Report of the Committee on the Future of the MIT Nuclear Reactor Laboratory

April 27, 2015

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1. Executive Summary

This report summarizes the findings and recommendations of the Committee on the Future of the MIT Nuclear Reactor Laboratory (NRL). The Committee was established by MIT Vice President for Research, Professor Maria Zuber, and its members (see Appendix A for both membership and charge) represented both internal MIT stakeholders as well as external perspectives. The Committee met twice in two-day sessions to hear from a variety of interested parties. The agendas for these meetings are contained in Appendix B.

The main facility of the NRL is the MIT research reactor (MITR), a 6 MW nuclear reactor that first reached criticality in 1958. Remarkably, this reactor remains one of the most important research reactors in the US, partly as a consequence of the foresight of its original leaders, and partly because it has been decades since the US has built any new research reactors.

The MITR is unique in the academic sector in its ability to support in-core studies of materials in a radiation environment similar to the light water reactors (LWRs) used for commercial power generation in the US and around the world. As these reactors age, maintaining their ability to operate safely, reliably, and economically beyond their original lifetime is an increasingly important objective, especially given the key role of the LWR fleet in mitigating carbon emissions. An important and related objective is the development of higher-performance fuels for incremental improvement for the current LWR fleet, including the study of more economic and accident-tolerant fuels. The MITR has supported in-core loops contributing to both goals for more than two decades.

More recently, new in-core experimental facilities have been developed and demonstrated to support materials and instrumentation testing for advanced reactor development, such as high-temperature gas reactors and fluoride salt-cooled high-temperature reactors. Unique irradiation facilities with temperatures up to 1400 °C or with fluoride salt are invaluable assets for US advanced reactor research and development programs, including the study of new fuel forms.

Another important attribute of the MITR is its ability to provide students with on-campus research experience working in radiation environments, conducting irradiations, and doing post-irradiation examinations. This is an increasingly rare asset in the US and is highly valued by prospective employers in government and industry.

Finding 1: *The MITR is a unique and irreplaceable national capability. It is especially valuable given (1) the strength of its in-core irradiation program; (2) the limited capabilities for such irradiation evaluations in the US; and (3) the ability to provide students with in-core experimental research experiences that are not available elsewhere. Furthermore, the MITR has an experienced and stable staff and, relative to reactor facilities at DOE laboratories, is more flexible and more easily accessible, and can provide services at lower cost.*

In its current core configuration, as noted above, the MITR has a very successful in-core research program. But the research impact of the reactor could be significantly enhanced through incremental improvements, including (a) enhanced ancillary facilities and capabilities such as additional instrumentation for monitoring and control of in-core standardized test rigs or LWR flow loops, and installation of hot cells with state-of-the-art post-irradiation examination (PIE) equipment, (b) modifying the existing fission converter to implement a unique sub-critical facility relatively quickly and at modest cost to support advanced reactor development efforts and potential fusion blanket concepts, and (c) implementing a digital control system for the reactor itself, thereby improving reactor performance and safety.

The MITR is already providing important research support for the new Department of Energy (DOE) program on fluoride-salt-cooled high-temperature reactors, and is poised to support a larger Chinese development program for this same technology. Several privately-funded advanced reactor development initiatives have been launched and will likely also seek support from research reactors such as the MITR to study their chosen materials and fuels.

A new national research reactor facility is an option under consideration by DOE to expand domestic fuel and materials testing capabilities. However, even if a new research reactor project went forward, it would not become available for more than a decade. In the meantime, the proven capability of the MITR staff to design and execute proof-of-concept experiments more quickly than at other research reactors, and to support in-core loops for studying non-LWR coolants and materials at high temperatures, should enable the NRL to contribute effectively to these efforts.

The Committee also heard about the status of the effort to convert the MITR from high-enrichment uranium (HEU) fuel to low-enrichment uranium (LEU) fuel. MIT seeks to carry out the first conversion among the remaining five high-performance reactors in the US, adopting a special high-density LEU fuel 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 the Global Threat Reduction Initiative to eliminate weapons-grade HEU from civilian use world-wide.

Finding 2: *Incremental improvements to the MITR could enhance its research impact significantly, both in relation to the existing LWR fleet and to US and international advanced reactor development efforts. There is a mature plan for conversion to LEU fuel with potential for US and world leadership.*

Beyond incremental improvements, the Committee also considered the possibility of major modifications or rebuilding of the reactor core to improve performance. This was done most recently in 1973-4 with the conversion to light water coolant/moderator and the addition of the heavy water reflector. At present there is a global shortage of fast neutrons, and there is the potential for new MITR designs to achieve higher fast fluxes. However, an increase of at most a factor of 2-3 could be achieved. While it could accelerate the identification of neutron fluence effects, it could also reduce the number and types of experiments that can be performed simultaneously.

Finding 3: *Major upgrades to or replacement of the MITR core would be costly and time-consuming, and the benefits would be modest. Therefore, undertaking a major core replacement or modification project would not be justified.*

The Committee then broadened its perspective, hearing a set of exciting presentations on topics related to one of the key areas in nuclear research, namely the study of materials under extreme radiation conditions. While the in-core research program has established the NRL as a major national asset for simulating LWR conditions and for conducting experiments to support advanced reactor design, there are needs in both fission and fusion research, as well as in other areas such as space exploration, where materials must be developed to withstand much higher radiation doses. The Nuclear Science and Engineering Department (NSE) has identified the science and engineering of materials in extreme radiation environments as a major focus of its new educational and research strategy, and NSE is building a strong faculty in this area.

The Committee learned about three major technology advances which, if implemented together with proposed MITR enhancements, and integrated with the in-core irradiation facilities, could create a world-leading center for radiation materials science that would be unequaled even by large, single-modality DOE user facilities, and cost much less.

First, advanced superconducting proton cyclotron technology developed at the MIT Plasma Science and Fusion Center (PSFC) will enable compact and cost effective cyclotrons to implant helium (a major factor in radiation damage) and irradiate in bulk (a few mm^3) with protons to levels of up to 100 displacements per atom (dpa). For comparison, it takes about a year in the core of the MITR to reach one dpa. (Materials in fusion reactors and some advanced fission reactors are expected to experience radiation damage of 200 dpa or more.)

Second, NRL staff scientists presented mature designs for compact and inexpensive x-ray source technology that would allow in-situ time-dependent characterization of these samples as damage is produced in the proton beam. X-ray scattering and imaging methods heretofore requiring the high brightness beams of large synchrotron facilities could be implemented locally, enabling in-situ studies for the first time.

Third, the Committee heard about a new neutron optics technology developed at the NRL which could make the thermal neutron beams from the reactor up to 100 times more effective for neutron scattering and imaging experiments to complement the x-ray techniques. Again, in-situ time-dependent studies could be carried out, since the neutron beams could be directed toward samples as they were being irradiated by the helium and proton beams.

Neutron and x-ray methods are known to be complementary in terms of sensitivity to structural details, and together they constitute the most important probes of the structure of bulk materials. Having an integrated capability to irradiate materials in the core of a high-performance reactor, or with intense accelerator beams, and interrogate those materials with high-brightness x-ray and neutron beams is unprecedented and transformational for such studies.

Finding 4: *There is an exciting opportunity for MIT to combine the existing and potential capabilities of the NRL, related developments at PSFC, and the strategic initiatives of NSE to establish scientific leadership and capability leadership in the field of radiation materials science more broadly. In-situ interrogation can open new frontiers in radiation materials science. Without new fast-spectrum research reactors in the US, there are major gaps in national capabilities. Since new fast reactors are unlikely, a paradigm shift is now underway concerning how to achieve high radiation damage in their absence. Accelerator-based irradiation facilities, combined with x-ray and thermal neutron interrogation, provide a rich opportunity to advance nuclear and non-nuclear material science.*

In order to fully support and exploit the facilities described above, and to further enhance the NRL's capability to perform a wide range of PIE on materials from the in-core program, including with unique x-ray and neutron methods, the Committee reviewed the existing NRL site plan. Additional laboratories, new state-of-the-art hot cell capabilities, and PIE instruments—such as electron microscopes and laser spectroscopies—would be required. The Committee noted the potential for new building construction of up to 50,000 SF which would have the required adjacency and capacity to house a new center for radiation materials science.

Finding 5: *For NRL to provide a new world-wide leadership role for MIT in radiation materials science, it must construct new facilities to accommodate accelerators; proton, x-ray, and neutron beams; hot cells; laboratories; and instrumentation adjacent to the reactor.*

During the Committee meetings, there were a number of presentations by young faculty members in NSE and other departments with ideas for utilizing both existing and potentially new facilities at the NRL. The availability of novel x-ray and neutron methods at NRL would open up new opportunities for research on non-nuclear materials that are likely to be of broad interest at MIT and would complement capabilities now planned for the new MIT nanoscience facility.

Finding 6: *An impressive cohort of young faculty now exists in NSE and other departments, and they have many ideas about how to engage with the NRL. The future development of NRL will provide an opportunity to enhance the physical sciences and engineering at MIT and attract and retain faculty across the Institute.*

Realizing this new vision for the NRL will require a substantial strategic effort by the many stakeholders at MIT and in the extended nuclear engineering community. The Committee considered the best approach for engaging the range of entities that could play keys roles in supporting the initiative. The National Research Council (NRC) conducted a thorough study of national facility funding models in 1999 and concluded that the most effective approach is to have one "steward" agency, with other interested partners participating in a cooperative arrangement.

Finding 7: *The NRC Cooperative Stewardship Model is an excellent approach for DOE-NE leadership in realizing the new vision for the NRL, together with a number or partners with strong interest in nuclear materials.*

The Committee recognized that the development of accelerator technology at MIT is currently dispersed across a number of small programs within the NRL, the PSFC, the Laboratory for Nuclear Science (LNS), and the Physics Department.

Finding 8: *There are significant opportunities for collaboration and integration among laboratories (NRL, PSFC, and LNS) and between departments (NSE and Physics) in developing new accelerator capabilities. New accelerators on the MIT campus would provide important new opportunities for research and education. NRL leadership could help achieve broad multi-disciplinary impact.*

Finally, the Committee became aware of the issues surrounding the Northwest campus area, which comprises nearly 10 acres of prime Cambridge real estate. Historically this area supported the development of medium-scale physical facilities such as the nuclear reactor, the Alcator tokamak, and high-field magnets, and it continues to provide the principal laboratory space for NSE faculty and students. This area is greatly in need of revitalization, but represents an enormous asset to MIT if properly developed to meet future needs.

Finding 9: *The Northwest campus/Albany Street area has the potential to become a new center for medium-scale experimental physical science facilities on campus.*

Recommendations

The above findings lead to the following three main recommendations concerning the future of the MIT NRL:

Recommendation 1: The MITR should continue to operate and the in-core research program be sustained in the near term.

Recommendation 2: MIT should develop a strategy to realize the new vision for the NRL described in this report to create a world-leading center for radiation materials science within 3 to 5 years. The Committee anticipates that MIT will need to advocate strongly with potential sponsors and perhaps consider novel funding models.

The new NRL complex would integrate key elements: (a) incremental improvements to the reactor's experimental program, including new instrumentation and control capabilities, expanded hot-cell capability, and a new sub-critical facility, to enhance the reactor's role in supporting current and advanced reactor development efforts; and (b) new accelerator-based methods for creating high damage levels in materials together with in-situ x-ray and neutron interrogation methods and supporting laboratories and facilities.

Recommendation 3: As MIT develops plans for the future of the Northwest campus, it should explore the broader opportunities for revitalizing this sector that could build on this new vision for the NRL.

2. Introduction

The Massachusetts Institute of Technology research reactor (MITR), which has been operational since the late 1950s, has a long and proud tradition of carrying out forefront research and educational training in the areas of fission engineering, radiation effects in biology and medicine, neutron physics, geochemistry and environmental studies. The reactor is in excellent physical condition and was recently relicensed by the Nuclear Regulatory Commission for an additional twenty years. Given MITR's past role and the opportunity to continue to operate it, the MIT Vice President for Research, Professor Maria Zuber, established a Committee on the Future of the Nuclear Reactor Laboratory (NRL) to help develop a vision for the Laboratory that could maximize its scientific and technical impact within the US and the international nuclear engineering enterprise. The Committee met twice in two-day sessions, during which it heard from a wide variety of stakeholders both within and external to the Institute. See Appendix A for membership and charge, and Appendix B for the agendas for the two meetings.

Research Reactors in the United States

There are over 30 operating US research and test reactors. These facilities are located at Department of Energy (DOE) sites, universities, and sites owned by other government agencies and industry. Many of these reactors began operating in the 1950s and 1960s. Most are multi-purpose facilities with missions that include isotope production, industrial processing, non-destructive interrogations, and performance evaluations of fuels, materials, components, or instrumentation. For university reactors, another important mission is the ability to provide students with hands-on experience in reactor operations, testing, and post-irradiation examination. Materials test reactors (MTRs), a sub-group of research reactors which are designed to operate at relatively high power density levels, are used in many fields, including the fission and fusion community, environmental science, materials engineering, and nuclear medicine.

MTR designs and operating modes vary significantly. A common design is a pool type reactor, where the core is a cluster of fuel elements sitting in a large pool of water that provides cooling and radiation shielding. Interspersed among the fuel elements in the core are empty channels for testing fuels or materials. Apertures to access neutron beams may be set in the wall of the pool. Tank-type research reactors are another common design. These reactors are similar to pool reactor designs, except that the core is in a tank with water, sealed at the top with forced cooling for heat removal. US MTR rated power levels range from less than 0.1 Watt to 250 MW. However, some reactors can safely be pulsed from fairly low power levels to very high power levels (e.g. 25,000 MW) for fractions of a second. All US research reactors operate with a thermal neutron spectrum. At this time, there are no fast flux irradiation facilities in the US. This gap is currently addressed by using foreign facilities or by harnessing options such as an experiment liner made from material that preferentially absorbs thermal neutrons so as to approximate a fast neutron spectrum irradiation. However, each of these options has limitations.

As shown in Table 2.1, there are only five US MTRs capable of steady state high flux operation (e.g., thermal fluxes above $1x10^{13}$ n/cm^2 sec and fast fluxes above 10^{14} n/cm^2 sec).

