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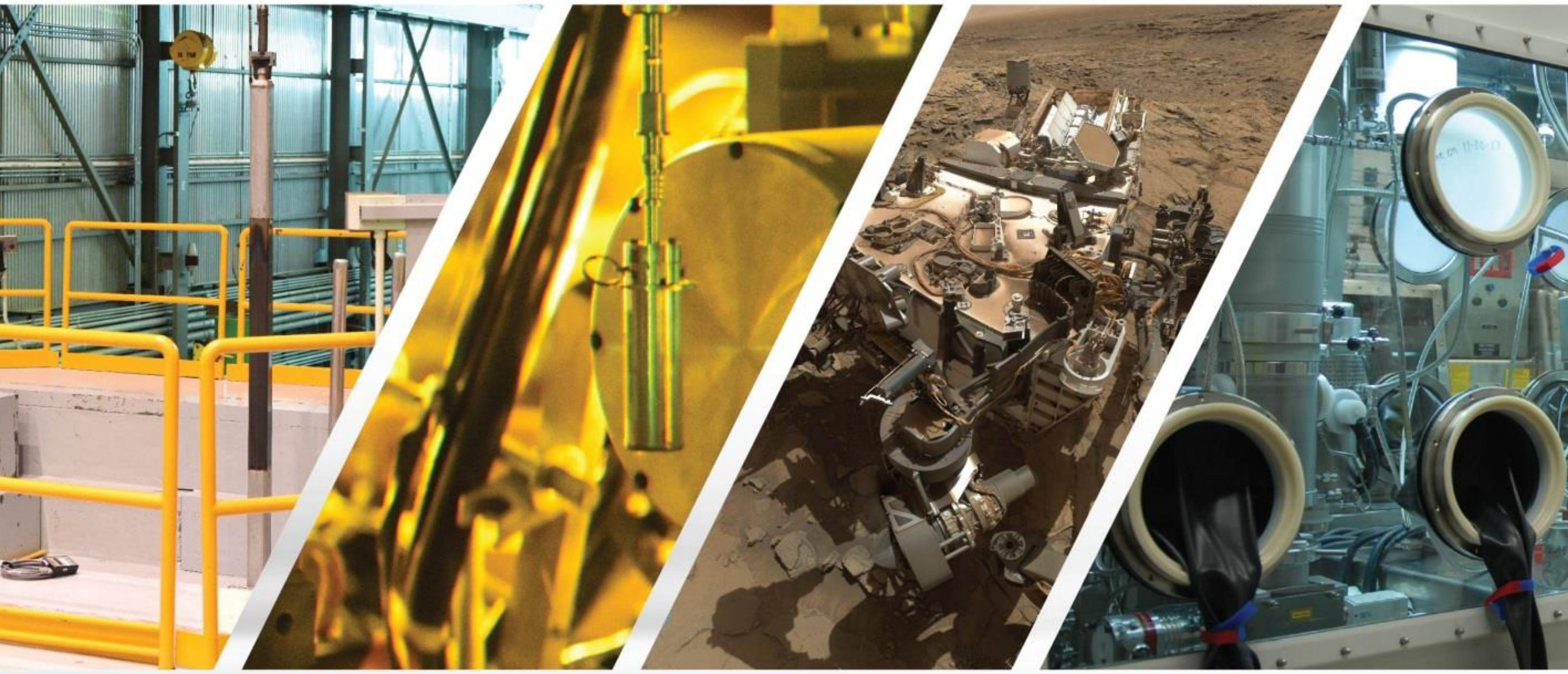

MATERIALS AND FUELS COMPLEX
Five-Year Science Strategy

February 2017

Idaho National Laboratory INL

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

INL/EXT-17-41117

Materials and Fuels Complex Five-Year Science Strategy

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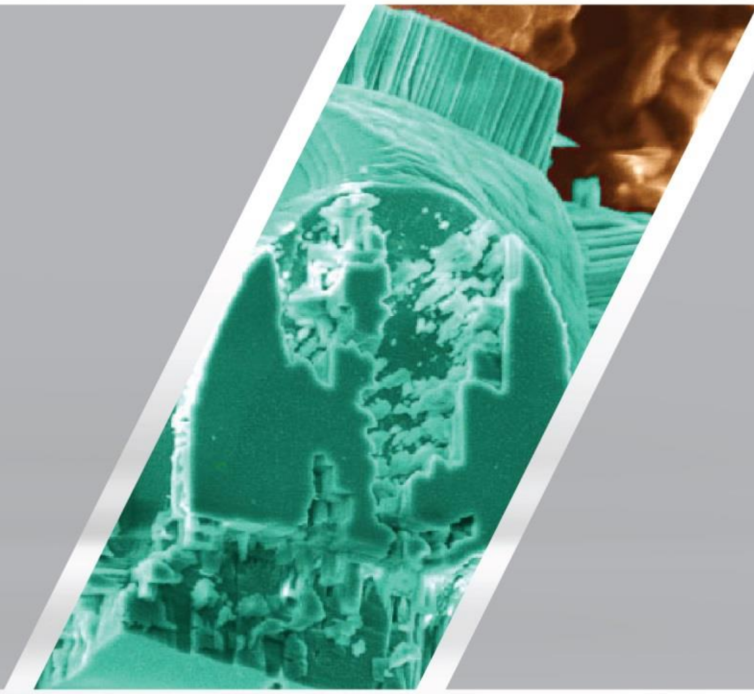

EXECUTIVE SUMMARY

Picture on the front depicts: INL scientists are studying whether mineral sequestration can help curb the impacts of carbon dioxide emissions. When CO_2 is injected deep into basalt formations, it dissolves in water and reacts with naturally occurring ions to produce stable secondary minerals (such as calcium carbonate, shown here in green) that will keep the carbon entombed within the rock for thousands of years.

