Nuclear Reactor Laboratory

The MIT Nuclear Reactor Laboratory (NRL) operates a research reactor (MITR) that has been in service since 1958. The MITR has now completed its 60th year of operation (its 43rd since the 1974–1975 upgrade and overhaul). The 6 MW research reactor has a long and proud tradition of forefront 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 United States, and it is the only research reactor located on the campus of a major research university that provides students with on-campus opportunities to participate in power-reactor-relevant materials and fuels irradiations and associated post-irradiation examinations. The MITR is an increasingly rare asset in the United States and is highly valued by researchers from US national labs, industry, and other universities.

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 the infrastructure and technical expertise to enable and support its use for research, development, education, and training. The highest priority is placed on operating the research reactor in a highly professional manner that ensures the safety of MIT and 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.

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 the laboratory. More important, it has proven itself to be a unique resource for assisting in the educational development of the next generation of nuclear engineers who will conceive, design, and manage the future of nuclear technology.

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 MITR core that is similar to that in light-water power reactors. Building on the expertise of the NRL research staff, other research programs have also led to expansion in the areas of reactor design, analysis, and benchmarking to support the development of a fluoride salt-cooled high-temperature reactor (FHR), the restart of the Transient Reactor Test Facility (TREAT), and neutron scattering and imaging applications.

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, and a materials characterization laboratory.

Laboratory Administration

NRL currently employs 48 individuals: 10 research staff, eight technical staff, 10 technical support staff, two academic staff, two administrative staff, two administrative support staff, two technicians, and 12 part-time student operators. NRL's organizational structure comprises three groups that work as a team to meet the short-term operational demands and long-term strategic challenges involved in operating a nuclear research reactor. These groups are Reactor Operations, Research and Services, and Administration.

The director of NRL is David E. Moncton. He and Lin-wen Hu (director, Research and Services), Gordon Kohse (deputy director, Research and Services), John Foster (director, Reactor Operations), and William McCarthy (deputy director, Environment, Health, and Safety Office [EHS]) make up NRL's senior management team. This leadership team works to sustain NRL's long-standing record of safe operation, to continuously maintain and improve upon the reactor facility's infrastructure, to carry out research projects, to design and conduct irradiation experiments, and to provide an environment of support and excellence for researchers and students.

Over the last three years, the laboratory's senior management team has undertaken focused efforts to expand the engagement of MIT faculty and research staff outside NRL and to achieve a more sustainable business model by reducing and eventually eliminating the need for general MIT funds to serve as a supplement in covering the MITR's operating costs. With respect to increased research volume and service revenue, six faculty members from the Department of Nuclear Science and Engineering (NSE), as well as faculty from the Departments of Materials Science and Engineering, Mechanical Engineering, and Earth, Atmospheric and Planetary Sciences, are now substantially engaged with the laboratory. More details on their programs and interests are provided below.

As noted, the other major initiative has been to reduce the level of MIT funding required to sustain the MIT reactor's operations. A strategy implemented over a decade ago was aimed at focusing the laboratory's mission on nuclear engineering studies, particularly experimental studies of new materials and sensors and their performance in high-radiation environments. The goals were to demonstrate the high value of the MIT reactor to this national mission and establish a strong argument for the Department of Energy (DOE) Office of Nuclear Energy to provide increased funding in the form of usage fees that more closely reflect the real cost of reactor operations. Over the last three years, increased usage fees have been accepted by our sponsors, and the NRL operating deficit has been significantly reduced. Continued efforts on this path can lead to a sustainable financial model within a couple of years.

Educational Impact

The MITR has been and continues to be used extensively to support MIT's research and educational missions. Some of the principal activities supporting education and training are described below.

Use of the Reactor for Laboratory Courses

The Department of Nuclear Science and Engineering is a long-standing user of one of the neutron beam ports equipped with a time-of-flight neutron spectroscopy facility for its course on radiation detection and measurement (this facility is described in more detail below). This course is required for all NSE juniors and is also taught to graduate students. Other NSE courses incorporate MITR experiments, including ones on reactor design and operation and reactor dynamics. NRL's subcritical graphite pile has recently been restarted for teaching and research at both the undergraduate and graduate levels. NRL staff members supported Professor Kord Smith of NSE in this effort, and the facility is being used for undergraduate and graduate reactor physics courses. It has also been used in demonstrations for a number of professional courses and for student visitors.