Table 2.1. Characteristics of High Performance US MTRs

Parameter	MITR-II	Missouri University Research Reactor	High Flux Isotope Reactor	Advanced Test Reactor	National Bureau of Standards Reactor
Power, MW	6	10	85	250	20
Type	LWR Tank with heavy water outer tank	LWR Tank	LWR Tank	LWR Tank	Heavy Water Tank
Owner	MIT	University of Missouri	US DOE/Oak Ridge National Laboratory	US DOE/Idaho National Laboratory	US Department of Commerce/NIST
Maximum Thermal Flux, n/cm^2-s	5.0 E+13	6.0 E+14	2.5 E+15	1.0 E+15	4.0 E+14
Maximum Fast Flux, n/cm^2-s	1.2 E+14	6.0 E+13	1.2 E+15	5.0 E+14	2.0 E+14
Irradiation capabilities	3 in-core positions (loops, instrumented test rigs, etc.) 2 graphite vertical reflector positions 9 channels 9 beam ports 2 rabbits	1 central flux trap 12 reflector positions 2 rabbits 3 bulk pool channels	37 in-core positions 42 reflector positions 4 beams; 12 neutron scattering instruments 3 rabbits	9 large flux traps (water loops installed in 5 positions) 36 reflector positions 1 rabbit	1 central flux trap 7 reflector positions, 2 rabbits
Other facilities	Co-located small hot cells /hot boxes with limited PIE capabilities; Neutron activation analysis	Radioisotope production, hot cells, processing	Gamma irradiation hot cells	Limited co-located hot cells but several large hot cell facilities located at nearby INL sites.	Extensive neutron detection instrumentation.

Three of these facilities are located on government sites, and the institutional barriers that are associated with access to federal facilities can complicate their use. The MITR is the only high performance university research reactor capable of performing in-core fuel and materials irradiations at prototypic light water reactor (LWR) flux conditions, and it is one of only three US MTRs capable of testing within pressurized loops containing water at pressurized water reactor (PWR) conditions, and the only US MTR that can test boiling water in its loops. The unique MITR design and knowledgeable NRL staff have established a long history of successfully performing instrumented fuels and materials irradiations at a significantly lower cost than is possible at other high performance US MTRs. There are also several distinguishing features that make the MITR unique, including the ability to perform loop testing with boiling water and the ability to train students to conduct such irradiations and associated post-irradiation examinations. Taken together, these attributes make the MITR a unique facility.

History of the MIT Reactor

The original reactor, the MITR-I, which operated from 1958 to 1973, was cooled, moderated, and reflected by heavy water. As such, its core was relatively large and its power density low. Also, there was significant tritium production which limited access to the core. The designers envisioned that the reactor would be used for experiments that were external to the core and the intended applications were neutron physics and scattering, medical research, and neutron activation analysis. To this end, more than a dozen beam ports were built around the core, a medical facility was constructed below the core, and several pneumatic tubes were installed to enable the irradiation of samples at the core periphery. There was also a blanket test facility in which assemblies of fuel rods for advanced reactor designs could be configured. Major experiments included:

- Neutron physics including refinement of charge neutrality measurements.
- Reactor physics of D_2O and H_2O moderated reactors.
- Fast breeder blanket neutronic studies.
- Boron neutron capture therapy using thermal neutrons.
- Use of neutron activation analysis for a variety of topics including mineral uptake in the human body using stable isotopes, analysis of meteorites and lava flows, and identification of the origin of air pollutants.

In addition to these ex-core activities, there was one in-core experiment performed on the MITR-I. This was an in-core loop for the evaluation of radiation effects on organic coolants.

In 1974 the MITR-II was put into operation. It was cooled and moderated by light water and hence had a small compact core. Major advantages were that its neutron flux was similar to that of large power reactors in terms of magnitude and spectrum, that its core was accessible (no tritium hazard), and that there was room for three simultaneous in-core experiments. The table in Appendix C is a list of the major in-core experiments conducted in the MITR-II.

The first major in-core experiment in the MITR-II was a loop that replicated conditions (temperature, pressure, radiation fields, heat flux, and certain flow parameters) in a PWR. This pressurized coolant corrosion loop was used to evaluate the effect of pH and other parameters on the production rate of corrosion products which became activated and generated high radiation dose rates throughout the primary system piping. The objective was to reduce radiation dose to maintenance workers on PWRs. The loop was state-of-the-art. No other university, or for that matter government research reactor, had such a capability. The next experiment was a boiling coolant corrosion loop which was utilized to study methods to reduce the carryover of short-lived radioactive isotopes from the boiling coolant to the turbine areas. Again, the objective was to reduce exposure to plant workers. The ability of the MITR to allow boiling coolant in its loops makes it the only US MTR that can perform such tests. The focus of the research then shifted emphasis from reactor systems to nuclear materials, and loops were built to investigate irradiation effects and corrosion mechanisms. These were often funded by the Electric Power Research Institute (EPRI) or by various Japanese utilities. They included:

- Irradiation-assisted stress corrosion cracking to study crack initiation and propagation under conditions of load as well as radiation and heat flux in BWR materials.
- Testing of in-vessel detectors related to measuring the oxygen potential in BWR primary coolant.
- Shadow corrosion in which materials that were separated from each other in a reactor vessel nevertheless exhibited a coupled corrosive effect in which the shadow of one component would appear on the other.

Other areas of research that were performed within the reactor's core involved the evaluation of new materials, both clad and fuel. To this end, the MITR received a license amendment from the Nuclear Regulatory Commission in 2003 that allowed the irradiation of small quantities of fuel (up to 100 grams of U-235) in the reactor. As a result, the in-core research program would ultimately become the main mission of the NRL as described in Section 3 below.

In parallel with these in-core experiments, ex-core uses of the reactor's neutrons continued. Major efforts involved verification of the linearity of the wave equation (neutron physics), design and construction of a fission converter for treatment of brain tumors using epithermal neutron beams, neutron activation analysis of pollution sources, and the closed-loop digital control of reactor power for spacecraft reactors. While these particular programs are no longer in place, the experience from them has led to a number of diverse initiatives which will be described in sections to follow.

Educational Impact

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

Use of the Reactor for Laboratory Courses. The Physics Department conducts one of the Junior Lab's experiments using the reactor's neutron chopper facility. The Department of Nuclear Science and Engineering either uses or has used the reactor as part of several courses, including ones on Reactor Design and Operation, Radiation Detection, and Reactor Dynamics.

Performance of Thesis Research at all Degree Levels. Since the 1950s, cutting edge research utilizing the MITR has been conducted by faculty, students, and scientists from MIT as well as other institutions. Students especially enjoy doing thesis work on the reactor because they have the opportunity to combine 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 utilized the reactor for their research. Some of the more exciting topics include the design and construction of the in-core loops, performance of experiments using those loops, design of the fission converter and characterization of its beam, digital closed-loop control of the reactor, investigation of the linearity of the wave equation, and a variety of geochemical studies, including analysis of meteorites and air pollution sources.

Training of Undergraduates to Operate the Reactor. More than 300 students have participated in the NRL's Reactor Operator Training Program. Every year, 4-6 undergraduates are hired to work part-time as licensed reactor operators. Individuals from all majors are welcome to apply. Selected students are placed in a rigorous training program that covers reactor systems, emergency planning, radiation health physics, reactor dynamics, etc. They then take a two-day exam administered by the US Nuclear Regulatory Commission and, if successful, are employed 10-15 hours per week to operate the reactor. Once they have a year of experience, they may take a second exam to obtain a senior reactor operator license. Many of our student operators tell us that the experience of working at the MITR was one of the highlights of their time at MIT.

Public Outreach. The NRL offers tours of the facility together with an introductory lecture on the reactor for high school students, local area colleges, and MIT parents/alumni.

3. The Current MITR In-core Research Program

In 2003, with the fuel irradiation license amendment in hand, the experimental strategy for the in-core loops greatly expanded. The first fueled experiment designed and irradiated in the MITR supported annular fuel development. Small samples of internally and externally cooled annular fuel rodlets with a vibration-packed fuel matrix were tested in the period 2003 to 2004 in the MITR to determine fission gas release rates and fuel dimensional and structural changes during irradiation under PWR conditions. The purpose of this innovative fuel design was to enable reduced peak fuel temperature and to achieve a significant increase of core power density while improving safety margins in commercial power reactors. Development of the annular fuel concept has been pursued in S. Korea and has reached the stage of readiness as a lead assembly test in a power reactor.

In 2005-2006, a new high-temperature irradiation facility was designed to achieve temperatures up to 1400°C in an inert gas atmosphere. Several sample types including SiC composite materials, matrix graphite for the high temperature gas reactor fuel compacts, and coated fuel particles (using ZrO_2 as a surrogate for UO_2), were irradiated in this first-of-its-kind facility.

In 2008, the MITR became part of the Advanced Test Reactor National Scientific User Facility (ATR-NSUF) operated by DOE's Idaho National Laboratory (INL), which is charged with performing fuel and advanced materials irradiation experiments and PIE crucial to existing and future generation reactors. One objective of NRL's research is to help accelerate DOE's fuel program by investigating options that would benefit light-water reactors (dominant in the world today), such as reduced corrosion of present-day cladding when used with high burnup fuel and improved fuel response to overheating accidents. This program is a key element in the DOE effort to improve the nuclear fuel cycle. It aims to develop fuel that is better able to withstand high power density, allow increased energy extraction during operation, and mitigate, if not eliminate, chemical reactions between its cladding and steam under accident conditions. Extensive testing of the various metallic and ceramic fuel options is needed to down-select the best options for full-scale qualification tests.

In the last decade, as shown in the table in Appendix C, demand for MITR's in-core experiment facilities has increased with a combination of ATR-NSUF funding, DOE grants, and direct funding through a variety of industrial entities (generally, the ultimate funding source is the DOE). Three types of in-core facilities have been demonstrated: a pressurized water loop, a general purpose inert gas irradiation facility, known as the in-core sample assembly (ICSA) that can operate up to 850 °C, and special-purpose in-core facilities that are designed to extend the in-core experimental envelope beyond what is achievable in the more standardized facilities such as the 1400 °C very high temperature irradiation and fuel irradiation experiments. A number of recent experimental programs are described in detail below.

Uranium-Zirconium Hydride Fuel

Hydride fuels (uranium–zirconium hydride) have been successfully utilized in many research and test reactors as well as in space programs. The added presence of hydrogen in the fuel provides neutron moderation within the fuel in addition to the traditional moderator. This approach allows for reducing coolant volume, effectively increasing power density, and possessing thermally-induced hydrogen up-scattering that accompanies Doppler feedback, a safety feature that has been exploited in TRIGA research reactors for several decades. Hydride fuel has also been proposed as an optimized matrix for the deep burn of plutonium and minor actinides. The proposed fuel could achieve TRU (transuranic elements) destruction fractions as high as twice that realized with MOX (mixed oxide) fuels. Of additional interest is the fuel-cladding interaction, and in particular the possible transport of hydrogen out of the fuel and into the cladding, which may cause cladding degradation during irradiation. To attempt to reduce this interaction, the gap between the fuel and cladding is filled with liquid metal (in place of traditional helium cover gas), which provides an excellent thermal bond and possible chemical protection to the cladding inner surface. The cladding surfaces are also pre-oxidized to help slow hydrogen diffusion. The proposed hydride fuel design, which was selected for this ATR-NSUF project, also incorporates a lead-bismuth eutectic bond that increases the gap thermal conductivity by two orders of magnitude and enables a higher power density for LWR applications.

The ATR-NSUF funded the irradiation of hydride fuel at LWR temperatures to obtain data on irradiation performance. The fuel rod design and experiment conditions were designed to simulate typical LWR operating conditions (geometry, flux, and temperature). Effective fuel thermal conductivity as a function of burnup was determined by real-time thermocouple measurements. Irradiation of three hydride fuel rodlets started in March 2011 and was completed in December of that year. Non-destructive examinations were conducted at MIT. Irradiated fuel samples were shipped to Pacific Northwest National Laboratory for destructive tests.

EPRI Silicon Carbide Composite Channel Box Project (BSiC)

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

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

This research is funded by the DOE Nuclear Engineering Enabling Technology (NEET) program. Irradiation started in August 2013 and continued until December 2013. During a planned interim examination, it was determined that the samples had experienced very high corrosion rates. The irradiation is temporarily on hold while full PIE is performed and additional development work on coated samples with higher corrosion resistance is carried out.

Westinghouse Accident Tolerant Fuel Project

As noted above, the hydrogen combustion events observed during the events at Fukushima have also created very strong interest in finding alternatives to the currently used Zircaloy™ alloy for fuel cladding. This interest is driven by the problematic behavior of Zircaloy™ in high-temperature steam, where rapid reactions can occur with generation of hydrogen and heat, compromising the ability of the cladding to maintain a "coolable geometry" for the fuel pins.

Westinghouse is leading a multi-institutional effort to design and demonstrate an advanced fuel concept with improved post-accident behavior that can be rapidly commercialized. The effort involves changes to both the fuel meat and the cladding, with MIT-NRL's contribution being to irradiation test candidate cladding materials. The primary replacement clad candidate is multi-layer SiC/SiC composite tubing which is an evolution from tubing previously tested in the MITR. Large-scale manufacture and bonding of this tubing may be an obstacle to near-term commercial deployment, so alternate clad concepts based on Zircaloy™ tubes coated with MAX-phases or glassy iron based materials will also be tested. A set of tube samples manufactured by General Atomics was installed in the MITR water loop in April 2014. They are operating at 280 °C and approximately 100 bar in PWR coolant chemistry. Weight loss of the samples will be the primary post-irradiation evaluation (PIE), but dimensional changes, surface morphology by SEM and mechanical property evaluation by burst testing will also be part of the PIE. A set of coated Zircaloy™ coupon specimens is also being irradiated. In a complementary project under this program, faculty in the MIT Nuclear Science and Engineering department are evaluating the behavior of the tube samples in out-of-pile high-temperature steam tests.

This research is funded by DOE Nuclear Engineering Enabling Technology (NEET) Program. Irradiation is scheduled to last for 230 full power days with several interim examinations. The first interim examination was completed in October 2014. Some of the tube samples were replaced by samples having one end sealed to test the sealing methodology under reactor conditions. The coupon specimens were replaced by new coupon samples produced by 3-D printing. This material is being investigated for application in 3-D printed fuel spacer grids that could be designed to have very low pressure drops and favorable vibration characteristics.