EXECUTIVE SUMMARY

The mission of the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) is to advance nuclear power as a resource that is capable of meeting the nation's energy, environmental, and national security needs by resolving technical, cost, safety, proliferation resistance, and security barriers through research, development, and demonstration. There has never been a more compelling time to develop sources of safe, clean, renewable, carbon-free base power for the United States. Over six decades of use, nuclear power has been proven to be a safe and reliable base alternative to fossil energy sources. The primary barriers to wider commercialization of nuclear power are the life-cycle costs of current plants, the long cycle associated with development of new nuclear technologies that may be more suitable for today's energy markets, and the regulatory risk associated with this investment in new nuclear technology. While many innovative nuclear energy concepts exist that match current energy market needs, the lengthy and expensive research, development, and demonstration process and uncertain prospects for licensing discourages investment of private capital.

The DOE-NE strategy both sustains the current reactor fleet and provides technology options for development of advanced nuclear energy systems. The strategy for moving innovative ideas to the marketplace centers on the Gateway for Accelerated Innovation in Nuclear (GAIN) Initiative. As the lead national laboratory for DOE-NE, Idaho National Laboratory provides much of the nuclear research, development, and demonstration capability needed to move nuclear innovation forward to deployment.

Incorporation of the test bed and demonstration platform concepts spanning across technology readiness levels (TRLs) is depicted in Figure E-1. GAIN bridges the two barriers that prevent innovative technologies from reaching the marketplace[a] by providing access to national resources critical to development of nuclear energy technology. Both of these barriers exist due to a perception of risk and a lack of appropriately matched risk capital in the energy technology market. The technological valley of death appears when laboratory researchers are unable to obtain the capital needed to demonstrate viability. Bridging this gap requires cost-effective access to capabilities that allow transition from proof-of-concept (TRL 3) to proof-of-performance (TRL 4). Coupled with improved data acquisition, analysis, modeling, and simulation methods, core nuclear research capabilities at the Materials and Fuels Complex (MFC) have the potential to increase the generation rate of knowledge relevant to this transition by more than an order of magnitude, significantly reducing technology development cycle times. MFC will also provide a central point from which DOE-NE's broader intellectual capital and physical research capability can be accessed.

The second barrier occurs when entrepreneurs seek capital to fund demonstration or first-of-a-kind commercial-scale projects or manufacturing facilities (TRL 6 to 8). Bridging this gap requires a cost-effective demonstration capability, allowing a focus on technology development as opposed to a focus on developing support infrastructure. Beginning in the 1960s, the MFC site was

[a] Jesse Jenkins and Sara Mansur, "Bridging the Clean Energy Valleys of Death: Helping American Entrepreneurs Meet the Nation's Energy Innovation Imperative," Breakthrough Institute (November 2011).

developed to demonstrate the Experimental Breeder Reactor-II and its associated fuel cycle. Although the Experimental Breeder Reactor-II mission was completed in 1995, the infrastructure required to support demonstration of advanced nuclear technology is actively maintained and upgraded by DOE-NE and represents a large fraction of the capability required for a future demonstration platform.