Performance of Thesis Research at All Degree Levels

Since the 1950s, cutting-edge research utilizing the MITR 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 they have acquired in the classroom with hands-on engineering. More than 200 SB, MS, and PhD theses have been completed by students who used the reactor for research on topics such as design and construction of in-core loops, low-enriched uranium (LEU) conversion, FHR design and analysis, and the biological effects and medical applications of radiation.

Two undergraduate theses have been completed and a PhD thesis is currently in progress using the restarted graphite pile. A PhD thesis investigation is ongoing to study tritium control and management for the fluoride salt-cooled high-temperature reactor. Another PhD research study is leveraging an innovative method developed for MITR's safety analysis to expand US fuel qualification test capabilities. In addition, a master's thesis investigation supported by the National Nuclear Security Administration is studying the impact of the MITR's low-enrichment fuel fabrication tolerances on reactor safety.

Training of Undergraduates to Operate the Reactor

More than 300 students have participated in NRL's Operator Training Program. Every year, four to six MIT undergraduates are hired to work part time as licensed reactor operators. Individuals from all majors are welcome to apply. The MITR training program is an invaluable educational opportunity for undergraduate students because it combines theoretical nuclear science and engineering studies with hands-on operational experience—in keeping with MIT's tradition of graduating students who know how to design and build systems. In addition, students who receive senior reactor operator (SRO) licenses obtain managerial experience by serving as shift supervisors. Students who have completed this training program have regularly reported that it was one of the highlights of their MIT experience.

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 136 tours for approximately 1,500 people. NRL staff members have collaborated with other groups at MIT and a variety of educational enrichment programs to discuss nuclear power, the role of research reactors, and the research done at the laboratory with middle and high school student groups.

Facilities and Resources

The MITR-II is the second of two research reactors that have been operated by NRL. The original reactor (MITR-I) achieved criticality in 1958. It was shut down in 1973 to allow an extensive upgrade and a conversion to the MITR-II, which offered a neutron energy spectrum and flux similar to a commercial light-water reactor. 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 were approved in 2010. The MITR was designated as a partner facility of the Department of Energy's Nuclear Science User Facilities (NSUF) in 2008 and serves a wide user base from other universities, national labs, and nuclear industry. The MITR-II is one of five US high-performance research reactors that uses highly enriched uranium (HEU) fuel. A further goal is for the reactor to be the first one in the United States to demonstrate the performance of a high-density low-enriched uranium (LEU) fuel after it 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, 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 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. These cranes are used for installation and removal of in-core and other experiments. A variety of shielded transfer casks are also available for transfers. There are two hot cells in the reactor hall. The larger cell is generally used for handling and disassembly of full-height in-core experiments. This cell is accessible for installation of the custom fixturing required for certain experiments. The smaller cell has been used to handle small, high-activity components and fuel from in-core experiments. Various types of post-irradiation-examination equipment, such as a remote balance, an optical micrometer, and a laser profilometer, have been installed and used in the small hot cell. The hot cells and the reactor spent fuel pool are also used to support packaging and shipping of irradiated samples to other facilities for post-irradiation examination.

Laboratory space within the reactor exclusion area includes two standard fume hoods and an inert-atmosphere, four-port glove box with a furnace dedicated to work involving irradiated fluoride salts and associated materials. 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 includes a xenon-flash thermal diffusivity instrument, HPGe gamma spectrometers, a liquid scintillation counter, and gaseous ^{3}H and ^{14}C collection and measurement instruments.

Sample preparation and analysis equipment purchased under a General Scientific Infrastructure Grant (to Professor Michael Short and David Carpenter) from DOE's Nuclear Energy University Program (NEUP) is now in routine use. This includes optical and scanning electron microscopes as well as sectioning and polishing equipment. An Instron mechanical testing machine with an environmental chamber that will be dedicated to irradiated material tests (through a NEUP General Scientific Infrastructure Grant to Professor Koroush Shirvan) has been received and is being installed in the exclusion area. In addition, planning is being finalized for purchase and installation of two modular hot cells in the back lab area under a NEUP Reactor Infrastructure Grant to Gordon Kohse and Lance Snead.

