT student reactor operators and for NSE subjects (22.01 Introduction to Nuclear Engineering and Ionizing Radiation, 22.06 Engineering of Nuclear Systems, 22.09 Principles of Nuclear Radiation Measurement and Protection, 22.011 Seminar in Nuclear Science and Engineering, 22.921 Nuclear Power Plant Dynamics and Control, and the reactor technology course for nuclear power executives).

Reactor Operations

Leadership of the reactor operations division is provided by Director of Reactor Operations Al Queirolo, Deputy Director of Reactor Operations, John Foster, Assistant Director of Reactor Operations Edward Lau, and Reactor Superintendent Sarah Don. The reactor operations group is responsible for supporting the operation and maintenance of the 6 MW research reactor. The group consists of both full-time employees and part-time undergraduate students. A majority 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 24-hour-a-day, 7-days-a-week operating schedule. In addition, there is one full-time project mechanic to support reactor mechanical maintenance. Reactor operations supported the following NRL research projects in FY2018: pressurized-water loop facility; molten fluoride salt irradiations; high-temperature in-core sample assembly capsule irradiations; 4DH4 diffractometer; and 4DH1 student spectrometer.

The reactor was maintained at a full power of 5.5 MW or higher. Total energy output for July 2017 to June 2018 was 28,384 megawatt-hours. This translates to 4,811 hours of operation at full power.

Major NRL maintenance and upgrade projects accomplished in FY2018 include:

- Reactor staff completed the annual gain determination for nuclear safety channels #5 and #6 low-range amplifiers.
- Reactor staff completed the annual efficiency test for the ventilation system charcoal filters.
- Reactor staff worked to resolve a long-term issue with the 4DH1 neutron beam. The beam port was opened up, cleaned out, repaired, and reassembled, restoring the beam's original characteristics and greatly improving its usability.
- Reactor staff replaced electronic transducer for primary system pressure sensor MP-4.
- Reactor staff worked with MIT Facilities to replace the air dryer for the reactor's compressed air system, and all associated piping, in the utility room. The dryer had failed in prior weeks, indicating a high-temperature condition.

- Reactor staff worked with MIT Facilities to abate two large laboratory areas of asbestos floor tiles and complete renovations.
- Reactor staff coordinated with contractors to replace one cooling tower support leg that had been previously damaged by a shipping truck.
- Reactor instrumentation staff replaced all electrical cabling and connectors on the main airlock inner door.
- Reactor staff replaced the motor for shim blade #3.
- Reactor staff replaced all the relays in the Withdraw Permit Circuit as preventive maintenance after two failed prematurely.
- Reactor staff coordinated with MIT's Department of Facilities to repair two ruptured steam coils in the containment building air handler unit heating coil bank. The two steam coils had failed and flooded the adjacent floor.
- Reactor staff coordinated with the Department of Facilities to replace and upgrade a 10,000-lumen containment dome light.
- Reactor staff coordinated with the Department of Facilities to replace all high-efficiency particulate air filters at the stack base.
- Reactor staff completed the biennial containment building pressure test.
- Reactor staff commissioned the new, upgraded cathodic protection system for the containment building.
- Reactor staff replaced the secondary hot cell blower motor, the medical room blower motor, and the two core purge blowers, and replaced all of their fan belts.
- Reactor staff completed an upgrade of the sentry radiation monitoring system, which complements the reactor security system.
- Reactor staff performed maintenance on the neutron transmutation doped silicon machine's conveyor and pushing machinery and tested all watchdog interlock switches.
- Reactor staff installed two lengths of armored, gel-filled fiber-optic cable and two new coaxial cables in preparation for an upgrade of Building NW12's fire alarm and fire protection system.

Many other routine 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 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 with 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's (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's (SRO) 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 2017 through June 2018, two sets of NRC examinations were administered at MIT: in September 2017, there were three candidates for the RO license; in February 2018, there was one candidate for the SRO license. Two undergraduate students are applying for licenses, one for RO and one for SRO, and are in training for the next NRC examinations. At least one other undergraduate student is applying for a SRO license. The NRC exam is scheduled for October 2018.