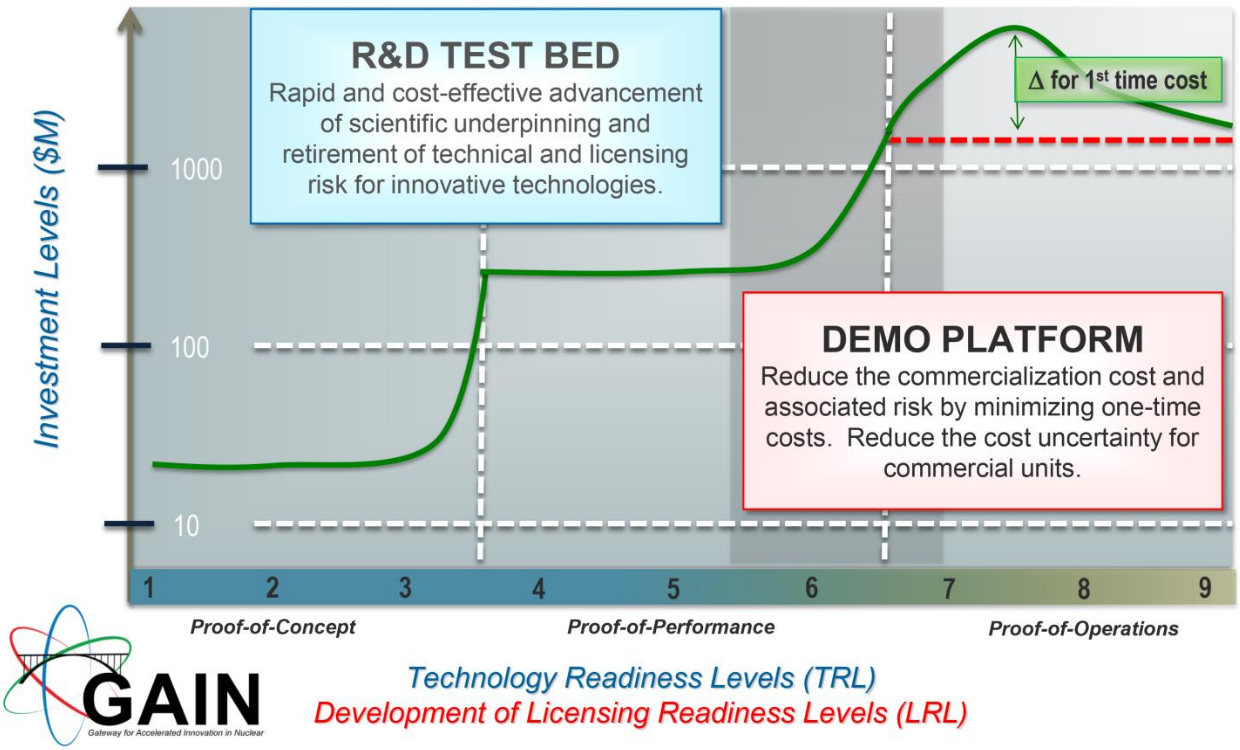

Figure E-1. GAIN provides support for development of nuclear energy technology for all TRLs. Barriers to innovation reaching the marketplace occur during transition from TRL 3 to 4 (i.e., technology barrier) and TRL 6 to 8 (i.e., commercialization barrier).

This plan outlines a strategy that builds and sustains DOE-NE research capability, increases access to MFC and broader DOE nuclear research capabilities, and anticipates demonstration of advanced nuclear energy technologies. Key features of this strategy include the following:

- Focusing research and capability development in areas where MFC has a core strength and leveraging partnerships and collaboration with Oak Ridge National Laboratory, Argonne National Laboratory, Nuclear Science User Facilities, university partners, and DOE's extended research network to fill the capability gaps
- Transitioning to a user facility-like model increases research capacity and allows improved access to nuclear research and development capability at MFC and DOE-NE's broader research network
- Implementing an operations model that improves the efficiency and reliability of operations, including near-term focuses on reducing deferred maintenance and addressing other repair needs, without compromising safety

- Reviving and improving historical MFC capabilities that support demonstration-scale activities.

Implementing this 5-year strategy will position DOE-NE to deliver an effective nuclear research, development, and demonstration capability that supports current programs while addressing issues that impact the ability of U.S. nuclear energy technology to keep pace with a changing world energy market.

This science strategy has an accompanying investment strategy titled, “The MFC Plant Health Investment Strategy,” which details the investments (i.e., both detailed scope and estimated costs) necessary for revitalizing the nuclear energy test bed at MFC.

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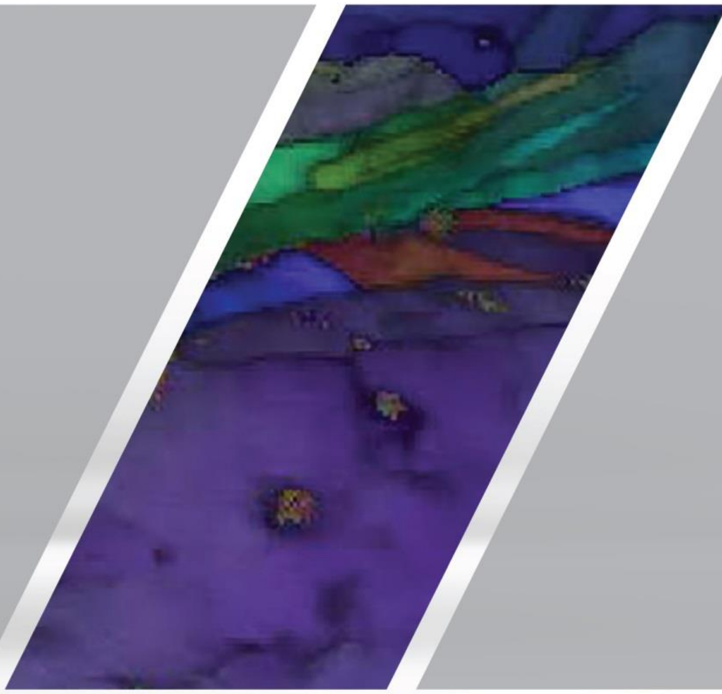
FIGURES