Neutron Beam Experimental Facilities

NRL's web-enabled neutron time-of-flight spectrometer can be operated locally or remotely over the Internet through a LabView™ interface. Hardware and software upgrades made during previous years improved the facility's reliability and supported a heavy schedule of student experiments in both the fall and spring terms. The beam repairs described in last year's report have greatly enhanced the student experience in NSE's 22.09/22.90 Principles of Nuclear Radiation Measurement and Protection laboratory course. Graduate students in the course now complete a neutron diffraction experiment in addition to a time-of-flight neutron spectrometry experiment. Undergraduate students benefit from shorter run times and improved statistics as a result of the higher intensity of the restored beam. Remote use of the facility by master's students from Aix-Marseille University in France has been scheduled for September of this year.

The MITR is home to a triple-axis neutron diffractometer and a neutron imaging facility. These facilities can be used to study the structure of materials and structural changes due to irradiation in support of the in-core irradiation program, MIT faculty work, and the work of outside users requiring access to neutron diffraction or imaging. The diffractometer is a standard triple-axis diffractometer equipped with a graphite monochromator and analyzer and He3 detectors. It has been used in a collaborative project with the Idaho National Laboratory (INL) for studies of novel nuclear fuel. 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 been used most recently in support of MIT research (as described below).

Research and Services

Lin-wen Hu is the director of the Research and Services division, and Gordon Kohse is the deputy director. This division consists of four groups: Reactor Experiments, Reactor Physics Analysis, Neutron Beam Applications, and Neutron Activation and Elemental Analysis. Staff members in the division lead a wide range of research projects and perform service irradiations. They have developed a robust program that assists MIT faculty, researchers, and students, as well as those outside NRL, in their use of the MITR and its irradiation facilities. Tasks undertaken by the 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 Undergraduate Research Opportunities Program students, and offering laboratory courses for professionals, undergraduates, and advanced secondary school students
- Expanding the user base for MITR's experimental facilities
- Contributing to the modeling and development of test reactors and small modular reactors by leveraging the NRL research staff's expertise in reactor design, instrumentation, and safety analysis
- Administering the NRL Seed Program, which solicits internal MIT proposals requesting cost-free access to MITR or NRL staff support

Reactor Experiments

David Carpenter is the leader of the Reactor Experiments group. NRL has a strong in-core experimental program that supports research in innovative instrumentation and advanced materials and fuels that are necessary for both existing and advanced power reactors. The laboratory 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 national 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 material and fuel behavior in a variety of radiation environments.

The MITR 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 a light-water reactor [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 capability of the MITR staff to design and execute proof-of-concept experiments more quickly and cost effectively than at other research reactors.

Close collaborations with national labs, universities, and domestic and international organizations have put the reactor experiments program at the forefront of worldwide research on recent advancements such as radiation-resistant fiber optics, fluoride salts, and accident-tolerant fuel cladding for commercial reactor use. The in-core irradiation program also supports the creation 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 MITR operation and experiments and cutting-edge research on advanced reactor concepts and innovative test reactor designs.

Technical support for MITR routine operations and research and development consists of the fuel management program and corresponding code development, the LEU conversion program, criticality safety analyses, and neutronics and thermal analyses for safety evaluation of reactor experiments. There were three major achievements in FY2019: (1) NRC agreed to review the preliminary safety analysis report submitted for the MITR LEU conversion; (2) two MIT senior theses, supervised by group members, were successfully completed; and (3) a research proposal demonstrating an autonomous reactor control framework using the MIT Graphite Exponential Pile (MGEP) was selected for a NEUP award.

Primary research activities in FY2019 included a technical investigation into licensing of a pebble-bed FHR; design, execution, and analysis of reactor transient tests at the MITR and INL's TREAT facility in support of advanced instrumentation development; and characterization, operation, and modeling of the MGEP.

Neutron Beam Applications

Research scientist Boris Khaykovich leads the Neutron Beam Applications group. Neutron beams enable 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, and new facilities are being built around the globe. MIT has a long tradition of leadership in neutron science, extending back to Professor Clifford Shull, who shared a Nobel Prize for pioneering neutron scattering techniques. Several years ago, under the direction of David Moncton and with the assistance of 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 MITR or national neutron facilities
- Establishment of a neutron scattering facility to support users from inside and outside MIT in conducting early phases of certain experiments more quickly than at large facilities
- Use of expertise established in neutron beam applications to support development of experimental methods for exploiting compact x-ray sources

Neutron Activation and Elemental Analysis

Michael Ames is the leader of the Neutron Activation and Elemental Analysis group. 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 MITR is equipped with two pneumatic systems that 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 NAA components can be applied separately to (1) produce radionuclides in a variety of forms for use as tracers in physical, chemical, and biological fate and transport studies; (2) induce neutron damage in sample materials; and (3) 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 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 group is on in-core experiments that support current and next-generation nuclear power reactor technology development. Several of these programs have related elements taking advantage of the expertise of the Reactor Physics Analysis, Neutron Beam Applications, and Neutron Activation and Elemental Analysis groups. In addition, there are research programs, such as the LEU conversion project, that do not involve any reactor experiment activity. Following a general overview of the in-core experimental program, this section offers brief descriptions of all of NRL's ongoing research programs.