Ultrasonic Transducers Irradiation Test (ULTRA)

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 (DOE-NE) research programs require that the long-duration radiation performance of fuel and materials be demonstrated. Such demonstrations desire enhanced real-time in-core instrumentation to detect microstructural changes under irradiation conditions with unprecedented accuracy and resolution. Ultrasound-based sensors, which can be used to measure temperature, thermal conductivity, gas pressure and composition, and microstructural changes, offer the potential to meet these instrumentation needs. In addition, several DOE-NE research programs have been investigating ultrasonic sensors for under-sodium viewing and in-service inspection measurements near the core. However, it is necessary to demonstrate the survivability of ultrasonic transducers in high flux irradiation environments before ultrasound-based sensors can be deployed in such conditions.

The ATR-NSUF has funded the ULTRA research program to (1) select candidate transducer materials; (2) perform high temperature irradiation tests in the MITR; and (3) conduct post-irradiation evaluation. The instrumented lead test is providing real-time data related to magnetostrictive and piezoelectric transducer survivability in a well-instrumented MITR irradiation test, which includes sensors for measuring temperature, thermal flux, and gamma levels. MIT-NRL staff has worked with INL staff, PSU researchers and other collaborators in experiment assembly design since March 2013. This irradiation, which started in February 2014, is conducted in the ICSA under an inert gas environment up to 450°C. To date, the transducers have received a fluence of 5×10^{20} n/cm^2, making this the first test to evaluate the performance of various types of piezoelectric and magnetostrictive transducers at such high fluences.

FHR Materials and Fluoride Salt Irradiation

In 2012 MIT, the University of California at Berkeley (UCB) and the University of Wisconsin (UW) initiated a project to develop the path forward to build a test reactor and ultimately a commercial fluoride salt-cooled high-temperature reactor (FHR). The project is funded by the DOE Nuclear Energy University Program to support development of advanced reactors and is led by MIT. Initially funded for three years, it was recently extended for an additional three years.

The FHR is a new reactor concept that combines high-temperature graphite-matrix coated particle fuel developed for high-temperature gas-cooled reactors (fuel failure temperature > 1650°C), liquid salts developed for cooling molten salt reactors (boiling point > 1400°C), safety systems originating from sodium fast reactors, and Brayton power cycle technology. This combination of existing technologies may enable the development of a large power reactor in which catastrophic accidents such as the Fukushima accident would not be credible, because the FHR fuel and coolant combination would 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 and reactor fuel/materials in a radiation environment. Salts and materials have been irradiated at temperature (700°C) in the MITR to determine suitability of candidate structural materials and surrogate fuel particles. The tests have multiple goals; however, the primary goals are to evaluate whether salt coolant may attack the FHR fuel and materials via radiation-enhanced corrosion and to obtain experimental data for tritium generation and transport.

The first in-core irradiation was a capsule irradiation consisting of the fluoride salt, SiC, nuclear grade graphite, Hastelloy-N, and SS316 samples. The experiment was installed in the reactor in mid-September of 2013 and ran for 1000 hours continuously, with temperature controlled at 700±3°C. A second irradiation in a dedicated facility was designed and fabricated to accommodate a larger volume of salt and materials, and was completed in 2014.

In-Core Crack Growth Measurement Facility

Crack growth of samples irradiated in loop tests in US MTRs are historically evaluated out-of-pile. Idaho National Laboratory (INL) has initiated a program to develop a technique to perform in-pile crack growth measurements using the direct-current potential-drop technique with active loading provided by a bellows assembly similar to those used at the Halden Boiling Water Reactor (HBWR) in Norway. As part of an INL funded project, NRL and INL staff have jointly developed a crack-growth test rig design suitable for testing in the ATR and MITR. The design will be based on existing technologies used at the HBWR, but specific components are modified to meet anticipated ATR-NSUF user requirements. MIT is in the process of fabricating a prototype crack-growth test rig. The first demonstration of this prototype is scheduled to begin testing in MITR's LWR loop in April 2015.

Future Outlook

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

A new national research reactor facility is an option under consideration by DOE to expand domestic fuel and materials testing capabilities. However, even if a new research reactor project went forward, it would not become available for more than a decade. Therefore the MITR will remain a critical asset for at least the remainder of its license lifetime (2031).

Finding 1: *The MITR is a unique and irreplaceable national capability. It is especially valuable given (1) the strength of its in-core irradiation program; (2) the limited capabilities for such irradiation evaluations in the US; and (3) the ability to provide students with in-core experimental research experiences that are not available elsewhere. Furthermore, the MITR has an experienced and knowledgeable staff and, relative to reactor facilities at DOE laboratories, is more flexible and more easily accessible, and can provide services at lower cost.*

4. Upgrading the MITR's Capabilities

The capability of the NRL to design and execute proof of principle experiments more quickly than at other test reactors has been demonstrated over the years. This has increased the demand for in-core irradiations of proposed new materials for both nuclear fuel and reactor structural materials at the MITR. This is likely to increase in the future due to the strong desire of power reactor owners to extend the operating licenses of existing LWRs. In addition, if efforts to reduce carbon emissions intensify in the coming years, additional new nuclear plants may be in demand.

Furthermore, the MITR capability is not confined to the testing of water cooled reactor technology and can, with properly designed in-core experiment facilities, investigate features important to reactors based on coolants other than water. Some advanced reactor designs provide higher coolant temperatures, which can improve economics through higher power cycle efficiency or bring nuclear energy closer to industrial applications by providing high-temperature process heat. A gas or salt coolant is able to deliver temperatures of 700 °C or higher. Liquid metal cooled reactors may be able to deliver higher temperature coolants than water-cooled reactors, but present designs are likely to be limited to the range of 500 °C. However, liquid-metal cooled fast reactors are better able to fission long-lived higher actinides, such as plutonium and americium. The MITR can contribute much to these advanced reactor studies. In fact, the MITR has already been used to study technology for advanced coolant concepts including (1) the response of TRISO particle simulant fuel to high temperatures, (2) the corrosion of structural materials in contact with molten salt, (3) the behavior of high-temperature materials such as SiC composite, graphite, MAXphases, (4) the release of polonium from neutron activated lead-bismuth coolant and (5) radiation effects on instrumentation in an inert gas environment. Hence, there are many opportunities to utilize in-core loops where the MITR will be a vital contributor in the development of nuclear energy technology options for the future.

Given this strong interest in the MITR capability, it is essential to make sure that this unique facility is most effectively utilized. It is evident that the research impact of the NRL could be significantly enhanced through specific incremental improvements, described below.

Enhanced Ancillary Facilities

Although the ULTRA test includes self-powered gamma detectors (SPGDs) and self-powered neutron detectors (SPNDs), temperature is the only in-core parameter that is typically monitored in real-time as part of the standard experimental facilities at the MITR. Similar to what is used in the Halden reactor and what is being developed for the French Atomic Energy Agency's (CEA) Jules Horowitz Reactor, standardized test rigs with radiation-hardened, high-temperature sensors are important for expanding the capabilities of the MITR experimental program. The use of sensors that provide real-time data to characterize changes in test and sample conditions eliminates limitations associated with only having post-irradiation data and maximize the scientific return on each irradiation test. In-core radiation detectors, such as SPGDs, SPNDs, gamma thermometers, CEA-developed miniaturized fission chambers, and INL-developed micropocket fission detectors provide the ability to monitor local power changes not captured by the reactor operations instrumentation located outside the core tank. The

INL-developed transient hot-wire probe permits the continuous measurement of the evolution of fuel or material conductivity during irradiation. Direct-current potential-drop (DCPD), linear variable differential transformer (LVDT), and diameter gauge instrumentation allow in-situ monitoring of crack growth, electrical resistivity, elongation/strain, pressure, and changes in diameter in the confined and harsh in-core environment[1].

The MITR has demonstrated real-time monitoring of in-core ultrasonic transducers. Ongoing INL and CEA efforts to develop and deploy ultrasound-based sensors using these transducers can be used to monitor changes in specimen geometry (e.g., swelling, thermal expansion) as well as the composition or pressure of gas spaces (e.g., fuel plena). In addition, the use of ultrasonic thermometers allows a temperature profile to be measured real-time by a single small diameter (< 1 mm) probe. Electrochemical potential probes, such as the Pt and Fe/Fe_3O_4 sensors deployed at the Halden reactor would permit in-water measurement of corrosion potentials that can exist only in the in-core radiolytic environment and cannot be otherwise captured, and the establishment of driven galvanic couples. These probes, along with the development of complimentary cabling systems at the MITR, could function as reference electrodes and permit measurement of on-line oxidation potentials for future specimens. As noted above, the Halden reactor is using such sensors in standardized test rigs, and CEA is developing standardized test rigs with such sensors. For improved testing efficiencies, it may be worthwhile to initiate a joint fuel vendor/MIT effort to develop well-instrumented standardized test rigs for fuel irradiations at the MITR.

Out-of-core instrumentation can also be improved to benefit the control of irradiations, facility safety, and experimental data collection. For PWR loops, reliable high-pressure, high-temperature flow rate monitoring is needed. Water chemistry monitoring equipment such as dissolved O_2 and H_2 sensors, pH, and electrical resistivity should be upgraded to take advantage of enhanced resolution and reliability of modern measurement techniques. Introduction of additional pressure, flow, and radiation sensors on all experiments would greatly enhance operational awareness of the facility status, provide better warning and troubleshooting capability in unanticipated situations, and help protect both experiments and personnel. To support all of this enhanced sensing capacity, the data acquisition and control hardware and software must be updated to modern, fully-supported configurations. This increases the signal capacity, improves reliability and security, and improves the overall conduct of irradiations enabling the production of higher-quality data.

The MITR post-irradiation examination facilities would benefit from a number of new investments. The hot-cell and hot-box facilities are critical to the handling and disassembly of in-core irradiation capsules. Replacement or repair of hot cells and manipulators would greatly improve the PIE workflow and permit better handling of delicate specimens and equipment and reduce operator fatigue. Because most-often requested PIE measurements are difficult or impossible with MITR facilities, customers are forced to either do without critical post-irradiation data or pay expensive transportation costs to other, more expensive, facilities to obtain such data. Dimensional measurement equipment, mass balances, and optical imaging (e.g., macro cameras and digital optical microscopes) equipment dedicated for use with highly-radioactive or contaminated specimens would fill out a basic yet critical set of capabilities. In addition, a basic scanning electron microscope with EDS capability, along with the cutting, mounting, and polishing equipment, all in a shielded location, would be a major addition to the MITR PIE portfolio as this is currently much desired but rarely feasible with existing on-campus facilities. Also, an x-ray fluorescence system (x-ray source, spectrometer, and XRF analytical software) would add the ability to identify elemental composition of both as-received and irradiated materials, and to measure low-energy x-ray sources. This is particularly important for identifying trace impurities for QA purposes, as well as analyzing thin surface films.

A Sub-Critical Facility

It is possible to modify the existing fission converter to implement a unique sub-critical facility relatively quickly and at modest cost to support advanced reactor development efforts and potential fusion blanket concepts. This novel concept will allow the expansion of an in-core experimental facility, typically constrained to 2 inches in diameter, to a much larger test volume more than 3 feet in diameter, and will permit a large, integrated test facility. Such a facility can support multiple research and development programs related to computer benchmarking, fuel development, materials corrosion, instrumentation and control, coolant chemistry, etc. As an example, consider the benefit to the development of the FHR, which is currently the subject of the above-described active research program. No FHR has ever been built; thus, a test reactor has been proposed as the next step before a commercial FHR can be deployed. An FHR test reactor is currently being planned in China.

In-pile loops with coolants, materials and fuels in test reactors have been the conventional approach commonly adopted in the nuclear industry for fuel and materials irradiation tests. It now appears possible to use a sub-critical facility, such as that proposed for the MITR, to go beyond component tests and perform an integrated FHR system demonstration to address the important technical challenges of tritium generation and control and materials corrosion in the combined salt and radiation environment. A feasibility study shows that a sub-critical FHR system driven by the MITR could produce about 20% of the power density of a reference FHR, and a similar neutron energy spectrum.[2] Such a facility is an ideal candidate for demonstrating the integrated effect of an FHR system with much lower capital costs than a test reactor, and it offers unique features such as representative neutronic characteristics, coupled thermal-hydraulics and radiolysis, and a large and flexible test volume compared to an in-pile loop.

The NRL is currently the only facility in the US that has dedicated facilities and a demonstrated track record for conducting FHR materials irradiation tests. A sub-critical facility would enable MIT and the US to maintain a leadership position in FHR research. With a versatile design, this facility would also allow internal component change-out and replacement to study other fuel designs (e.g., pebble fuel) or coolant options (e.g., NaF-ZrF4), and potentially also fusion blankets that utilize fluoride salt for breeding tritium.

A Digital Control System

In order to maintain operational viability in the coming years, it is imperative that the existing reactor infrastructure be updated, particularly the control room instrumentation. An upgrade to digital instrumentation and controls would not only improve reliability, but could also serve as a showcase for human factors engineering as well as for Nuclear Regulatory

Commission licensing of digital instrumentation. A simulator should also be considered for training MITR operators and MIT students. Such a system for the reactor would improve reactor performance, reliability, safety; and a companion simulator would greatly improve operator training.

Conversion to Low Enrichment Uranium

The Committee also heard about the status of the effort to convert the MITR from high-enrichment uranium (HEU) fuel to low-enrichment uranium (LEU) fuel. MIT seeks to carry out the first conversion among the remaining five high-performance reactors in the US, adopting a special high-density LEU fuel 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 the Global Threat Reduction Initiative to eliminate weapons-grade HEU from civilian use world-wide.

Impact on the Nuclear Technology Community

The advanced fission and fusion technology communities are charged with developing and qualifying the technologies necessary to turn fission or fusion reaction energy into useful power. Most recently, these advanced nuclear systems have been focused on higher temperatures (400 to 900°C) than existing light water fission reactor systems to improve overall energy conversion efficiency. Such systems include high temperature gas-cooled reactors, liquid metal fast reactors, molten salt reactors, and corresponding systems employed as fusion reactor blankets. These fission and fusion systems share many technical issues that require testing involving an interdisciplinary combination of materials, chemical and nuclear technologies to resolve.