TABLES

ACRONYMS

AL	MFC Analytical Laboratory
DOE	Department of Energy
EBR-II	Experimental Breeder Reactor-II
EFF	Experimental Fuels Facility
FASB	Fuel and Applied Sciences Building
FCF	Fuel Conditioning Facility
FMF	Fuel Manufacturing Facility
FY	fiscal year
GAIN	Gateway for Accelerated Innovation in Nuclear
HFEF	Hot Fuel Examination Facility
IASCC	irradiation-assisted stress corrosion cracking
IMCL	Irradiated Materials Characterization Laboratory
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LWR	light water reactor
MFC	Materials and Fuels Complex
NE	DOE Office of Nuclear Energy
NNSA	National Nuclear Security Administration
NSUF	Nuclear Science User Facilities
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
R&D	research and development
RAL	Remote Analytical Laboratory
RD&D	research, development, and demonstration
RPS	radioisotope power systems
SPL	Sample Preparation Laboratory
TREAT	Transient Reactor Test Facility
TRIGA	Training, Research, Isotope, General Atomics
TRISO	tristructural isotropic

TRL	technology readiness level
TRU	transuranic
ZPPR	Zero Power Physics Reactor Facility



INTRODUCTION

Picture on the front depicts: During nuclear reactor operation, an oxidation process within the fuel's protective cladding results in the creation of compounds called hydrides. Hydrides do not significantly impact the performance of modern reactors, but can lead to embrittlement and cracking during long-term fuel storage. By combining modeling with experimental work, researchers can predict hydride orientation under dry storage conditions as a function of stress and irradiation history. A technique called electron backscatter diffraction generated data for this inverse pole figure map, which illustrates the orientation of hydride constituents in nuclear fuel cladding.

1. INTRODUCTION

The primary mission of the U.S. Department of Energy's (DOE's) Office of Nuclear Energy (NE) is to advance nuclear power as a resource capable of meeting the nation's energy, environmental, and national security needs by resolving technical, cost, safety, proliferation resistance, and security barriers through research, development, and demonstration (RD&D) as appropriate.[b] DOE-NE's program is guided by the following four principle objectives:

1. Develop technologies and other solutions that can improve reliability, sustain safety, and extend the life of current reactors.
2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.
3. Develop sustainable fuel cycles.
4. Understand and minimize the risks of nuclear proliferation and terrorism.

Further innovation is necessary for nuclear energy to provide the maximum benefit toward the nation's energy goals and to maintain the United States' historical leadership in nuclear energy, which is steadily eroding. While innovative ideas and concepts exist, the RD&D needed to bring these ideas to a commercial readiness is lengthy and expensive. DOE-NE's strategy for moving innovative ideas to the marketplace centers on the Gateway for Accelerated Innovation in Nuclear (GAIN)[c] Initiative. Idaho National Laboratory (INL) acts as the integrator for the GAIN initiative and provides much of the nuclear research and development (R&D) capability needed to develop advanced nuclear energy technology and provide the basis for moving this technology toward commercialization.

In all industrial and commercial sectors, advances in technology result from a continuous cycle of RD&D. An understanding of the fundamental physical behavior of materials and systems is required to predict the response those materials and systems have to changes in design. This knowledge is obtained through research and shaped through development. Subsequent demonstration ensures a system operates as designed. In the nuclear industry, this RD&D cycle must be robust enough to ensure the safety of the system is sufficient to protect itself, workers, and the public. Once proven, the system can be licensed for operation. Specialized facilities are needed to conduct the full range of nuclear RD&D activities that result in deployment of new nuclear energy technologies. These facilities are complex, highly regulated, and very expensive to develop and maintain. Because of this, most are owned by the U.S. federal government (i.e., DOE and the Department of Defense) and operated by the national laboratory contractors. As such, these facilities are not operated in a manner that makes them easily accessible by entities trying to commercialize innovative nuclear components and systems.

Recognizing these challenges, DOE has established GAIN with a goal to make state-of-the-art nuclear RD&D capabilities available in a manner that allows the cost-effective development of innovative nuclear energy technologies from conception to commercial readiness. GAIN's objectives are twofold:

1. Faster and less expensive maturation of the technologies toward engineering-scale demonstration
2. Reduced risk of commercial deployment and the cost uncertainty associated with commercial units, which typically require construction and operation of a demonstration system.

Additionally, DOE-NE has been working over the past decade to establish a comprehensive nuclear RD&D capability at INL's Materials and Fuels Complex (MFC). MFC (Figure 1-1) was constructed and operated for more than 30 years as a reactor and fuel cycle demonstration site, supporting operation of the

[b] "Nuclear Energy Research and Development Roadmap: Report to Congress," U.S. Department of Energy, Office of Nuclear Energy (April 2010).

[c] gain.inl.gov

Experimental Breeder Reactor-II (EBR-II) and four other research reactors. MFC maintains this core capability to support existing and future missions and demonstrations. Through GAIN, these core capability assets will be made available to the nuclear industry. These assets can be used to inform the selection of appropriate technologies for development, help further that development, and establish the operating envelope necessary to provide a sound technical basis for an integrated demonstration at an appropriate scale. Effective use of this capability has the net effect of reducing the financial risks for investors and building a strong technical case for licensing of demonstration units.

Figure 1-1. Materials and Fuels Complex.