NRL's in-core experimental program has been seamlessly integrated into various US industry- and government-funded programs, such as NSUF, the Accident Tolerant Fuel Program, the Advanced Reactor Program, and other DOE Office of Nuclear Energy initiatives. The MITR was designated as NSUF's first partner facility and has played a key role in performing various NSUF-funded irradiation experiments since 2008. The proven capability of the NRL staff to design and successfully execute complex proof-of-concept experiments and to deploy in-core loops for studying both LWR and non-LWR coolants and materials at high temperatures is and will remain an essential national capability. NRL's unique expertise and capabilities have established its reputation to rapidly demonstrate the survivability of new sensors and instrumentation components and to develop rigs for irradiation testing. In addition, it is anticipated that several recently launched, privately funded advanced reactor development initiatives will seek support from NRL to study their chosen materials and fuels. There are also international efforts in need of the MITR's capabilities. For example, the fluoride salt-cooled high-temperature reactor program has attracted substantial support from a large Chinese development program.

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

- The high neutron flux, the flexible core design, and the MITR's 24-hour-a-day, seven-day-a-week operating schedule
- 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
- The continuing collaboration with the NSUF program, which is to the benefit of both the Idaho National Laboratory 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, we provide 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 generation of hydrogen and heat, compromising the ability of the cladding to maintain a "coolable geometry" for the fuel pins.

Westinghouse is leading a multi-institutional effort to design and demonstrate an advanced fuel concept with improved post-accident behavior that can be rapidly commercialized. This research is funded by the DOE Nuclear Engineering Enabling Technology Program. The effort involves changes to both the fuel meat and the cladding; NRL is conducting irradiation tests of candidate cladding materials and associated end plug sealing methods. A leading replacement candidate is multi-layer SiC/SiC 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 alternate clad 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 Program 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 have continued and are planned through the rest of the year and beyond. These irradiations have included a series of advanced in-core sensors for real-time monitoring of fuel and core conditions as well as additional zircaloy samples contributed by Professor Michael Short.

After irradiation, the Westinghouse samples and sensors have been examined in the NRL hot cell facilities. Also, Professor Short's samples have been examined using our scanning electron microscope/energy dispersive x-ray spectroscope and then characterized, packaged, and provided for analysis at other MIT facilities.

Solving Problems for 21st-Century LWRs with Innovative Cladding Coatings

Similar to the Westinghouse project, this Exelon-funded project is investigating advanced power reactor fuel cladding materials. The goal is to identify cladding material compositions and coatings that can reduce corrosion and crud buildup, thereby increasing reactor safety and performance. This NRL collaboration is led by Professor Michael Short (NSE) with additional leadership from Professors Matteo Bucci (NSE) and Evelyn Wang (Department of Mechanical Engineering).

In this project, the MITR pressurized water loop facility was used to expose zircaloy and other metal samples to pressurized water reactor conditions during the first quarter of 2019. The project also included zircaloy and steel cladding materials contributed by Professors Ju Li and Koroush Shirvan (NSE). After irradiation, these samples were moved to the NRL hot cell facilities for examination. After decay, they will undergo additional characterization of their surface and bulk properties.

In-Core Sensor 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 Office of Nuclear Energy research programs has been investigating ultrasonic transducers for both under sodium viewing and in-service inspection measurements near reactor cores. A long-term irradiation based on ultrasonic transducers was completed in FY2015, followed by post-irradiation examination and planning of the next irradiation test.

A second in-core instrumentation test (ULTRA2) was completed in April 2017. In addition to a second generation of ultrasonic transducers, this test included fiber optic temperature sensors provided by the University of Pittsburgh and the French Centre d'Energie Atomique. All of these instruments were read in real time, allowing for 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. In addition, they can be used to investigate other parameters such as mechanical strain, pressure, and gas composition. The irradiation facility also included drop-in samples of advanced doped optical glasses provided by AFO Research. The irradiation of ULTRA2 was completed in March 2018, and it was moved to the NRL hot cell facilities for post-irradiation examination. During the first quarter of 2019, all of the glass specimens and fiber optic sensors from the irradiation capsule were extracted. These fibers were then shipped to Westinghouse laboratories for further analysis of their properties.