The proposed upgrades to the MITR will increase its flexibility and capability to conduct irradiation experiments that are necessary to qualify these key fission and fusion technology concepts. The goals of the upgrades are not to increase the neutron flux since there are current DOE facilities that provide very high flux levels. Instead, by strategically improving testing capabilities, the MITR will meet the unique needs of the fission and fusion technology communities in a more cost-effective manner than if they were implemented in the DOE test reactor facilities. Improved in-pile instrumentation can track the in-situ behavior of the test article (usually a unit cell of a fission core or fusion blanket), which can be used to obtain valuable experimental data for computer code validation. The proposed sub-critical facility would offer unique integrated testing capabilities to expand the existing in-core experiment program. Many of the technical issues associated with high temperature fission reactor and fusion blanket technologies require testing in a loop at prototypical pressures and temperatures in the presence of a neutron flux. A properly scaled test loop in the sub-critical facility would provide a seminal capability to study chemistry/corrosion control and tritium permeation/control in a neutron environment, which are key feasibility issues for these systems. This type of loop would have immediate value for current molten salt reactor designs (and, with modest changes in the materials, the corresponding molten salt fusion blanket). In the longer term, a liquid metal loop could support corrosion studies for a lead-cooled fast reactor or a lead-lithium fusion blanket. This capability would build upon the successful water chemistry/corrosion loop that has been operating in the MITR for decades to support light water reactor technology.

Finding 2: *Incremental improvements to the MITR could enhance its research impact significantly, both in relation to the existing LWR fleet and to US and international advanced reactor development efforts. There is a mature plan for conversion to LEU fuel with potential for US and world leadership.*

Possible New or Improved Core

Beyond incremental improvements, there is the possibility of major modifications or rebuilding of the reactor core to improve performance. This was done most recently in 1973-4 with the conversion to light water coolant/moderator and the addition of the heavy water reflector. At present, there is a global shortage of fast neutrons; and there is the potential for new MITR designs to achieve higher fast fluxes. However, an increase of at most a factor of 2-3 could be achieved. While this could accelerate the identification of neutron fluence effects, it would also reduce the number and types of experiments that could be performed simultaneously. Therefore, a major redesign of the core to achieve higher fast fluxes does not appear to be justified. However, a power increase would enhance utilization capabilities. The infrastructure necessary for such a power increase should be determined. Eventual conversion of the MITR to LEU fuel is not expected to adversely affect utilization as long as the power level is increased to maintain flux levels.

Finding 3: *Major upgrades to or replacement of the MITR core would be costly and time-consuming, and the benefits would be modest. Therefore, undertaking a major core replacement or modification project would not be justified.*

5. A Broader Vision for the NRL

Materials under Extreme Radiation Conditions

The Committee heard a set of exciting presentations on topics related to one of the key areas in nuclear research, namely the study of materials under extreme radiation conditions. While the in-core research program has established the NRL as a major national asset for simulating LWR conditions and for conducting experiments to support advanced reactor design, there are needs in both fission and fusion research, as well as in other areas such as space exploration, where materials must be developed to withstand much higher radiation doses. The MIT Nuclear Science and Engineering Department has identified the science and engineering of materials in extreme radiation environments as a major focus of its new educational and research strategy, and NSE is building a strong faculty in this area.

Three major technology advances were presented which, if implemented together with proposed MITR enhancements and integrated with the in-core irradiation facilities, could create a world-leading center for radiation materials science that would be unequaled even by large, single-modality DOE user facilities, and would likely cost far less.

Advanced Superconducting Proton Cyclotron Technology. This technology, developed in collaboration between the Department on Nuclear Science and Engineering (NSE) and the MIT Plasma Science and Fusion Center (PSFC), will enable compact and cost effective cyclotrons to implant helium (a major factor in radiation damage) and irradiate with protons in bulk (a few mm^3) to levels of up to 100 displacements per atom (dpa) or more. For comparison, it takes about a year in the core of the MITR to reach one dpa. Materials in fusion reactors and some advanced fission reactors are expected to experience radiation damage of 200 dpa or more. A key feature of the system would be independent control of the helium/dpa ratio which would allow simulation of radiation damage environments ranging from fission to fusion.

Evidence was presented that a new, unique high-energy based radiation damage facility could be developed to serve the medical, fission, and fusion needs at a reasonable cost. This would enable accelerated (but controlled) damage rates on macroscopic samples, and as mentioned above, independent control of bulk He per displacement, and elevated, variable and controlled sample temperature. A particle accelerator delivering protons of energy up to 50 MeV with intensities up to 1 mA and with helium and ion capabilities would meet all requirements. An innovative gas cooling target chamber would also be required. The achievement of 50 MeV energies (for protons) would allow for a uniform damage distribution through practical sample dimensions with the Bragg peak energy dissipated in a helium beam stop. This is unlike that for lower energy system where the Bragg peak is absorbed within the sample leading to very non-uniform damage distributions.

Since 2002, the PSFC Technology and Engineering Division/NSE team has pursued the development of compact, superconducting cyclotrons. These are typically about an order of magnitude lighter and more compact than cyclotrons using normal conducting magnets. They have been realized for beam radiotherapy, isotope production, and nuclear materials detection. Typically, they have been based on cold iron and cryo-cooled NbTi coils with B_{max} = 5 Tesla, eliminating the need for liquid helium. Recently, the ironless superconducting concept has been developed. A key feature of the superconducting cyclotron concept is that the overall physical size of the facility can be reduced to university-manageable.

Another key feature of the superconducting cyclotron system concept has been the development of a unique target & chamber system that makes use of helium gas-jet cooling for the sample as well as helium as the beam stop. This concept allows for much the much higher heat loading that would be needed for the higher energy and current beams. The target chamber is also designed to allow active loading of samples-another unique feature.

The committee was convinced that the compact, superconducting cyclotron technology and expertise at PSFC is well matched to the accelerator requirements of a new radiation damage facility. The detailed configuration of multiple cyclotrons to enable the optimal facility should be pursued with priority.

Further, a cyclotron delivering proton beams as specified above would be of great utility to experimental particle physicists in the Laboratory for Nuclear Science who are interested in employing such an accelerator technology to generate neutrino beams for fundamental physics experiments. A new cyclotron at the MIT campus would likely attract an R&D effort funded through LNS focused on neutrino physics.

Compact High-Brilliance X-ray Source Technology. NRL staff scientists presented mature designs for compact and inexpensive x-ray source technology that would allow in-situ time-dependent characterization of these samples as damage is produced in the proton beam. X-ray scattering and imaging methods heretofore requiring the high brightness beams of large synchrotron facilities could be implemented locally, enabling in-situ studies for the first time.

Compact x-ray sources offer attractive capabilities at only a small fraction of the cost and size of large national user facilities (e.g. Advanced Photon Source, National Synchrotron Light Source II). They are complementary to such national facilities, with the biggest advantage being the flexibility derived from location at the NRL. This flexibility is an advantage for two reasons. First is the proximity of the facility to researchers, i.e., the researchers do not have to travel to national facilities on a strict schedule that is sometimes a hindrance to the type of experiments that can be done. Second, and more importantly, such proximity enables the researchers to design and test complex experiments, such as the proposed in-situ proton irradiation experiments, and it enables much more flexibility in schedule and beamtime than at a national facility.

The system being designed and proposed by NRL is based on inverse-Compton scattering (ICS) with a high repetition rate linac system. The ICS source[3] consists of an electron linear accelerator (linac) and high-power laser each producing short pulses that collide head-on to generate intense x-rays. The linac and photoinjector RF structures were designed in collaboration with SLAC, building on the success of the technology behind their x-ray free-electron laser known as the linac coherent light source (LCLS). At the exit of the linac, short pico-second-long bunches of electrons emerge at energies in the range 15-50 MeV to collide with 100 mJ ps pulses of intense laser light at wavelengths between 0.5 and 1 micron. The laser systems employ cryogenically cooled amplifier technology developed at MIT Lincoln Laboratory. The resulting monochromatic x-ray pulses can be tuned over a wide range of photon energies from a few to 100 keV. This tuning is accomplished by varying the electron energy over the available range. The high energies are particularly valuable for studying nuclear materials because they allow penetration into bulk samples of heavy metals, and they allow access to the K absorption edges of Uranium and other actinides.

While large synchrotrons have higher flux and brightness in the range up to 30 keV, their spectrum falls off rapidly at the high energies so useful to nuclear materials. It is expected that the great flexibility and local availability of the ICS sources will more than compensate for the lower flux. All other laboratory sources are many orders of magnitude weaker than the proposed source and cannot support the advanced x-ray methods enabled by synchrotron and ICS sources. The opportunity to train students and staff to design and carry out sophisticated x-ray materials studies on campus without the barriers of travel and schedule, and to perform in-situ studies of radiation damage processes present unique opportunities that cannot be matched by other institutions or the large synchrotrons.

High Performance Neutron Optics. This technology, also developed at the NRL, could make the thermal neutron beams from the reactor up to 100 times more effective for neutron scattering and imaging experiments to complement the x-ray techniques. Again, in-situ time-dependent studies could be conducted, since the neutron beams could be directed toward samples as they were being irradiated by the helium and proton beams.

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

Currently, neutron imaging is done using the simplest possible optical design, that of pinhole cameras. The image of a neutron source is projected through a small aperture onto a detector. These instruments use apertures, which are much smaller than neutron sources, in order to achieve spatial resolution of about 10 microns. Given the low brightness of the neutron sources, such pinhole cameras are extremely inefficient in terms of signal rate and signal-to-noise ratio. State-of-the-art neutron imaging instruments require tens of minutes for one high-resolution image and tens of hours for a full tomographic set. In addition, the resolution is limited by detector pixels, which cannot be made smaller than a few microns. The Wolter focusing optics offer a qualitatively new way of implementing neutron radiography. Wolter mirrors play the role of the image-forming lenses in microscopes. NRL researchers and collaborators at NIST, NASA, and ORNL have recently demonstrated mirrors-based neutron imaging.[4] Based on these demonstrations, NIST is building a novel mirrors-based neutron imaging facility. Utilizing the high collection efficiency and magnification power of the optics the goal is to achieve spatial resolution approaching 1 micron, while significantly reducing the time for tomographic imaging. Based on this experience, it is expected that such a neutron microscope can be built at NRL for in-situ measurement of radiation damage.

Small-angle neutron scattering (SANS) is another neutron method of great importance for studying soft and hard materials, including irradiated nuclear materials. Several groups at MIT are using SANS, which is only available at two national facilities in the US (ORNL and NIST). Standard SANS instruments are very long (10 to 30 m), because they are also designed as pinhole cameras. The use of Wolter optics will allow for building a compact instrument at NRL with high signal rate, comparable to that of larger reactors.[5] Therefore, such a facility will have a high impact within the proposed NRL program, and the Wolter concept has the potential to transform neutron scattering and imaging much more broadly.

Neutron and x-ray methods are known to be complementary in terms of sensitivity to structural details; and together, they constitute the most important probes of the structure of bulk materials. Having an integrated capability to irradiate materials in the core of a high-performance reactor, or with intense accelerator beams, and interrogate those materials with high-brightness x-ray and neutron beams is unprecedented and transformational for such studies. Having such compact x-ray and neutron characterization capabilities at MIT would provide the opportunity to establish thought leadership and capability leadership in the field of characterization, including physics, chemistry, biology and materials sciences.

Impact on the Nuclear Materials Community

The nuclear materials community is focused on studying the response of materials to radiation damage induced by neutrons. For light water reactors, typical damage rates are between 1 and 5 dpa. However for more advanced fission reactor systems like fast reactors, dpa levels of fuel cladding and structural materials are in the range of 100 to 200 dpa. For fusion reactor systems, damage levels of 200 to 400 dpa are greater because the fast flux is higher. In addition, the higher peak neutron energy for fusion (14 MeV compared to 2 MeV in fission systems) causes nuclear reactions that produce helium and hydrogen in the material lattice. Therefore, the proposed cyclotron facility, which can produce such high dpa rates and deliver both protons and helium, is very well matched to these materials challenges.

The nuclear materials community has traditionally argued that a fast test reactor is needed to obtain prototypic neutron energy levels to study and eventually qualify fast reactor cladding and structural materials. Fast test reactors existed in the US in the 1970s and 1980s; but those have been shut down, and no such facilities exist today. For fusion, with no operating reactor systems, billion-dollar accelerator based systems have been proposed but never built.

Over the last few years the advances in materials modeling and simulation at the meso-scale and the prospect of no new fast neutron test facilities on the horizon (for either fission or fusion) have caused a paradigm change in the nuclear materials community. It is now believed that significant advances can be made in radiation damage material science through advanced meso-scale modeling combined with ion and/or proton irradiation to impart damage. Furthermore, accelerator-based systems can impart the ion and/or proton damage very quickly, which can also significantly reduce the overall development time for nuclear materials. The key scientific question that remains is whether the damage produced by ions/protons is similar to or can be correlated to neutron damage. This hypothesis is currently under study via several DOE grants in key US universities.

Thus, this vision for developing the NRL into a facility that can interrogate materials in-situ with both advanced x-ray and neutron instrumentation will open new frontiers in radiation material science. The ability of the facility to provide either neutron irradiation in the MITR core, or proton/ion irradiation with the accelerator facilities, is unique. With improved in-pile irradiation instrumentation in reactor test rigs, the ability to track and monitor the neutron damage in real time is possible. With the proposed proton/ion irradiation using cyclotrons (and the ability to also independently implant helium to simulate the fusion environment), in-situ characterization of the damage evolution is possible. The proposed x-ray and neutron characterization tools, when used for in-situ characterization and for advanced post-irradiation examination, will offer unprecedented opportunities to develop new understanding about radiation damage effects in materials at the nanoscale. The complementarity of two approaches (reactor for neutrons and cyclotron for charged particles) will provide the richest opportunity to advance the science. This vision offers MIT the opportunity to establish both scientific leadership and capability leadership positions in the field of radiation materials science.

Finding 4: *There is an exciting opportunity for MIT to combine the existing and potential capabilities of the NRL, related developments at PSFC, and the strategic initiatives of NSE to establish scientific leadership and capability leadership in the field of radiation materials science more broadly. In-situ interrogation can open new frontiers in radiation materials science. Without new fast-spectrum research reactors in the US, there are major gaps in national capabilities. Since new fast reactors are unlikely, a paradigm shift is now underway concerning how to achieve high radiation damage in their absence. Accelerator-based irradiation facilities, combined with x-ray and thermal neutron interrogation, provide a rich opportunity to advance nuclear and non-nuclear material science.*

Construction of New Support Space

In order to fully support and exploit the facilities described above, and to further enhance the NRL's capability to perform a wide range of PIE on materials from the in-core program, including with unique x-ray and neutron methods, the Committee reviewed the NRL site plan shown in Figure 5.1. Additional laboratories, new state-of-the-art hot-cell capabilities, and PIE instruments—such as electron microscopes and laser spectroscopies—would be required. The Committee noted the potential for new building construction of up to 48,000 SF which would have the required adjacency and capacity to house a new center for radiation materials science. A possible new laboratory building could provide high-bay space for the cyclotron and x-ray accelerators, and three neutron beams could be brought into the hot cells (C) or the accelerator area (A) for in-situ studies. Up to 40,000 ft^2 of office and laboratory space could be provided by a three-story building on parcel (B) and second floor over the accelerator high bay. A fourth neutron beam (D) could accommodate a cold source for small angle neutron scattering.