Consistent with the goals of DOE-NE, INL has identified two strategic initiatives:

- Accelerate deployment of advanced nuclear energy technologies by delivering a U.S. nuclear test bed. A test bed is defined as a platform for conducting RD&D in a rigorous, reproducible manner that manages risk, overcomes barriers to deployment, and facilitates commercialization of new ideas and technologies, including deployment of a small modular reactor.
- Advance management and disposition of nuclear waste by addressing existing inventories of spent nuclear fuel and high-level waste, supporting continued operations of existing reactors, and developing infrastructure for small modular reactors and advanced reactors.

1.1 A Science Strategy for the Materials and Fuels Complex

INL intends for MFC to continue its support of current missions while enabling new projects and missions as part of revitalizing and growing the nuclear energy test bed. The strategy described in this document will guide the efforts to build, expand, and sustain DOE-NE research capabilities at MFC, increase access to MFC, and revitalize the existing MFC nuclear infrastructure. The strategy also anticipates and guides the preparations necessary for demonstration of advanced nuclear energy technologies in support of DOE and INL strategic objectives.

MFC's existing core research and/or production competencies exist in the following areas:

- Nuclear fuels
- Radiation damage in cladding and in-core structural materials
- Fuel recycling
- Focused basic research
- Nuclear nonproliferation and nuclear forensics
- Space nuclear power and isotope technologies.

The strategy for MFC entails building and improving on these core competencies, introducing new and revitalized capabilities, and introducing new business and operations models to help transform MFC into a complex capable of supporting large RD&D projects. The strategy for MFC is presented in several parts; each focusing on an element needed for success.

Key features of this strategy as summarized in the executive summary include the following:

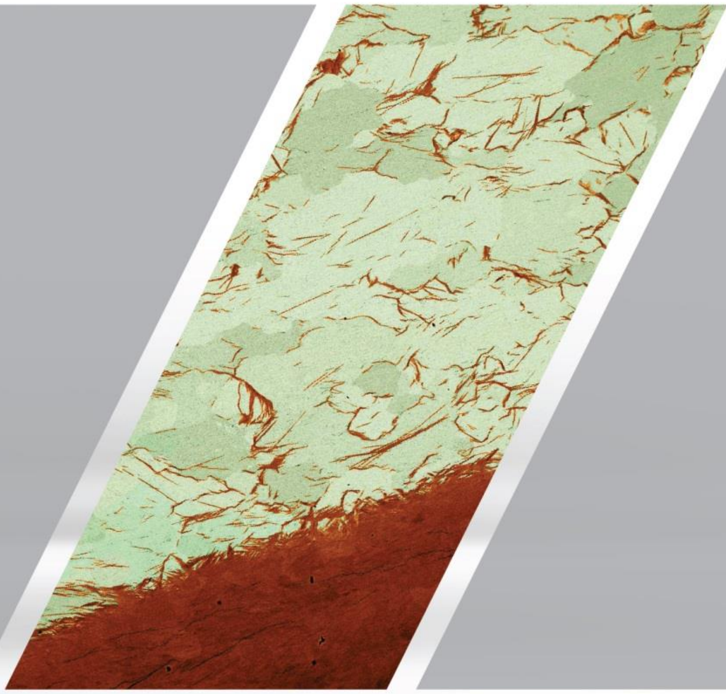
- Focusing research and capability development in areas where MFC has a core strength.
- Prioritizing and pursuing funding for construction of needed capabilities where none exist.
- Leveraging the key GAIN partnerships with Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, and others.
- Developing relationships and furthering partnerships with DOE-NE's extended research network to fill capability gaps that will not be added to MFC.
- Improving or establishing relationships with U.S. universities to further extend MFC's research network, provide a pipeline for recruiting future staff, and positively influence the educational programs whenever possible.
- Reviving and improving historical MFC capabilities that support demonstration-scale activities of nuclear systems.
- Supporting the programmatic objectives by maintaining, improving, and constructing new support infrastructure, as needed, to ensure the safe operation of MFC.
- Working with customers, partners, and regulators to develop improved methods for achieving regulatory approval in support of commercializing advanced nuclear energy technology; continued safe, economic, and secure operation of current nuclear systems; and management and disposition of used nuclear fuel.
- Establishing a leadership model that promotes collaboration across the multiple MFC organizations, takes ownership for MFC, and is accountable for delivering results to achieve the outcomes desired (and documented) in this strategy. Reliable performance with respect to schedule, budget, safety, and quality are critical to meeting DOE and INL goals.

- Implementing an operations model that improves the efficiency, reliability, and safety of MFC operations.
- Transitioning to a user facility-like model that increases research capacity and allows improved access to nuclear R&D capability at MFC. This model will ensure that a cadre of expert staff and a state-of-the-art research capability are available to support an effective implementation test bed and may include extending the user-facility model to DOE-NE's extended research network, as appropriate.