Two new in-core sensor irradiation projects were initiated during 2019, both with NSUF funding. The PFOX irradiation, a follow-on of the ULTRA2 project, incorporates lessons in the materials' performance to select better fiber optic and ultrasonic sensors. This project is led by Professor Kevin Chen from the University of Pittsburgh. The project's fiber and ultrasonic sensors were irradiated together in the MITR inert gas facility at 650°C for one cycle. During irradiation, the performance of each sensor was monitored to record real-time changes in performance with radiation damage and temperature. After irradiation, the fibers were extracted and shipped to Westinghouse for examination. A second cycle of irradiation of additional fibers at the MITR is scheduled for the first quarter of 2020.

A separate sensor irradiation is now underway for Professor Yanliang Zhang at the University of Notre Dame. This project is irradiating two dozen miniature thermal conductivity probes in the MITR inert gas facility at moderate temperatures (less than 400°C). These probes utilize microscopic metal printing to produce sensors on radiation-resistant ceramic substrates. After irradiation, these sensors will be extracted in the NRL hot cell facilities for characterization.

Materials and Fluoride Salt Irradiation

MIT, the University of Wisconsin, and the University of California, Berkeley, initiated a series of cooperative integrated research projects to develop the path forward to a test reactor and ultimately a commercial fluoride salt-cooled high-temperature reactor. 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.

Testing in the MITR addresses this concern and is also intended to help verify models for tritium generation and transport.

With additional funding support from the Chinese Academy of Sciences, a series of four first-of-a-kind irradiations of FLiBe and FHR materials were completed in the MITR. Subsequently, a research effort funded by the startup company Kairos Power, along with several Chinese research organizations, continued to analyze the materials irradiated in these experiments and to measure and model the transport and holdup of tritium.

NRL staff also continue to work on two other research projects to accelerate the FHR technology demonstration: design of a transportable FHR and design of a sub-critical facility at the 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 up to 30% of a reference FHR. Recent research activities focus on the detailed thermal-hydraulic design of the sub-critical facility for both nominal (forced convection) and loss-of-primary-flow (natural convection and/or fully drained) conditions. In particular, heat pipes placed at the periphery of the active zone have been shown to be satisfactory as a back-up heat removal system. Further optimization of the heat pipe arrangement is being studied.

Transient Reactor Test Facility Restart Support

The Transient Reactor Test Facility, located at the Idaho National Laboratory, was restarted during 2018. The facility has been used to study LWR and sodium-cooled fast reactor fuel under a variety of transient conditions. Members of the NRL Research and Services division are part of an integrated research project funded by DOE. This effort includes developing an instrumentation plan for TREAT and designing and operating a test instrumentation facility for use in the MITR and the Oregon State TRIGA Reactor. During FY2018, MITR irradiation tests at low power were carried out on a set of neutron detectors and gamma detectors. These sensors were subsequently installed at and irradiated in TREAT. This set of steady-state and transient tests represented the first experiments at TREAT carried out by an outside organization since the restart of the reactor. The data gathered from these tests of sensor performance and TREAT operating characteristics were evaluated by researchers at NRL and used as the basis for several publications. This included benchmarking of modeling and simulation codes used to understand the static and transient behavior of the MITR and TREAT.

Low Enrichment Uranium Conversion Program

The goal of this research program is to convert the MITR from HEU to LEU fuel. The NRL staff aims to carry out the first conversion among the remaining five high-performance reactors in the United States, adopting a special high-density LEU fuel currently undergoing qualification tests. While 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 of eliminating weapons-grade HEU from civilian use worldwide. A major objective of the MITR's LEU conversion is to maintain the HEU core performance, and a previous feasibility study showed that a power upgrade to 7 MW was necessary.

After a new MITR LEU U-10Mo monolithic fuel design with graded fuel meat thickness was developed, LEU conversion impacts on in-core experiments and accident analyses were completed. The nuclear and thermal-hydraulic design has been evaluated and confirmed to meet operational safety requirements. A preliminary safety analysis report on LEU fuel conversion was completed and submitted to the US Nuclear Regulatory Commission for review. In addition, transition cycles to reach an equilibrium core using the new LEU fuel design were evaluated and demonstrated feasibility of conversion with a full core of fresh LEU fuel elements. Work on detailed MITR LEU fuel specifications and fabrication tolerances is being carried out as a master's research thesis in collaboration with the reactor conversion and fuel fabrication pillars of the Reduced Enrichment Research and Test Reactors Program. A draft LEU core startup plan was completed during FY2019.