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 presidential level 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 and licensing requirements. All members of the NRL organization are keenly aware that safe operation of MIT's reactor 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.

Security

In FY2018, NRL security continued to meet NRC regulatory requirements. A week-long NRC inspection focused on security and the physical security plan for the reactor was conducted in November 2017. No violations were identified.

Reactor Operations coordinated with the Facilities Department to replace two damaged panels of the high-security fence in the back yard. The damage had been caused by snow plowing in the area and was identified by reactor staff during routine internal inspections.

The 19 new digital cameras that were installed by MIT Information Systems and Technology in FY2017 as phase one of an overall camera upgrade continued to operate with minimal problems. In May 2018, MIT's Information Technology Policy Committee approved NRL's petition for an exception to the MIT camera image policy. The MIT Reactor Safeguards Special Subcommittee for Security recommended launching phase two of the camera upgrade once this approval was received.

The new "guard tour" card reader continued to perform well throughout the fiscal year. It was a topic of discussion in the biennial management meeting between the NRL and MIT Police, which took place in April 2018. MIT Police who are performing patrols in the area present their ID to the card reader, which authenticates their access and maintains a record of their patrol. The system was well received by the patrol officers because of its convenience and ease of operation.

In FY2018, NRL received a grant from the US DOE to upgrade its security radiation monitoring system (RMS). The upgraded system, the Sentry-RMS, was installed for a month of parallel operation in spring 2018 and commissioned in June 2018, replacing the older GTRI-RMS equipment. It serves well as an alternative security system for the reactor, entirely independent from the principal systems described in the reactor's physical security plan.

In late June 2018, the Cambridge Fire Department issued a Memorandum of Understanding in which it committed to receiving reactor radiation protection training from MIT's Environment, Health, and Safety Office (EHS) every two years. This resolved the last remaining question in an NRC Request for Additional Information regarding the frequency of first-responder training in the reactor's physical security plan.

Annual training of the MIT Police took place weekly in spring 2018. It included all continuing officers, all new officers, and the eight new civilian dispatchers recently added to MIT Police headquarters.

Environment, Health, and Safety Activities

In FY2018, all EHS Level II inspections were completed on time. The EHS coordinator led these inspections, along with NRL's EHS lead contact and an EHS safety officer. Also included were reactor operations and representatives of users of the areas under inspection.

In October 2017, new EHS Managing Director Tolga Durak met with the NRL director and EHS coordinator, who provided comments and input on the role of EHS in making industrial safety-related improvements at NRL. The EHS coordinator assisted in laboratory upgrade projects, including the NW12 fire alarm and fire protection system study, the NW13-112 experiment preparation laboratory renovation, and the containment dome light replacement project.

Reactor Radiation Protection

Radiation protection coverage is provided by the Reactor Radiation Protection Program of 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 full-time; three part-time technicians; and a part-time administrative support staff member. Routine activities include 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' instructions. An EHS officer (Joe MacLeod from the safety program) serves as NRL's EHS team member under the EHS management system's organizational structure; he provides expertise on industrial safety matters. NRL has a robust as-low-as-reasonably-achievable program; the program's policies, procedures, and metrics have resulted in improvements to the facility's day-to-day safety and efficiency.

New stack radiation monitors were purchased with money from a DOE NEUP grant and installed in a new outbuilding. These new monitors replace older equipment that used outdated technology. Over the next year, the system will be calibrated and characterized; when fully functioning, it will be integrated with NRL's existing control monitoring system.

Appointments, Awards, and Events

NRL added Muhammad Abir, postdoctoral associate, to the academic staff. Marshall Wade was hired as a senior reactor operator.

John Bernard, compliance officer, retired as of June 30, 2018. Mary Young, administrative officer, left NRL to accept another position at the Institute.

NRL and NSE celebrated the re-start of MIT's graphite pile on the 75th anniversary of the Chicago Pile's (CP-1's) first human-caused nuclear fission chain reaction.

David E. Moncton
Director