This strategy also includes important strategic research initiatives to develop significant new RD&D capabilities anticipated to enable impactful outcomes in the future. These initiatives are described as follows and are embedded throughout Section 4:

- Development and demonstration of additive manufacturing for nuclear fuels, fuel assembly components, and irradiation experiments.
- Integration of experimental and modeling and simulations efforts to improve nuclear energy RD&D efficiency and outcomes, reduce nuclear energy RD&D timelines and costs, demonstrate the science-based approach, and, ultimately, enable the ability to develop and demonstrate more predictive modeling and simulation capabilities.
- Development of instrumentation and methods that dramatically increase post-irradiation examination (PIE) throughput, provide higher quality data, and/or expand our capabilities to support nuclear energy RD&D.
- Development and demonstration of technology that enables the EBR-II spent fuel treatment product to be used to fuel a future test or demonstration reactor (i.e., improve the Fuel Conditioning Facility [FCF] process to produce uranium with acceptable quality specifications and radiation levels that support manual fuel fabrication).
- Develop and demonstrate the ability to manufacture Training, Research, Isotope, General Atomics (TRIGA) fuel at MFC.

Implementing this strategy will position DOE-NE to deliver an effective nuclear R&D test bed capability in support of current programs and further build an accessible, comprehensive, reliable, and cost-effective nuclear RD&D. This capability will play a key role in addressing issues that currently impact the ability of U.S. nuclear energy technology to keep pace with a changing world energy market.



CORE STRENGTHS AND CAPABILITIES THAT SUPPORT THE NUCLEAR RESEARCH AND DEVELOPMENT TEST BED

Picture on the front depicts: During nuclear reactor operation, an oxidation process within the fuel's protective cladding creates compounds called hydrides. This scanning electron microscope image shows the orientation of hydride constituents, which helps INL researchers analyze the long-term effects of fuel storage.

2. CORE STRENGTHS AND CAPABILITIES THAT SUPPORT THE NUCLEAR RESEARCH AND DEVELOPMENT TEST BED

MFC and associated INL facilities provide critical expertise and capability that support the development of advanced nuclear energy technology. The infrastructure necessary to support nuclear energy development is outlined in Table 2-1.[d] Capabilities that are currently active or planned and funded to achieve operational status are identified, as well as historical INL capabilities where the critical infrastructure that supported them still exists. Future capability needs are somewhat dependent on specific technologies.

Table 2-1. Infrastructure necessary to support nuclear energy development.

Capability	Current Capability	Planned Capability	Future Needed Capability	Historical Capability
Thermal test reactor	Advanced Test Reactor (ATR)			
Transient Test Reactor Test Facility (TREAT)		TREAT		
Fast spectrum testing capability			X	EBR-II
In-pile instrumentation for targeted phenomena	Multiple, including ATR and TREAT			
Nuclear materials characterization and examination	Hot Fuel Examination Facility (HFEF), Analytical Laboratory (AL), Irradiated Materials Characterization Laboratory (IMCL)	Sample Preparation Laboratory (SPL)		
Out-of-pile testing with radioactive materials (IMCL and SPL)	IMCL	SPL		
Reconfigurable thermal-hydraulic loops of different scale and heaters	University and industry capabilities		X	
Component fabrication and testing (e.g., machine and instrumentation and controls shops and Engineering Development Laboratory)	Multiple			
Process development and testing (e.g., FCF and HFEF)	FCF and HFEF			
Reactor physics testing	ATR-C			Zero Power Physics Reactor (ZPPR)
Centralized modeling and simulation knowledge and validation function			X	

[d] Kemal Pasamehmetoglu, "U.S. DOE-NE Programs and Nuclear Energy Innovation Workshops," *NEA International Workshop on Nuclear Innovation*, July 7 and 8, 2015.

Capability	Current Capability	Planned Capability	Future Needed Capability	Historical Capability
Ion beam facilities	Capabilities at Nuclear Science User Facility (NSUF) partner facilities			
Analysis of radioactive materials at Basic Energy Sciences user facilities	Advanced Photon Source, National Synchrotron Light Source–II		Increased access	
Modeling and simulation and high-performance computing	Multiple		X	
Reactor-specific fuel fabrication capabilities			X	

Reactor-specific fuel fabrication capabilities are also required to support a reactor demonstration. These capabilities may be commercially available or require a demonstration plant located near the reactor.

2.1 Core Strengths of the Materials and Fuels

MFC successfully supported demonstration of EBR-II and its associated research and testing programs over a period of nearly 30 years. Building on this foundation, DOE-NE has invested heavily in the core research instruments and infrastructure at MFC and TREAT over the last decade to maintain a viable national nuclear research capability. This core capability includes engineering-scale, microstructural, and chemical characterization of irradiated fuels and materials, spent fuel processing and treatment, transient testing, radioanalytical chemical analysis, fuel fabrication, component fabrication and testing, nuclear material storage and transportation, waste handling, engineering, and support infrastructure. These virtually irreplaceable capabilities, coupled with ongoing DOE-NE investments in advanced research capability, are a national asset. Continuing investment in these areas over the next decades will increase facility reliability and cost effectiveness and fill gaps in capabilities that are critical to support DOE-NE research and the nuclear energy test bed. MFC also plays a central role in accessing DOE-NE's extended research network by providing valuable sample material, sample preparation, shipping, and logistical support for research at other facilities through DOE-NE's NSUF.