Finding 5: *For NRL to provide a new world-wide leadership role for MIT in radiation materials science, it must construct new facilities to accommodate accelerators; proton, x-ray, and neutron beams; hot cells; laboratories; and instrumentation adjacent to the reactor.*

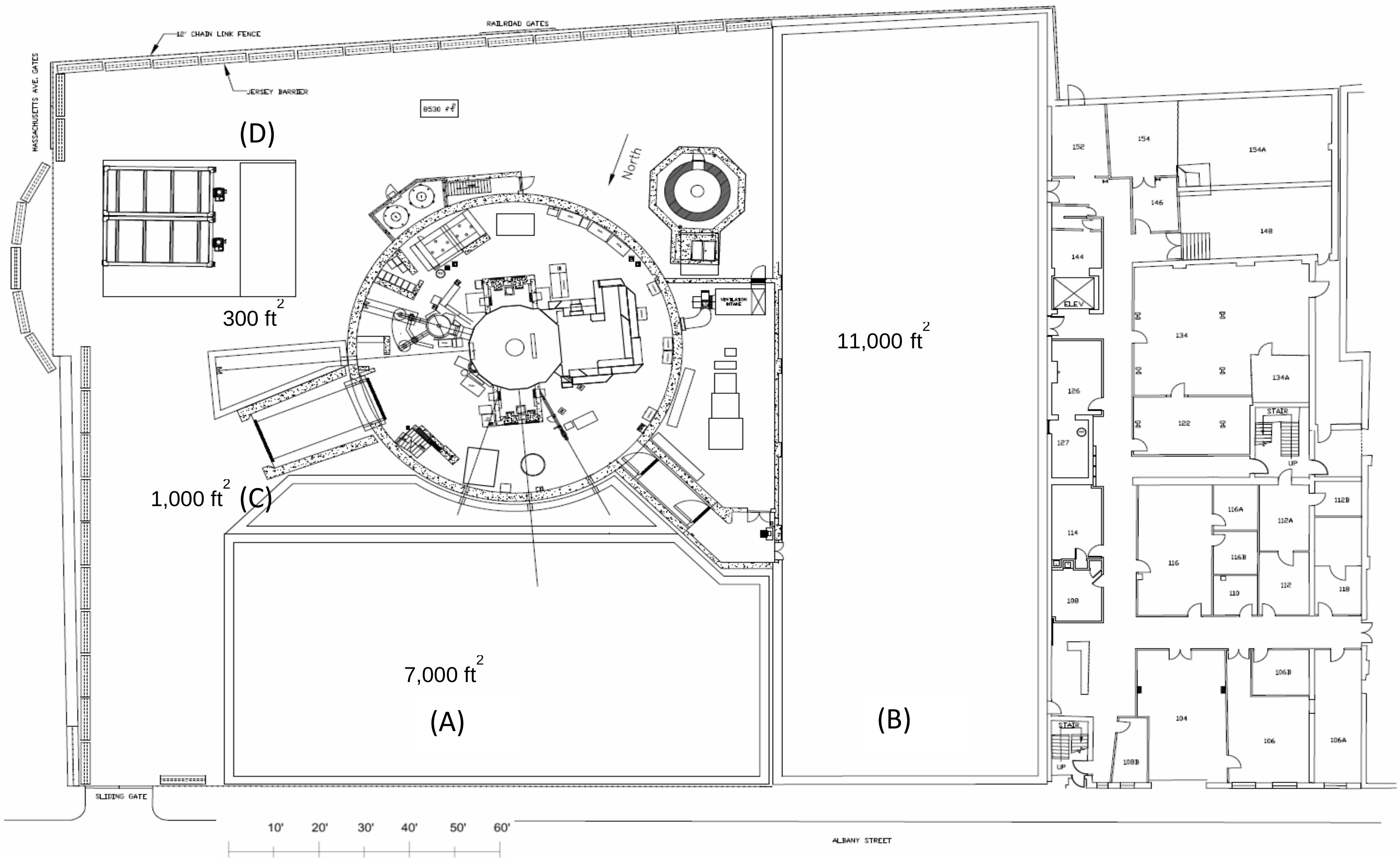

Figure 5.1. The NRL site plan shows opportunity for new construction adjacent to the reactor. The 7000 ft^2 (A) parcel is located in the existing parking lot, whereas the 11,000 ft^2 (B) parcel requires the removal of one-story building currently in poor condition. The area designated as 1000 ft^2 in area is envisioned as a hot-cell facility.

6. Faculty Interest

The Committee heard a number of presentations by young faculty members in NSE and other MIT departments with ideas for utilizing existing and proposed new facilities at the NRL.* Several of these colleagues subsequently provided written comments on how the new facilities could contribute to their research, and their comments are excerpted below.

Those with the greatest interest in the proposed NRL facilities will likely be researchers interested in the development of nuclear fission and fusion reactors, and in particular in the development and characterization of materials suitable for deployment in intense radiation environments. Several faculty members in NSE are studying nuclear materials, as are faculty in the Department of Materials Science and Engineering (DMSE) and research staff in the Nuclear Reactor Laboratory (NRL) and the Plasma Science and Fusion Center (PSFC). The proposed facility would present outstanding research and education opportunities for these researchers and their students. The combination of proton/ion accelerator facilities capable of producing accelerated but controlled rates of radiation damage and advanced *in situ* x-ray and neutron probes would offer world-leading capabilities in experimental radiation materials science on a reasonable timeline and on an experimental scale suitable for Ph.D. projects. The ability of the facility to control the ratio of helium accumulation to displacement damage would also open up new possibilities for fusion material studies.

In addition, the availability of novel x-ray and neutron methods at NRL would create new opportunities for research on non-nuclear materials that are likely to be of broad interest at MIT. This would complement the capabilities now planned for the new MIT Nano building, which will bring MIT's materials characterization capabilities up to par with those of other leading universities in key dimensions of performance. Beyond this, the new compact x-ray and neutron characterization and proton/ion cyclotron capabilities proposed for NRL offer a pathway to put MIT clearly ahead of its competitors in the field of materials characterization, in terms of both thought leadership and capability leadership, and involving physics, chemistry, biology and materials sciences.

MIT faculty and research staff with specifically nuclear interests whose research is likely to be supported by an upgraded NRL are listed in Table 6.1. Table 6.2 lists other MIT researchers who may also benefit from having access to x-ray and neutron characterization of materials. Similar to Professor Yildiz of NSE, several of the faculty in this second group (Dinca, Roman, Shao-Horn, Surendranath) are engaged in molecular-level studies and designs of surfaces for catalysts, electrocatalysts, and corrosion protection in energy and environmental applications. They typically use in-house x-ray spectroscopy and diffraction techniques, and some are frequent users of national facilities such as NSLS at Brookhaven National Laboratory, the Advanced Light Source at Lawrence Berkeley National Lab, and the Advanced Photon

* The Committee also heard presentations from several members of the NRL staff, including Dr. William Graves, Dr. Lin-Wen Hu, Dr. Boris Khaykovich, and Dr. Gordon Kohse. These presentations, too, contained many ideas for utilizing the proposed new capabilities of NRL. This section focuses on the prospects for external involvement in an upgraded NRL.

Source at Argonne National Lab. Their research could benefit greatly from the availability of local higher-brilliance sources to decipher the near-surface structure that is critical to the functionality of the materials they are studying. In particular, the ability to carry out *in situ* experiments where the material is investigated while under reaction conditions (temperatures, electrochemical potentials, reactive gases or liquids) would advance these studies, and such experiments cannot be performed with the laboratory x-ray sources for spectroscopy or diffraction that are currently available at MIT.

It should be noted that the list of MIT faculty in Table 6.2 is a partial list, based on the Committee's current knowledge, and there are likely others who could be added to it. It is also notable that many of the faculty on both lists are at a relatively early stage in their careers, suggesting that the proposed new facility could offer benefits over an extended period.

Finding 6: *An impressive cohort of young faculty now exists in NSE and other departments, and they have many ideas about how to engage with the NRL. The future development of NRL will provide an opportunity to enhance the physical sciences and engineering at MIT and attract and retain faculty across the Institute.*

Faculty Input

Several of the faculty listed in Tables 6.1 and 6.2 presented their ideas to the Committee and subsequently submitted written comments on how they might expect to use the current and potential future capabilities of NRL in their research. These comments, in some cases edited for brevity, are included here:

Professor Rafael Jaramillo:

X-rays offer a unique view of structure, composition and processes in materials. The advent of third generation synchrotron sources created an explosion of new applications of x-rays due in large part to the availability of contrast modes that were not possible with older sources. One prominent example is x-ray absorption spectroscopy, which is sensitive to short-range order and chemical information. Now the forefront of x-ray science has moved to studying materials in space and time, and many types of x-ray microscopes are being developed to use focused beams and to perform time-resolved, pump-probe experiments. A major goal of these technical developments is to enable *in situ* studies of energy technologies, combining the bulk penetration depth of hard x-rays with nanometer resolution, picosecond timing, and the full suite of x-ray contrast modes. Exciting examples include degradation studies of solar cells during accelerated lifetime testing, measuring crack formation in lithium ion battery cathodes during repeated cycling, and studying radiation damage in materials for nuclear reactors. These studies and more are carried out by MIT faculty using synchrotrons all over the world.

The emphasis on combining spatial resolution, temporal resolution, and *in situ* sample environments creates opportunities for new types of x-ray sources to perform high impact research. Large synchrotrons and linear accelerators will probably always offer the highest beam brightness. However, for many experiments, the brightness is not as important as other considerations such as beam coherence or the sample environment, and the success of an x-ray

Table 6.1: MIT Faculty and Staff in Nuclear Science and Engineering and Related Fields Whose Research Interests Overlap with the Proposed NRL

Ron Ballinger#	Professor, NSE and DMSE	Corrosion and environmental effects on materials behavior; electrochemistry; advanced materials for fusion systems; nuclear fuel performance analysis
Jacopo Buongiorno	Associate Professor, NSE	Boiling heat transfer; reactor design and safety; nanofluids for nuclear applications
Areg Danagoulian	Assistant Professor, NSE	Nuclear security; nuclear detection and nuclear forensics; treaty verification; nonproliferation
Ben Forget#	Associate Professor, NSE	Computational reactor physics; multiphysics methods; nuclear data
Charles Forsberg#	Principal Research Scientist, NSE	Fluoride salt-cooled high temperature reactors; hybrid energy systems; nuclear fuel cycles; high-temperature solar-thermal power systems
Mujid Kazimi*	Professor, NSE and MechE	Advanced LWR fuels; fuel performance modeling; compact steam generators; novel reactor design
Richard Lanza	Senior Research Scientist, NSE	Compact superconducting accelerators for medicine and security; accelerator-based inspection systems; phase-contrast x-ray imaging; radiation detectors
Ju Li#	Professor, NSE and DMSE	Nanomaterials for energy; *in situ* electron microscopy; physical metallurgy and mechanics; computational materials science
Joe Minervini	Senior Research Engineer, PSFC and NSE	Applied superconductivity, electromagnetics, low temperature measurements, superconducting magnet design and development
Michael Short#	Assistant Professor, NSE	Mesoscale nuclear materials science; nuclear alloy development; non-contact radiation damage quantification; CRUD/fouling deposition and prevention
Dennis Whyte#	Professor, NSE	Magnetic fusion energy; plasma-surface interactions; accelerators and surface analysis
Bilge Yildiz*	Associate Professor, NSE and DMSE	Surface science on ionic-electronic solids; advanced materials for solid-oxide fuel cells, electrolyzers, corrosion and computing; materials behavior in harsh conditions

*Member of Committee on the Future of the Nuclear Reactor Laboratory
#Presented to the Committee

Table 6.2: Partial List of MIT Faculty and Staff in Fields Other than Nuclear Science and Engineering Whose Research Interests Overlap with NRL

Tonio Buonassisi	Associate Professor, Mechanical Engineering	Photovoltaics, predictive process simulation, defects, multiscale characterization, photoelectrochemistry
Michael Demkowicz[#]	Associate Professor, DMSE	Computational materials science; structural and environmental materials
Mircea Dincă	Associate Professor, Chemistry	Functional chemistry of inorganic and metal-organic materials
Rafael Jaramillo[#]	Assistant Professor, DMSE (starting: 9/15)	Energy materials; magnetism in solids, oxides and chalcogenides
Yuriy Roman	Assistant Professor, Chemical Engineering	Heterogeneous catalysis; materials design
Yang Shao-Horn	Professor, Mechanical Engineering	Electrochemical energy conversion and storage technology; photoelectrocatalysis; nanostructured materials
Yogesh Surendranath	Assistant Professor, Chemistry	Interfacial chemistry of energy conversion

[#]Presented to the Committee

facility hinges on these multiple factors. For example, a highly coherent beam can track individual solid dislocations in space and time using lens-less imaging. Combining this capability with a radiation source such as the proposed proton cyclotron would create a powerful instrument for studying *in situ* radiation fatigue. This example also highlights the value of proximity in developing difficult experiments. MIT faculty are active synchrotron users, and have exciting ideas for how to address important materials problems using x-rays. However, we are handicapped relative to colleagues in places such as Stanford, Cornell and Chicago by the lack of a local facility. Challenging experiments are not well suited to the limited and irregular access time that is typical for synchrotron user facilities. A local x-ray facility with strong performance characteristics, combined with the ingenuity of the MIT community, would become a pioneer in x-ray materials characterization, similar to the role that the MIT reactor played in the history of neutron scattering.

Professor Ju Li:

MIT's materials research communities (DMSE, ChemE, MechE, NSE, BE, CEE, AeroAstro, Physics, Chemistry, etc.) will benefit tremendously from an on-campus bright x-ray source, neutron source, and proton/ion beam facility. Currently, while world-famous for materials research, MIT's materials characterization infrastructure leaves much to be desired. We lack high-end materials characterization tools. In my group, if we want to do aberration corrected TEM, we go to Brookhaven; for 3D atom probes, we go to Harvard; for environmental

TEM, we have to go to Brookhaven or even China. In three years, *MIT.nano* will definitely change some of that, but will only achieve parity. We will not have advantages over our peers (Harvard's CNS was launched in 2002; UPenn's Singh Center was launched in 2012). An on-campus bright x-ray source, neutron source, and ion beam would make MIT No.1 for materials characterization.