Neutron Optics Research Program

The Neutron Beam Applications group conducts neutron optics research aimed at 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 studies are funded by DOE, the Department of Commerce (DOC), and INL. A DOE-funded collaboration with a small company (Electroformed Nickel Inc.) is tasked with the production of focusing neutron mirrors that could be used in future neutron-scattering facilities. A DOC-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 applied pressure. Another DOE-funded project designed and tested conical analyzers for novel polychromatic powder diffractometers.

Determination of the Molecular Structure of Molten Salts

The goal of this new program is to measure the molecular structure of molten salts for molten-salt reactors through neutron and x-ray diffraction and spectroscopy along with ab initio molecular dynamic simulations. The program, funded by NEUP, is a collaboration between NRL (with Boris Khaykovich and Guiqui (Tony) Zheng as principal investigators) and NSE (Professor Ju Li and QJ Li). Initial measurements of newly prepared salt samples have been scheduled at the Oak Ridge National Laboratory.

NRL Seed Program

In the fall of 2017, the NRL Seed Program was established by Lin-wen Hu as a means to cultivate new research areas and to obtain data in support of pursuing externally funded research proposals. The 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 brief synopsis of their proposed work. Four categories of experiments are considered under the program: (1) small-scale dedicated irradiation experiments, (2) shared-use in-core experiments, (3) neutron beams and instruments, and (4) materials characterization and post-irradiation examination.

Six proposals have been selected from various academic departments at MIT since the inception of the Seed Program. The first proposals, awarded in fall 2017, were submitted by Anu Agarwal (principal research scientist, Microphotonics Center) and J.J. Hu (associate professor, Department of Materials Science and Engineering), Matteo Bucci (assistant professor, NSE), and Michael Short (assistant professor, NSE). The spring 2018 proposals were submitted by D. Cem Tasan (assistant professor, Department of Materials Science and Engineering), Mingda Li (assistant professor, NSE), and David McGee (associate professor, Department of Earth, Atmospheric and Planetary Sciences).

In FY2019, three proposals were selected for awards: “Radiography Examination of MGEP Fuel Slug Inner Dimensions for High-Quality Neutronics Benchmark” (Professor Kord Smith, NSE), “Structure Characterization of Weyl Semimetals TaP and NbP Using Neutron Diffraction” (Professor Li, NSE), and “Process Optimization of Metal and Polymer Additive Manufacturing via Neutron Imaging” (Professor John Hart, Department of Mechanical Engineering).

Services

Irradiations and experiments conducted over the past year include the following:

- Activation of gold-198 seeds for brachytherapy
- Activation of ytterbium-168 pellets in support of a cancer treatment study
- Activation of uranium foils for detector calibration at the Los Alamos National Laboratory and the Ciambrone Laboratory at Patrick Air Force Base
- Activation of silicon carbide and polyethylene cable component samples and NAA standards for the University of Alabama
- Activation of metallic single crystal samples and Teflon samples for the MIT Department of Nuclear Science and Engineering
- Neutron activation of silicon wafers to study radiation-induced photonic defects for the MIT Materials Processing Center
- Activation of europium samples for the MIT Junior Physics Lab
- Activation and NAA of copper samples for the MIT Physics Department
- Activation and NAA of epoxy samples for the MIT Department of Nuclear Science and Engineering
- Activation and NAA of various sample materials and structural components for the NSUF Boise State Transmission Control Protocol Experiment
- Neutron radiography of mineral samples for the MIT Department of Earth, Atmospheric and Planetary Sciences
- Neutron radiography of boiling water through a sapphire window for the MIT Department of Nuclear Science and Engineering
- Neutron radiography of un-irradiated fuel plate samples in support of an NSUF fuel characterization project