It is also notable that INL's National and Homeland Security Science and Technology Directorate is integrated into many of the facilities conducting R&D activities for nuclear nonproliferation and counterproliferation, nuclear forensics, nuclear facility security, nuclear material safeguards and material accountability and control, critical infrastructure protection, cyber security, and materials technology. MFC also supports important research for the Naval Reactors Program.

2.1.1 Materials and Fuels Complex Facilities

Figure 2-1 presents a map of the MFC facilities. Additional information on each facility is presented in Appendix A. Robust research capabilities exist in the following areas:

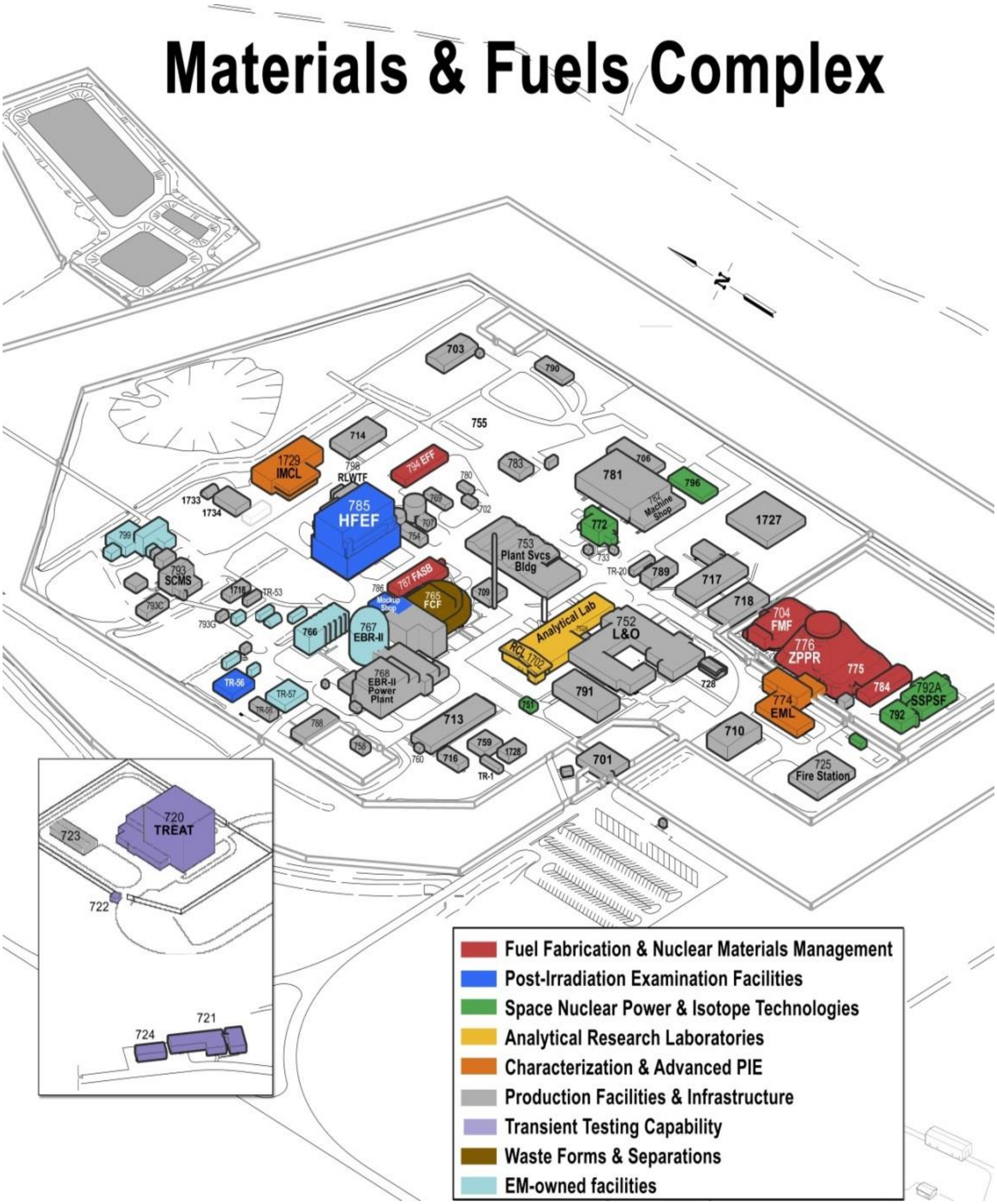


Figure 2-1. Materials and Fuels Complex.