UC Berkeley has the Advanced Light Source (ALS), Stanford has the Stanford Synchrotron Radiation Lightsource (SSRL), and Cornell has the Cornell High Energy Synchrotron Source (CHESS), all within 2000 feet of their main campus. Competing with these peer institutions in materials research without a bright x-ray source is like fighting with one arm. To do one synchrotron experiment for 4 days, the burden of writing a user proposal to DOE, planning travel and accommodation, and then actually travelling to the facility adds 300% to the overall effort; moreover, the time latency can delay publication by ~ 6 months. An on-campus bright x-ray source would put us on a par with Cornell, Berkeley and Stanford.

A bright neutron source would further tip the scales in our favor. Wolter mirrors can focus neutrons from the MIT Reactor by a factor of 100 and will make us truly unique in being able to do small-angle neutron scattering (SANS) on campus. Neutron scattering has high complementarity with x-rays, and SANS is especially good for investigating soft matter and materials with light elements or spin polarization. Implementing Wolter mirrors could indeed make MITR useful for material studies.

The compact superconducting cyclotron will produce high-energy ion beams for radiation materials science investigations that will complement the in-core neutron irradiation damage capability provided by MITR. This is critical for the development of new materials necessary for advanced nuclear reactors such as the TerraPower traveling-wave reactor funded by Bill Gates, and the thorium-fueled molten salt reactors currently under development in China.

There will be excellent complementarity between an on-campus bright x-ray source, a neutron source, a high-energy ion beam, and *MIT.nano*. These four facilities, located within 1000 feet of each other, will be much more potent than their linear sum. With the much lower latency in access, MIT students and researchers will truly have the infrastructure that will give them an edge over peer universities.

Professor Michael Demkowicz:

On materials in extreme environments: A facility for testing materials behavior at hundreds of dpa and with He and/or H co-implantation would carry significant interest for prototyping, screening, and assessing novel materials meant for service in extreme environments. Moreover, the work that has been done to date in this area shows that many materials exhibit surprising and non-intuitive behavior when driven so extremely far from equilibrium. Our current, near-equilibrium understanding of materials behavior is of limited utility in predicting the variety of novel responses that may be expected at extremely high doses and implanted impurity concentrations. A facility capable of investigating these phenomena would not only carry unique technological benefits: it would also break new ground in fundamental materials science issues, with attendant impact on fields as diverse as medicine, geology, and astrophysics.

***On neutron imaging**:* X-ray scattering is the workhorse of current day-to-day, lab-scale materials characterization. Neutrons may be used in many of the same techniques that have been developed for x-rays, such as reflectometry, diffraction, and radiography. However, unlike x-rays, which interact with matter primarily through electrons, neutrons interact primarily with atomic nuclei. Thus, they provide complementary information to x-rays. For instance, while H and Li are almost undetectable using x-rays, they are easily detectible with neutrons. An on campus, easily accessible facility that enables routine neutron characterization of materials would give MIT a unique competitive edge in day-to-day materials characterization activities.

Professor Michael Short:

From my point of view, there is a great opportunity to realign some of the capabilities of NRL towards revolutionary advances in the field of nuclear materials for Gen IV fission and commercial fusion reactors. The creation of a sub-critical facility would enable the in-situ interrogation of simultaneous corrosion and irradiation, which are the major issues preventing the economic implementation of concepts like the lead fast reactor (LFR), which would otherwise be a front runner for both power production and waste burning.

In addition, the ability to insert major instrumentation into a sub-critical facility would propel one of my new research thrusts, radiation quantification by laser-induced surface acoustic waves, from the single-effect laboratory to the integrated materials study. The sub-critical facility would enable the investigation of dose-rate and environmental conditions on the accumulation of radiation damage, shifting the focus of this traditionally empirical field to a more mechanistic and fundamental understanding of the self-criticality and accumulation of mesoscale radiation damage.

Finally, this new reincarnation of the MIT-NRL would fit far better with planned major improvements at the PSFC, including the proposed 12MeV and 250MeV compact, superconducting proton cyclotrons. One of the largest issues in radiation materials science is the equivalency between charged particle and neutron irradiation, currently the subject of a major DOE integrated research program (IRP) headquartered at the University of Michigan. The combination of the high-dose-rate proton accelerators with the sub-critical facility at the NRL would make MIT the country's single capable facility for solving this problem in an integrated manner. Its effects will be wide and far reaching, as the standard practice in the community is to use heavy ions or protons as a surrogate for neutrons, without full justification of their comparative use.

The increased lab space, hot cell facilities, and auxiliary rooms for neutron imaging, ultrabright x-ray creation, and other characterization and interrogation techniques will add even more to the suite of tools required for serious radiation materials science. Some vital capabilities of major user facilities, such as the Brookhaven National lab's NSLS-II cyclotron and the Oak Ridge National Lab's Spallation Neutron Source (SNS), would then become available at the NRL. This would transform the NRL further into a world-class, multipurpose facility that through a combination of sponsored research and external user fees, could enhance and diversify its research portfolio.

Dr. Zach Hartwig (with Professor Dennis Whyte and Dr. Richard Lanza):

Incorporating accelerators into future plans for the NRL would provide enhanced research opportunities and extend the capability of MIT to advance a new vision for accelerator-based nuclear and materials science. As discussed in several sections in this report, the proximity of an in-core neutron irradiation source with intermediate energy ion accelerators will enable MIT to investigate the unresolved question of fidelity between the material response to neutron and ion irradiation and to experimentally validate novel, higher efficiency approaches to accelerator-based irradiation experiments. One example of the synergy between MITR and ion accelerators involves understanding the effect of radiation damage on superconductivity in a new generation of high-temperature superconducting (HTS) materials. These materials are being considered for use in magnets within high-radiation environments such as nuclear fusion, high-energy physics, and medical isotope cyclotrons, where the ability to engineer radiation hard materials is critically important. The PSFC is pioneering new accelerator techniques for inducing ion and neutron radiation damage in HTS samples that may drastically decrease irradiation times, allowing for faster iteration in development of radiation-hard HTS magnet designs. MITR would provide the crucial ability to efficiently validate these new techniques with traditional in-core neutron irradiation all within the same facility. Additional advantages to MITR could be considered, such as the ability to perform in-situ ion beam analysis within the hot cells used for analysis of irradiated materials.

Intermediate energy ion accelerators (~30 MeV to ~250 MeV) at MIT would also extend current research capabilities and open up new frontiers in nuclear science and engineering to a university-scale facility. Such accelerators would enable research into new nuclear reactions and less common particles for active interrogation of smuggled special nuclear materials (SNM) at portals. For example, such machines can access high energy gamma and meson (pion, muon) production reactions, which can be used to research methods for highly penetrating interrogation of shielded SNM. The use of ultracompact superconducting cyclotrons for this purpose would allow the design of small, portable, and cost-effective systems to enhance nuclear security. Another important application would be to reproduce in the laboratory the extreme radiation conditions found in low Earth orbit to study the impact of space weather on satellite operation and lifetime. Intermediate energy ion accelerators can be used to simulate the effect of the high energy charged particles on satellite components, enabling research into the effects of radiation damage on sensitive microelectronics and assessment of radiation- hard circuitry designs. Testing new designs for inexpensive, compact dosimeters for general deployment on small satellites - such as the new generation of small microsatellites for telecommunications - would also be possible. The application of such intermediate energy accelerators to the analysis of materials from extreme environments, such as the plasma-facing components used in nuclear fusion devices, would be transformative, extending present-day analysis from the surface (~microns) to the bulk (~millimeters) and opening up new nuclear reaction channels for analysis. Finally, new techniques are being developed using ion implantation to customize surface curvatures with micron precision via targeted surface stress relaxation. This technique has a wide range of applications, including x-ray telescope gratings and mirrors, thin film optics engineering, and semiconductor manufacturing. Access to intermediate energy accelerators would enable higher precision curvature control and larger curvature corrections, which could lead to new applications.

Professor Areg Danagoulian:

The MITR is a highly versatile facility for performing research in reactor systems, material science, as well as in the development of neutron scattering instruments. The neutron beams provided by the reactor could be used to study detectors operating in high intensity environments. In addition to the reactor, acquisition of new particle accelerators and thus expansion of an already existing accelerator-based research effort will significantly boost NSE's research profile. Accelerators can produce particle beams with important applications in the field of nuclear security. Ion beams, in particular, can be applied to nuclear security, material science, and to such medical applications as isotope production and radiation oncology.
The deuteron and proton beams can be used indirectly to trigger various nuclear reactions, which will result in the emission of monochromatic photons. These can be applied towards radiography, and active interrogation. A good illustration of such application is the Monochromatic Radiography program which is taking place at MIT-Bates, using a 3MeV RFQ deuteron accelerator. Also, threshold reactions from proton reactions produce angle-tuned monochromatic neutrons, which can be combined with (n,γ) reactions to produce highly sought monochromatic tunable gammas. At higher energies of >250MeV other exciting developments become possible, involving proton radiography, as well as production of muon and pion beams which can be instrumental in cargo security. Collaboration with industrial organizations which develop such accelerators will be important in the longer term. Radiation oncology relies on ion beams, where leveraging of the Bragg peak can significantly improve the efficiency of radiation therapy. Finally, the use of on-campus proton beams has been proposed by groups at Laboratory for Nuclear Science (LNS) to perform experiments of neutrino physics. This will create opportunities for collaboration between NSE and LNS not only in the usage of accelerators and detectors, but possibly also in a future program of accelerator physics.

Similar to ion beams, electron beams have been instrumental in enabling applications in nuclear security. 1-10MeV electron accelerators are used to produce intense bremsstrahlung photon sources which make part of radiographic and active interrogation techniques in cargo security applications. Such sources, combined with photofission, could enable fresh and spent fuel enrichment measurements via neutron multiplicity analysis. The Zero Knowledge Treaty Verification program currently hinges on the use of the 3MeV Van De Graaff accelerator at High Voltage Research Lab (HVRL). As the future of the "Albany corridor" takes shape, it is important to include the electron accelerators in the mix of tools that could drastically empower the field of nuclear security.

Efforts are presently underway to strengthen on-campus accelerator capabilities, including the renovation of current facilities, refurbishment of existing accelerators, and the acquisition of new, higher energy machines.

Dr. Charles Forsberg:

The unique capability of the MITR is to conduct small-scale first-generation irradiation experiments such as materials in 700°C salt. The shutdown of various reactors at national laboratories has resulted in a system where the U.S. has in terms of in-core loops the MITR and two high-performance materials test reactors. From a national perspective the ability to conduct such small-scale experiments is essential to help provide the data that will determine if larger, more capable, and much more expensive experiments should be done in large test machines. The MITR experiments also provide the early irradiation learning curve that improves the likelihood of success of experiments in the larger test reactors.

There is discussion of fast flux testing capability with 100 to 200 dpa capabilities. As a point of reference, the Terrapower once-through fast reactor ultimately wants clad materials to withstand up to 550 dpa, which may be achieved by the proposed proton cyclotron with adequate current and irradiation time. If one can get to these levels, then I suspect Terrapower may become a supporter and it would powerfully strengthen the case to DOE for such capabilities—including the nonproliferation groups in DOE. A once-through fuel cycle running on natural or depleted uranium is far cheaper than the traditional fast reactor fuel cycle so the Terrapower goal is about both vision (nonproliferation) and the economics requirement. Today there are only two transformative reactors on the table: (1) the FHR with baseload reactor core operations and variable electricity output, and (2) Terrapower with a once-through fuel cycle using cheap depleted uranium 30 times more efficiently than an LWR.

The MITR is uniquely able to install a subcritical facility—this, again, is the consequence of shutdown over the last several decades of various test reactors at DOE sites. That capability becomes a national asset for a serious development program for salt cooled reactors but is also a unique capability for several advanced reactors.

Professor Jacopo Buongiorno:

The technology of micro/nano-engineered surfaces for enhancement of safety and economics of LWRs, which is being developed in NSE, consists in engineering the surface of the fuel cladding to enhance boiling and quenching heat transfer. Data generated at MIT have shown that engineered micro/nano structures on the boiling surface can produce very large enhancements of the Critical Heat Flux (by as much as ~100%) and Leidenfrost, or quenching, temperature (by as much as ~150°C). The features that enable such effects are capillary wicking, obtained through a combination of hydrophilicity and porosity, and surface roughness, engineered at the nano- and micro-scale. There are major opportunities for power uprates and increased safety in LWR plants, where CHF and quenching determine the thermal margins during normal operation and loss of coolant accidents, respectively. However, several gaps exist on the path to commercialization: (i) the performance of the engineered surfaces must be confirmed in CHF and quenching tests at prototypical reactor conditions (i.e., full reactor pressure, temperature, flow rates); (ii), durability of these surface structures in the aggressive reactor core environment must be demonstrated; (iii) costs added to the fabrication of fuel rods must be minimal; (iv) a licensing framework for use of the engineered surfaces in reactors must be developed. Item (ii) is particularly challenging given the intense neutron/gamma radiation fields and complex chemistry (e.g. boric acid, lithium hydroxide, zinc acetate, zinc oxide, noble metals, products of radiolysis) present in LWR cores. The MITR can play an essential role here given its capabilities to accommodate in-core loops that simulate LWR chemistry and radiation.