- 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 temperatures, measurements of neutron wavelength and time of flight, and measurements of attenuation coefficients for eight shielding materials
- Use of the reactor for training of MIT student reactor operators and for NSE classes (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 John Foster, director of reactor operations; Edward Lau, assistant director of reactor operations; and Sarah Don, reactor superintendent. The Reactor Operations group is responsible for supporting the operation and maintenance of the 6 MW research reactor. The group consists of full-time employees and part-time undergraduate students. The majority of the members of the group are licensed by NRC, and most hold a senior reactor operator license. These licensed individuals perform reactor shift duties to support the reactor's 24-hour-a-day, seven-day-a-week operating schedule. In addition, there is one full-time project mechanic to support reactor mechanical maintenance. In FY2019, Reactor Operations supported NRL research projects in the following areas: pressurized water loop facilities, molten fluoride salt irradiations, high-temperature in-core sample assembly capsule irradiations, 3 GV vertical thimble foil irradiations, 1PH1 and 2PH1 pneumatic tube samples, 4DH4 diffractometers, and 4DH1 student spectrometers.

During the past year, the reactor was maintained at a full power of 5.5 MW or higher. Total energy output from July 2018 to June 2019 was 29,826 megawatt-hours. This translates to 5,055 hours of operation at 5.9 MW.

Major Nuclear Reactor Laboratory maintenance and upgrade projects accomplished in FY2019 included the following:

- Annual gain determinations for low-range amplifiers on nuclear safety channels 5 and 6
- Annual efficiency tests for the ventilation system charcoal filters
- Motor replacements for control blades 3, 4, and 5
- Replacement of the D_2O recombiner blower belt and pulley assembly
- Installation of a pressure switch in the D_2O helium system line to the recombiner to provide for low flow condition control room indication
- Replacement of control blade 1 and its drive and magnet
- Replacement of control blade 4

- Annual control blade worth measurements
- Chemical cleaning of the main primary heat exchanger
- Manual cleaning of the fill for both cooling towers and replacement of broken fill pieces
- Coordination with MIT Facilities to perform cleaning and maintenance of high-voltage electrical equipment in the utility room
- Coordination with MIT Facilities to replace containment dome lighting
- Installation of remote open permit switches for the 4DH1 and 4DH4 neutron beams
- Replacement of the DL-6 reflector tank level indicator with more reliable technology
- Coordination with MIT Facilities to install a new water meter to monitor wastewater discharge to the sewer
- Replacement of the shield coolant system flow meter PF-10
- Re-routing and shielding of nuclear instrumentation cabling routes for DWK 250 channels 3 and 4
- Annual inventory of heavy water
- Repair of the 3GV6 vertical irradiation thimble cooling jacket
- Rebuilding of the secondary system Bernoulli filters
- Coordination with MIT Emergency Management to install two automated external defibrillators in Building NW12

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

Initial Operator Training Program and Requalification Training Program

The Reactor Operations group trains up to 10 new operators each year in pursuit of an NRC license to operate the MIT nuclear reactor. This diverse group of trainees comprises mostly MIT undergraduates (typically starting in their freshman year) but also includes full-time staff members, US Navy nuclear program veterans, and select undergraduates from neighboring Boston universities.

The Initial Operator Training Program is rigorous and covers topics such as reactor theory and dynamics, radiation detection and safety, and mechanical and instrumentation systems. The level of instruction is comparable to that offered in undergraduate courses covering the same topics. The endpoint of the MITR training program is a multifaceted examination, administered by NRC, that consists of a written component, an operational component (reactor startup), an oral board, and a reactor plant walkthrough. Successful student candidates receive a reactor operator license and continue to support the reactor as part-time operators. After the students gain operational experience, most are offered the opportunity to participate in a second training program that leads to a senior reactor operator license. Full-time candidates begin supporting routine MITR operations and evolutions as licensed reactor operators or SROs.

From July 2018 through June 2019, two sets of NRC examinations were administered at NRL. In October 2018, two MIT students and one student from the Berklee College of Music obtained SRO licenses; in March 2019, two MIT students obtained reactor operator licenses and two full-time staff members obtained SRO licenses. Eleven candidates are currently preparing for NRC licensing examinations: seven MIT undergraduates, one full-time staff member, and three students from neighboring universities (University of Rhode Island, Suffolk University, and Boston University).

Following successful completion of the Initial Operator Training Program, operators begin continuous training through the NRC-mandated Requalification Training Program. The objectives of this program are to verify that licensed individuals remain proficient on routine operations, to refresh knowledge of operations that are performed infrequently, to provide for timely reviews of facility and procedural changes by all licensed personnel, and to ensure improvements in any areas of performance weakness that are identified. These objectives are accomplished through monthly lectures, on-the-job training, and annual written and oral examinations. The Requalification Training Program is managed by an in-house requalification program coordinator, and it is audited annually by NRC to ensure that all requirements are satisfied.