Professor Ronald Ballinger:

The study of materials in radiation environments is critical for improving the reliability of modern thermal fission reactors, the development of next generation thermal fission reactors, the development of fast fission reactors, advanced medical and non-destructive evaluation techniques, and the eventual development fusion reactors. The ability to test fission and fusion relevant materials in environments with high neutron fluxes is limited to research reactors, high energy accelerator based techniques such as spallation and D-T target fusion. However, these methods induce radiation damage at similar or lower rates than the power reactors themselves. Since most materials in reactors and fusion applications must have lifetimes of several tens of years or greater, the development of new methods of testing materials with high neutron or neutron-like damage rates will greatly benefit the field of nuclear material science in that, done properly, accelerated damage rates can allow exploration of dpa regimes at end of life in shorter times. We have proposed a novel accelerator-based materials test facility (MTF) for simulating bulk radiation damage in material up to ~1 mm thick. Neutron radiation damage is simulated by inducing displacement damage with high energy protons.[†] The MTF will use superconducting cyclotrons to accelerate two beams; helium and protons. Protons can be used to simulate neutron damage, provided that the Coulombic interaction is taken into account as needed to correlate with an equivalent level of neutron damage. Protons can be accelerated in a compact, superconducting cyclotron to high energies. The companion helium beam allows for the uniform implantation of helium to simulate a second materials damage effect that occurs in nuclear reactors. Independent control of the He/dpa ration can thus be achieved. There will be good complementarities between the capabilities of this accelerator-based test facility and the x-ray and neutron sources proposed for the upgraded MIT NRL. Other important capabilities of the MIT Reactor include the ability to conduct environmental corrosion and chemistry studies in LWR environments. For these types of studies an upgrade of the capabilities in this area, especially in the hot/cell materials handling/PIE area, is critical, and indeed is critical for any future irradiation studies at the reactor.

[†] See Appendix D.

7. Strategic Considerations

Stewardship Responsibility

The NRL, as we envision it, has the potential to become a significant and unique national resource and will require resources commensurate with that mission. In the late 1990s, the National Research Council (NRC) tasked a committee to study various models for planning, operating and supporting major materials research facilities. The study goal was to identify a model that would be effective during the anticipated evolution of the respective user communities and their interests, as well as recognizing the financial constraints and missions of the federal agencies that support research facilities. The NRC committee recognized that a multidisciplinary facility has two components: the core of the facility and the individual experimental units that used the facility. Historically there had been a range of approaches for funding the core facility, from models in which funding was based on dispersed sources to models where a single agency assumed the primary financial steward role. The models involving dispersed sources could include access fees (or user fees) levied on each user, or models in which multiple agencies, or multiple programs within a single agency shared the funding responsibility. After thorough consideration, the dispersed-sources models for core facility funding were rejected in favor of a model where there was a single steward agency for the core facility. In order to promote the optimal development and use of the individual experimental units (such as neutron beamlines on a reactor) based on the core facility, the steward agency would be expected to develop cooperative partnerships with other funding entities. Thus the Cooperative Stewardship Model was introduced in the NRC report[6] of this study published in 1999.

The Cooperative Stewardship Model was designed for facilities generally larger than the NRL, such as storage ring x-ray sources or neutron sources with many users whose research was supported by different agencies in addition to the agency (usually the Department of Energy or the National Science Foundation) that was the steward of the facility. However, the present Committee believes that the model provides an appropriate framework to develop the NRL into the facility that we envision. Responsibility for the core facility would reside with the steward agency. Responsibility for the experimental components, including training and support of new users, could reside with the steward and it could also reside with the sponsors of the experimental units---the partners---which could be either other government agencies or organizations in the private sector. For the NRL, the Department of Energy (DOE) has long provided support in the form of fuel for the MITR and more recently for some system upgrades. The DOE’s mission to address US nuclear energy needs makes it the logical steward agency.

As discussed within Sections 2 and 3, MITR attributes make it uniquely capable among university research reactors for meeting irradiation testing needs of DOE and of the US nuclear enterprise, allowing it to successfully address diverse irradiation testing needs for the existing fleet and DOE advanced reactor programs. The NRL’s demonstrated experimental and training capabilities, its experienced and knowledgeable staff, and flexible, easy-to-access irradiation and PIE facilities are unique, making it a lower cost option not available elsewhere. Given the limited number of current US high-performance irradiation facilities and the enhanced capabilities envisioned within this report that will expand the NRL customer base, DOE's mission dictates that this agency assume the stewardship role for the enhanced NRL proposed within this report.

We believe that DOE's stewardship role might be most effectively accomplished with the DOE Office of Nuclear Energy as the steward, and the Office of Science as a major partner. Other partner agencies might include the National Nuclear Security Administration (NNSA), the Department of Defense, the Department of Homeland Security and the National Science Foundation.

Finding 7: *The NRC Cooperative Stewardship Model is an excellent approach for DOE-NE leadership in realizing the new vision for the NRL, together with a number or partners with strong interest in nuclear materials.*

Serving a National User Community

Section 6 describes the interest in the proposed new vision for the NRL reported to the Committee by a substantial number of MIT faculty. This interest is critically important for the MIT administration to support the proposed new developments, particularly financing of the new space which will be required. If DOE-NE is to assume the stewardship role discussed above, it is equally important that there be a substantial external (to MIT) national user community with strong interest in studying the properties of nuclear materials with the unique proton, x-ray and neutron methods described in Section 5. This Committee is confident that such a community exists based on its experience with the NSUF user program, the substantial user community at the Michigan Ion Beam laboratory, and the participants in DOE programs on fuels and materials, as well as the Committee's knowledge of industry interests. It will be important for the success of this initiative at NRL that a significant outreach effort be undertaken to better characterize this national community, to better understand their infrastructure needs, and to engage them in developing the optimal conceptual designs for the new facilities.

Choices for the Future

The Charge to this Committee focused on developing a "*vision for future MIT leadership in nuclear technology R&D and education*" and the Committee is very enthusiastic about the vision that has emerged. The Committee was not requested to consider the option of shutting down the MITR and terminating the NRL mission, and perhaps there are other alternatives that will also emerge as the MIT administration considers the situation. The cost of implementing the vision proposed in this report will be significant. We note, however, that every alternative will have substantial cost—for example, the decommission of the MITR will likely cost $40M or more. Developing a concrete understanding of the costs and the benefits of each potential option for the future will greatly improve the decision process.

Other Considerations

Accelerator Technology at MIT. The Committee recognized that the development of accelerator technology at MIT is currently dispersed across a number of small programs within the NRL, the PSFC, the Laboratory for Nuclear Science (LNS), and the Physics Department.

There are 15 faculty in the Department of Physics who conduct research in experimental nuclear and particle physics. Particle accelerators are essential tools for their research. Recently, a concentration in accelerator physics has been established in the MIT undergraduate physics. New on-campus accelerators would be a significant educational resource for the Physics Department providing unique capabilities to educate and train MIT students and young researchers.

Finding 8: *There are significant opportunities for collaboration and integration among laboratories (NRL, PSFC, and LNS) and between departments (NSE and Physics) in developing new accelerator capabilities. New accelerators on the MIT campus would provide important new opportunities for research and education. NRL leadership could help achieve broad multi-disciplinary impact.*

Development of the Northwest Sector. Finally, the Committee became aware of the issues surrounding the Northwest campus area, which comprises nearly 10 acres of prime Cambridge real estate. Historically this area supported the development of medium-scale physical facilities such as the nuclear reactor, the Alcator tokamak, and high-field magnets, and it continues to provide the principal laboratory space for NSE faculty and students. This area is greatly in need of revitalization, but represents an enormous asset to MIT if properly developed to meet future needs.

Finding 9: *The Northwest campus/Albany Street area has the potential to become a new center for medium-scale experimental physical science facilities on campus.*

Recommendations

The above findings lead to the following three main recommendations concerning the future of the MIT NRL:

Recommendation 1: The MITR should continue to operate and the in-core research program be sustained in the near term.

Recommendation 2: MIT should develop a strategy to realize the new vision for the NRL described in this report to create a world-leading center for radiation materials science within 3 to 5 years. The Committee anticipates that MIT will need to advocate strongly with potential sponsors and perhaps consider novel funding models.

The new NRL complex would integrate key elements: (a) incremental improvements to the reactor's experimental program, including new instrumentation and control capabilities, expanded hot-cell capability, and a new sub-critical facility, to enhance the reactor's role in supporting current and advanced reactor development efforts; and (b) new accelerator-based methods for creating high damage levels in materials together with in-situ x-ray and neutron interrogation methods and supporting laboratories and facilities.

Recommendation 3: As MIT develops plans for the future of the Northwest campus, it should explore the broader opportunities for revitalizing this sector that could build on this new vision for the NRL.

Acronyms and Abbreviations	
ALS	Advanced Light Source (Berkeley)
ANL	Argonne National Laboratory
APS	Advanced Photon Source
ATR-NSUF	Advanced Test Reactor National Scientific User Facility
BNL	Brookhaven National Laboratory
CANES	Center for Advanced Nuclear Energy Systems
CEA	French Atomic Energy Agency
CHESS	Cornell High Energy Synchrotron Source
CNS	Center for Nanoscale System (Harvard)
DCPD	Direct-Current Potential-Drop
DMSE	Department of Materials Science and Engineering
DOE	Department of Energy
DOE-NE	Department of Energy, Office of Nuclear Energy
ED	Energy Dispersive X-ray Spectroscopy
EPRI	Electric Power Research Institute
FHR	Fluoride Salt-Cooled High-Temperature Reactor
HBWR	Halden Boiling Water Reactor
HEU	High-Enrichment Uranium
HTS	High-Temperature Superconducting Materials
HVRL	High Voltage Research Lab
ICS	Inverse Compton Scattering
ICSA	In-Core Sample Assembly
INL	Idaho National Laboratory
IRP	DOE Integrated Research Program
LNS	Laboratory for Nuclear Science
LBNL	Lawrence Berkeley National Laboratory
LCLS	Linac Coherent Light Source
LEU	Low-Enrichment Uranium
LFR	Lead Fast Reactor
LNS	Laboratory for Nuclear Science
LVDT	Linear Variable Differential Transformer
LWR	Light Water Reactor
MITR	MIT Research Reactor
MOX	Mixed Oxide
MRF	Materials Test Facility
MTR	Material Test Reactor
NASA	National Aeronautics and Space Administration
NEET	(DOE) Nuclear Engineering Enabling Technology

NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration
NRC	National Research Council
NRL	Nuclear Reactor Laboratory
NSE	Nuclear Science and Engineering Department
NSLS	National Synchrotron Light Source
ORNL	Oak Ridge National Laboratory
PSFC	Plasma Science and Fusion Center
PIE	Post-Irradiation Examination
SANS	Small-Angle Neutron Scattering
SEM	Scanning Electron Microscope
SNM	Special Nuclear Material
SPDG	Self-Powered Gamma Detectors
SPND	Self-Powered Neutron Detectors
SSRL	Stanford Synchrotron Radiation Lightsource
TRISO	Tristructural-Isotropic Fuel
TRU	Transuranic Elements
UCB	University of California at Berkeley
ULTRA	Ultrasonic Transducers Irradiation Test
UW	University of Wisconsin

Appendix A

Charge to the Committee on the Future of the MIT Reactor

Today the research being undertaken at the reactor is excellent and covers a range of current interests, but the total research volume is not large (about $4M), and the participation of MIT faculty is limited. Commercial revenues and reactor usage charges recover only about half of the reactor's operation expense, with the remainder supported by Institute overhead.

In light of this situation, the committee should consider the potential for increased MIT faculty involvement in research at the NRL across the full range of relevant academic disciplines. Particular attention should be paid to the relationship between NRL and the Department of Nuclear Science and Engineering (NSE). Given the mission and plans of NSE to provide scientific and engineering leadership in developing energy and non-energy applications of nuclear technology, the essential question arises:

How can the NRL – either in its present form, or in a modified or entirely new configuration – contribute most effectively, together with NSE, to realizing a vision for future MIT leadership in nuclear technology R&D and education?

In considering this question, it should be recognized that future options fall into two categories — namely, scenarios that involve the continued operations of the reactor, perhaps with upgrades, and ones that imply decommissioning in order to implement entirely new capabilities. The committee should be as specific as possible in recommending a future course of action, including practical steps to achieve the best outcomes in support of the recommended vision.

The committee should take into account the role that NRL plays today in the national nuclear energy R&D program, as well as its possible role in future national and international efforts to develop advanced nuclear systems with enhanced economic, safety, and security characteristics.

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Appendix B

Agenda

First Meeting of the Committee on the Future of the MIT Reactor

November 4-5, 2014

Tuesday, November 4th

8:30 am	**Welcome and Charge**
8:35 am	**NSE Perspective, Richard Lester**
8:50 am	**NRL Overview, David Moncton**
8:45 am	**Reactor Overview, Thomas Newton**
9:30 am	**Reactor Tour**
10:00 am	**Break**
	Summary of Existing Programs
11:00 am	- In-core Experiments, Gordon Kohse
11:30 am	- Neutron Scattering, Boris Khaykovich
12:00 pm	- Compact X-ray Sources, William Graves
	- Fluoride Salt High Temperature Reactor, Charles Forsberg (Tomorrow)
12:30 pm	**Lunch**
	Future Concepts
1:30 pm	Accelerators
	- Proton Cyclotron for Materials Irradiation, Ronald Ballinger
2:00 pm	- Small Accelerators for Neutrino Physics, Daniel Winklehner
2:30 pm	New Sub-Critical Facility, Lin-Wen Hu
3:00 pm	**Break**
	Brainstorming
3:15 pm	- Michael Demkowicz
3:45 pm	- Benoit Forget
4:15 pm	- Michael Short

4:45 pm	- Dennis Whyte
5:15 pm	- Jacopo Buongiorno
5:45 pm	**End**
7:00 pm	**Dinner – Sidney's Grille, Le Méridien *Cambridge***

Wednesday, November 5th

8:30 am	Fluoride Salt High Temperature Reactor, Charles Forsberg
9:00 am	**Open Discussion**
10:00 am	**Confirm December Agenda**
12:00 pm	**End**

Agenda

Second Meeting of the Committee on the Future of the MIT Reactor

December 8-9, 2014

Monday, December 8th

8:30 am	**Review First Meeting and Agenda**
	Reactor Upgrade Possibilities
9:00 am	LEU Conversion, Tom Newton
9:30 am	Discussion of Other Options, Newton, Driscoll, Kazimi
10:00 am	**Break**
	Personal Perspectives
10:15 am	- Pete Miller (by teleconference)
10:45 am	- David Hill (by teleconference)
	Industry Perspectives
11:15 am	Terrapower, Bob Mulford (by teleconference)
12:00 pm	**Lunch**
	Cyclotron Options – Richard Milner
	Discussion of NRL Site Planning Options
	Brainstorming Cont.
2:15 pm	Kurt Terrani, ORNL
2:45 pm	Ju Li, NSE
3:15 pm	Rafael Jaramillo, ME
4:00 pm	**Break**
4:30 pm	Discussion with Maria Zuber, MIT Vice President for Research
5:30 pm	**Discussion**
6:00 pm	**END**
6:30 pm	**Dinner**