Security

In FY2019, NRL security continued to meet NRC regulatory requirements. Over the past year, two independent audits were performed regarding security: an in-depth review of the MITR physical security plan and its implementing procedures in October 2018 and a physical security review (which has been added to the routine annual independent audit) in April 2019. No regulatory violations were identified.

In January 2019, Reactor Operations coordinated with Information Systems and Technology (IS&T) and the MIT Police to perform a system-wide comprehensive test of the MITR security system, assisted by technicians from Siemens Building Technology. Issues identified during the test, including malfunctioning multiplexers, have been resolved satisfactorily. However, the aging condition of the existing cameras from 2009 remains an open concern. The 19 new digital cameras that were installed by IS&T in FY2017 as phase 1 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 Special Subcommittee for Security of the MIT Reactor Safeguards Committee recommended launching phase 2 of the camera upgrade once this approval was received.

In March 2019, Reactor Operations coordinated with IS&T and contractors to obtain quotes for the phase 2 camera upgrade, which would involve replacement of all remaining 2009 cameras. Next, a source of funding must be identified.

In May 2019, the Special Subcommittee for Security reviewed and approved a series of updates made by Reactor Operations to the physical security plan and a number of related procedures. In June, a copy of the updated plan was filed with NRC.

In FY2018, NRL received a grant from the US Department of Energy to upgrade its Radiation Monitoring System (RMS). The upgraded system, the Sentry-RMS, was commissioned in June 2018. Throughout FY2019 it served without problems as an alternative security system for the reactor, entirely independent from the principal systems described in the reactor's physical security plan.

Annual training of the MIT Police took place in four sessions in spring 2019. The training included all continuing officers, all new officers, and all civilian dispatchers working at MIT Police headquarters. As usual, each of the half-day sessions included a facility walkthrough, radiation protection training, reactor procedures and patrols, and EHS biosafety training.

Emergency drills were conducted with the MIT Police and all other related on-campus emergency response organizations in September 2018 (radiological emergency exercise) and December 2018 (medical emergency exercise). The medical drill also included off-campus agencies: the Cambridge Fire Department, Professional Ambulance, and Mount Auburn Hospital. Both drills were performed satisfactorily and generated many lessons learned to share among all participants.

Environment, Health, and Safety Activities

A pair of EHS level II inspections were completed in FY2019. One started in December 2018 and was completed in January 2019, and the other started in May 2019 and was completed in June. The EHS coordinator led these inspections, along with NRL's EHS lead contact and an EHS safety officer. Also included were Reactor Operations staff members (for cross training) and representatives of area users (for area inspections). In September 2018, the EHS coordinator and EHS lead contact completed a comprehensive EHS survey on their roles and responsibilities.

The EHS coordinator assisted in laboratory upgrade projects including an NW12 fire alarm and fire protection system study, an investigation of the wastewater treatment system in NW13 for compliance with Massachusetts Water Resources Authority requirements, and further renovations of the NW13-112 experiment preparation laboratory.

Reactor Radiation Protection

Radiation protection coverage is provided by the EHS Reactor Radiation Protection Program. Although this is a separate organization within MIT, it is very responsive to the NRL management team. Personnel include an assistant director who serves as the reactor radiation protection officer (William McCarthy), two EHS officers, one full-time and three part-time technicians, 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 NRL are as low as reasonably achievable in accordance with applicable regulations and Institute committees. An EHS officer (Joe MacLeod from the safety program) serves as the NRL-EHS team member under the EHS management system organizational structure and provides expertise on industrial safety matters. NRL has a robust ALARA (as low as reasonably achievable) program. ALARA-related policies, procedures, and metrics have resulted in improvements to the facility's day-to-day safety and efficiency.

Appointments and Awards

Selene Victor was hired as a financial coordinator.

Alex Kingsbury, Peggy Watson-Brownell, and Kyle Clapper were hired as full-time senior reactor operators.

Akshay Dave was promoted to research scientist.

Interim administrative officer Rose Rizzo left NRL to accept another position at the Institute.

Reactor utilization manager Tom Bork received an Infinite Mile Award.

Lin-wen Hu has been elected as a fellow of the American Nuclear Society for her "outstanding leadership and contributions to facility design, modifications, safety analysis and licensing."

David E. Moncton
Director