Tuesday, December 9th

9:00 am	**Discussion of Recommendations**
10:00 am	**Report Writing**
11:30 am	**Develop Plans for Finalizing Report**
12:00 pm	**END (Lunch Available)**

Appendix C: Table 1. MITR In-Core Experiments (as of January 2015)

Facility	In-Service	Purpose of Experiments
PCCL	1989	Measure effect of pH on corrosion product transport and ex-core radionuclide deposition to optimize PWR chemistry specifications
BCCL	1990	Evaluate effect of chemical additives on N-16 carryover and benchmark radiolysis codes
IASCC	1990	Test effects of coolant chemistry on IASCC of BWR alloys
SENSOR	1994	Test in-vessel detectors for ECP and crack growth rate and investigate crack arrest by hydrogen water chemistry
Shadow Corrosion	1999	Test clad samples with various counter materials and gaps under BWR conditions to investigate shadow corrosion
Alumina Fiber Composite Clad**	2000	Test of alumina-based ceramic fiber composites as potential cladding material under PWR conditions
Annular Fuel**	2004	Demonstration of VIPAC annular fuel under irradiation and test of manufacturing process
Shadow Corrosion	2004	Phase II of 1999 Shadow Corrosion Loop
ECP	2004	Electrochemical characterization of in-core coolant and oxides to investigate mechanisms of shadow corrosion
HTIF**	2005-2006	Irradiation of SiC/SiC composites and surrogate TRISO fuel particles up to 1600ºC in inert gas
ACI Loop**	2006-2007	Investigation of corrosion and mechanical property behavior of triplex SiC/SiC composite clad tubing under PWR conditions.
ACI Loop	2009	Continued irradiation of clad tubing samples from previous ACI with addition of next generation, smaller diameter tubing
ACI Loop*	2009-2012	Continued irradiation of tubing samples with addition of bonding specimens to evaluate end-cap bond processes
New ICSA*	2010	Evaluate thermal design of capsule incorporating "gamma susceptor" for passively heated irradiations up to 900°C
Mo-99 Irradiation	2010 (Pilot)	Evaluate (n,γ) production of Mo-99
High-T ICSA irradiation of "Max Phases" **	2010-2011	Irradiation of five different ternary carbides and nitrides of Ti for post-irradiation evaluation of properties with possible applications in high temperature gas reactors
Hydride Fuel*	2011-2012	Irradiation of novel liquid-metal bonded uranium-zirconium hydride fuel rods in Zircaloy-4 cladding for LWR applications
LUNA (ICSA)**	2012	Evaluation of irradiation damage in fiber optic sensors manufactured by Luna Innovations Inc. for use as in-core temperature monitors
Fluoride Salt and FHR materials (FS-1)**	2013	Corrosion and tritium transport measurements with SiC, surrogate TRISO particles and metal coupons irradiated in liquid lithium fluoride-beryllium fluoride salt at 700°C.
ULTRA*	2014-	Performance testing of multiple magnetostrictive and piezoelectric ultrasonic sensors under irradiation in inert gas
ACI Loop (BSiC)**	2013-2014	Corrosion, creep, and corrosion product transport testing on SiC BWR channel box coupons under BWR core conditions
ACI Loop (WATF)**	2014-2015	Investigation of corrosion and mechanical property behavior of new SiC/SiC composite fuel cladding under PWR conditions
Fluoride Salt and FHR materials (FS-2)**	2014	Corrosion, chemistry control, tritium and radioactive gaseous products transport measurements with graphite, C/C composite, SiC composite, surrogate TRISO particles, and metal coupons irradiated in liquid lithium fluoride-beryllium fluoride salt at 700°C. Larger salt volume than FS-1.

*Experiments funded by ATR-NSUF **Experiments funded by other DOE programs, such as NERI, NEET, NEUP, SBIR, STTR etc.

PCCL = PWR Coolant Chemistry Loop	ECP = Electrochemical Potential	ICSA = In-Core Sample Assembly
BCCL = BWR Coolant Chemistry Loop	HTIF = High-Temperature Irradiation Facility	FS=Fluoride salt
IASCC = Irradiation–Assisted Stress Corrosion Cracking	ACI = Advanced Cladding Irradiation	

APPENDIX D

A Superconducting Cyclotron Accelerator Based Materials Test Center for Surface and Bulk Radiation Damage Studies

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Summary

A novel, superconducting cyclotron accelerator-based materials testing center is proposed for simulating bulk radiation damage in material (1-3 mm thick) and achieving at least 100 dpa per year proton dose or several hundred dpa/month heavy ion dose. The center will provide critical materials science that addresses fundamental questions related to radiation damage in fusion systems, by providing required data that approach those from full 14MeV neutron sources at a fraction of the cost of larger facilities (SNS, IFMIF). The center will exploit recent advances in superconducting magnets, advanced gas-jet cooling for heat removal, computer-aided design, rapid prototyping and manufacturing, as well as miniaturization, to design the smallest and cheapest proton, helium and heavy ion accelerators for the energy range of 30-100 MeV, which will achieve volumetric irradiation of materials. The three-beam center will allow independent variation of helium and proton dose rates (He/dpa ratio), while also providing static or dynamic active mechanical loading of material. The center will be fully equipped for sample production, irradiation, and subsequent analysis. Advanced instrumentation for analysis will include a full range of analytical analysis tools (SEM, TEM, FIB, Atom Probe, SIMS, etc.), aimed at direct visualization of radiation damage structures, and direct validation & verification of simulations of radiation damage in fusion systems.

1. Introduction: The study of materials in radiation environments is critical for the development of fusion systems. In fusion reactors, neutrons typically damage materials through two mechanisms: the displacement of atoms in the material, and the accumulation of helium from (n,α) reactions and α-decay of activated nuclei. These processes depend strongly on the neutron spectrum and the physical and nuclear properties of the material. Since neutrons have relatively long mean free paths, the damage occurs within the bulk of the material, causing changes to the material's atomic structure leading to macroscopic changes affecting its mechanical and thermal properties. The accumulation of helium eventually degrades the material on its own but also stabilizes voids, which aggravates swelling.

The ability to test fusion relevant materials in environments with high neutron fluxes is limited to research reactors and high energy accelerator based techniques, such as spallation and D-T target fusion. However, these methods induce radiation damage at similar or lower rates than the power reactors themselves. Since most materials in fusion applications must have lifetimes of several tens of years or greater, the development of new methods of testing materials with high neutron or neutron-like damage rates will greatly benefit the field of nuclear material science in that, done properly, accelerated damage rates can allow exploration of DPA regimes at end of life on substantially shorter timescales.

Simulation of neutron damage with ion irradiation is an established technique [1, 2]. The long range Coulomb interactions of the protons increase the damage rate per ion by several orders of magnitude as compared to neutrons. This allows for accelerated radiation damage rates when irradiating materials. However, these techniques are limited by the difficulty of heat removal from samples and are constrained by low energy (< 5 MeV) beams which can only produce near surface (< 100 μm) damage in materials. To simulate neutron-like damage effects that are uniform throughout the bulk of the sample, high energy proton beams (≈ 30-40 MeV) are required. With recent developments in accelerator technology, it is now possible to achieve these high energies with compact (∼2 m diameter) superconducting cyclotrons instead of linear accelerators (10-100m length).

2. Accelerator Based Materials Test Center

2.1 Beam Lines: There is a need for a materials testing facility that can accurately and quickly access material properties. In order to achieve relevant DPA values in a reasonable time, the facility would have to achieve at least 50-100 dpa per year. Currently, there are no fast spectrum or fusion material test facilities, and there are only two major thermal spectrum test facilities (ATR and HFIR). The International Fusion Materials Irradiation Facility (IFMIF) has been proposed for construction within the next decade. IFMIF would use a high energy deuteron beam and a tritiated target to produce fusion neutrons and would have the ability to test hundreds to thousands of samples at once. However, the projected cost of IFMIF is estimated to be several billion dollars, and it would be limited to damage rates on the order of 10-20 dpa per year of operation.

A novel accelerator based materials test center is proposed for simulating bulk radiation damage in material up to 1-3 mm thick. Superconducting cyclotrons will be used to accelerate three beams; helium, protons, and heavy ions. Protons can be used to simulate neutron damage, provided the Coulombic interaction is taken into account as needed to correlate with an equivalent level of neutron damage. Protons can be accelerated in a compact, superconducting cyclotron to high energies. A companion helium beam would allow for the uniform implantation of helium to simulate a second materials damage effect that occurs in fusion reactors. Independent control of the He/DPA ratio would thus be achieved. A third heavy ion beamline can provide for very rapid DPA rates for thin (<100 micron) samples. Figure 1 shows a schematic view of the three beam line facility. Also shown is a schematic of the target chamber. As mentioned above, the key features of the beam facility are the use of superconducting cyclotrons (high energy with small footprint) and gas jet cooling (high heat removal capacity). The high energy assures that the Bragg peak lies outside of the specimen, which results in uniform damage through the material of engineering significance.

2.2 Analytical Capabilities: The use of high energy beams will result in significant material activation. For this reason, the center will need facilities and a set of analytical instruments that can handle radioactive material. These instruments will include a complete analytical electron microscopy suite (Scanning Electron, Focused Ion Beam, Transmission Electron, Secondary Ion Mass, and Atom Probe Tomography). Specimen preparation, before and after irradiation, will be provided via a dedicated facility that includes hot cells (currently available via the MIT Nuclear Reactor Laboratory). In addition to post irradiation analysis, the center will allow for in-situ measurements during irradiation.

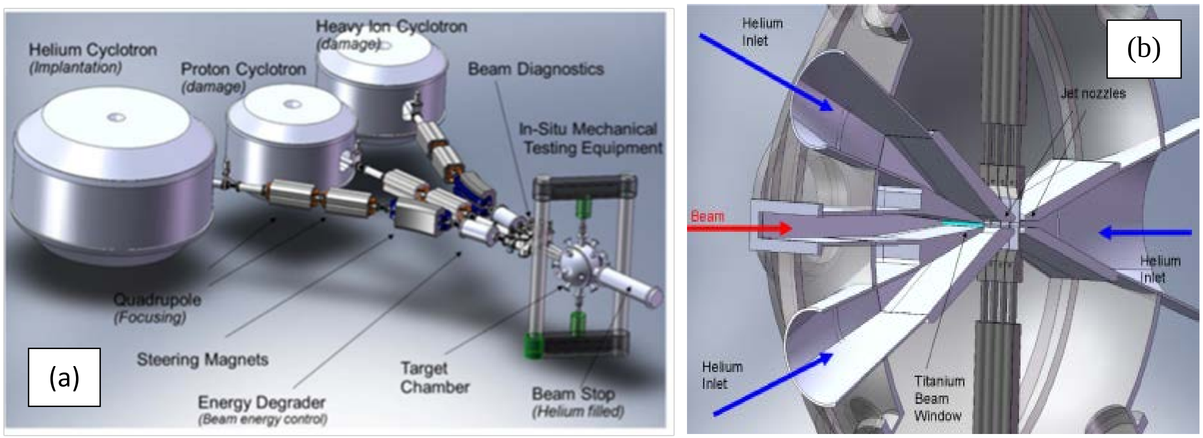

Figure 1. Triple cyclotron beam line for protons, helium, and heavy ions (a). Target chamber (b).

<u>2.3 Additional Infrastructure:</u> The proposed center would have the significant advantage of being co-located with several other facilities that would provide greatly enhanced overall capabilities when taken together. The combination of the MIT Nuclear Reactor Laboratory (hot cells, material handling experience), the Plasma Science and Fusion Center (overall fusion science expertise), Plasma Surface Interaction (PSI) Science Center (ion beam analysis capabilities), and the Alcator C-Mod Tokamak experiment along with the unique, industrial-like infrastructure (design, construction, operation of high performance vacuum systems) will result in a truly world class comprehensive fusion materials research nexus. Additionally, the infrastructure associated with these facilities and the experience in operating these facilities will serve to reduce programmatic risk as well as cost.

3. Other Considerations

<u>3.1 Addressing Fusion-Specific Grand Challenges:</u> The proposed center will provide a low cost approach to addressing the following fusion scientific grand challenges[3]:

1. CD1 - Develop a rigorous scientific understanding and devise mitigation strategies for deleterious microstructural evolution and property changes that occur in materials exposed to high neutron fluences and high concentrations of transmutation-produced gases from a 14 MeV peaked neutron source,
2. CD2 - Develop science-based design criteria that account for degradation of materials subject to severe time-dependent, thermo-mechanical, high temperature loadings, including effects of 14 MeV neutron irradiation,
3. CD3 - Comprehend and control the processes that drive tritium permeation, trapping, and retention in neutron radiation damaged materials with microstructures designed to store large amounts of helium in numerous, nanometer-scale bubbles.

[3] DOE/SC-0419, "Fusion Energy Science Advisory Committee Report on Opportunities for Fusion Materials Science and technology Research Now and During the ITER Era, Feb. 2012.

<u>3.2 Impact Beyond the FES Mission:</u> While the center will be focused on the fusion environment, the variable energy nature and ion flexibility (He, Protons, heavy ions) would allow the center to simulate environments spanning fission and fusion reactors. The ability for independently varying temperature, DPA rate, and He/DPA ratio, none of which could previously be decoupled in any other experiment, sets this facility apart from any other.

<u>3.3 Context of Facility Related to World Effort in Fusion:</u> The center would provide a "bridge" between what is currently available for radiation damage studies and what may be envisioned in the future. The center could be up and running in a fraction of the time required to build larger, non-accelerator based facilities. Needed data for fusion science could be obtained in a much more timely manner, which is critical to pushing the science forward. The center would become an international nexus for fusion materials science.

<u>3.4 Readiness of the Facility Concept:</u> The keys to the success of the center are the successful design and construction of the compact cyclotrons using superconducting magnet technology and the successful design and construction of the target chamber. In particular, the heat removal concept using gas-jet cooling must be successful. Compact cyclotron technology is mature with the exception of the use of superconducting magnets. However, recent developments in this area indicate that this technology is ready and will be successful [4-6]. Gas jet cooling, while not used for the more conventional, low energy, LINAC machines, has been used in other applications in the fusion community and conservative analysis indicates that the heat removal capability will be adequate [7,8]. All other components are "off the shelf" items. We thus judge that the facility can be constructed successfully, but will require that the above engineering challenges be addressed to minimize programmatic risk.

<u>4. Timescale:</u> First beam in 2 years; full 3 beam facility in operation within 5 years.

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