- Fuel fabrication and nuclear material management facilities used to develop new fuels and fabrication processes:
    - Fuel Manufacturing Facility (FMF) – Fabrication of fuel using Hazard Category 2 quantities of uranium, plutonium, and minor actinides in various gloveboxes. For example, the Neptunium Repackaging Glovebox is used to repackage and recertify containers used to ship Np-237 in support of the Pu-238 Supply Project.
    - Fuels and Applied Sciences Building (FASB) – Multi-program radiological laboratory focused on casting, processing, and property measurements of uranium-based materials. FASB also houses specialized hot cells for conducting irradiation-assisted stress corrosion cracking (IASCC) measurements on high-dose-rate materials critical to understanding materials aging in the current reactor fleet; this is the only capability of this type in the United States and one of two in the world.
    - Experimental Fuels Facility (EFF) – Multi-program radiological laboratory focused on machining and fuel rod assembly of uranium-based materials, including accident-tolerant fuels and metal fuels.
    - ZPPR – Nuclear material storage and nuclear nonproliferation detection laboratory that supports DOE-NE, the National Nuclear Security Administration (NNSA), the U.S. Department of Defense, and the Department of Homeland Security.
- PIE:
    - HFEF – PIE and testing of a wide range of nuclear fuels and materials. Provides an entry point for shipments to the research complex with extensive cask-handling capabilities. Focuses on engineering-scale performance measurements through nondestructive characterization. Capability for Hazard Category 2 quantities of nuclear fuel and materials.
    - IMCL – State-of-the-art analysis of irradiated fuels and materials on the microstructural to atomic scales. Tightly coupled with HFEF. Handles Hazard Category 2 quantities and high dose rate materials as a user facility. Outfitting with research equipment and shielded cells is in progress. Initial operation with highly active materials will begin in Fiscal Year (FY) 2017. Installation of all currently funded research capability will be completed prior to FY 2018.
    - Electron Microscopy Laboratory – Radiological laboratory focusing on microstructural analysis of unirradiated fuels and materials and small quantities of irradiated fuels and materials.
    - SPL – Future facility focused on analysis of irradiated structural materials. Closes an identified nuclear energy research capability gap by greatly increasing sample throughput and nanoscale research capability. SPL will provide a central point for DOE-NE research collaborations because of its ability to prepare, analyze, and ship alpha-free materials to universities, industry partners, and other DOE user facilities for research. This network provides specialized capabilities and access to a greater portion of the national intellectual capital. SPL currently has an approved mission need.
- Analytical research laboratories:
    - AL – Complete chemical and isotopic characterization capabilities that include shielded cells for chemical analysis and state-of-the-art methods for analysis of fuels and materials up to Hazard Category 3 limits. Transuranic (TRU) thermophysical property measurements and TRU casting capabilities.
    - Radiochemistry Laboratory – Development of bench-scale methods for aqueous reprocessing technology.

- Waste forms and separations:
  - FCF – Capability for conducting world-class research on pyrochemical processing and capability for handling sodium-bonded spent nuclear fuel.
  - Remote Analytical Laboratory (RAL) (Idaho Nuclear Technology and Engineering Center [INTEC] CPP-684) – RAL is one of DOE's newest hot cell facilities. The facility is currently maintained in standby mode. It may be reactivated in the future as a resource for nuclear test bed support or development of isotope technologies.
  - INTEC-653 – Material recovery processes and unirradiated pilot plant capability.
- Space nuclear power and isotope power:
  - Space and Security Power Systems Facility (MFC Buildings 792 and 792A) – Used for final assembly, testing, and interim storage of radioisotope power systems (RPS) for use by National Aeronautics and Space Administration and other customers. The Space and Security Power Systems Facility is a Hazard Category 2 non-reactor nuclear facility. This facility is fully funded by space nuclear power program sponsors and it was built in 2004. Appendix B contains detailed descriptions of the Space Nuclear and Isotope Technologies facilities and planning basis.
  - Engineering Development Laboratory (MFC Building 772A) – Used to fabricate, assemble, mock-up, and test various R&D and production equipment, mostly for space nuclear power customers. The facility includes equipment and gloveboxes for welding, including an electron-beam welder, furnaces for bake-out of graphite components, forming equipment for heat source hardware, and various machine tools.
  - Radioisotope Systems Training and Servicing Facility (INTEC Building B21-625) – Used to store, service, and conduct training for the radioisotope thermoelectric generator transportation system and other storage-related hardware for space nuclear power customers.
  - Radioisotope Conference and Learning Facility (MFC Building 751) – Used to display models and actual components that have been used in historical space nuclear power systems. Previously scheduled to be torn down; however, this building now highlights the significance of MFC's role in space and is now often included in tours by MFC visitors.
- Transient testing capability:
  - TREAT – Transient testing of nuclear fuels is needed to develop and prove the safety basis for advanced reactors and fuels. The current critical infrastructure gap will be addressed through resumption of operations at TREAT and development of supporting scientific infrastructure. The TREAT reactor is located near MFC and relies on MFC capabilities for assembly of experiment modules to be inserted into TREAT, PIE, and other essential support services. In addition to large-scale testing, the TREAT facility's open core design provides an ideal platform for understanding the response of materials and fuels to irradiation on a fundamental level (Figure 2-2).

Figure 2-2. Transient Test Reactor at MFC.

Coupled with ATR irradiation capabilities, improvements to measurement technology and expanded data analysis, modeling, and simulation capabilities, MFC research capabilities have the potential to increase the rate of knowledge generation that directly supports nuclear energy innovation one to two orders of magnitude. This large increase in information generated by R&D, coupled with a demonstration capability, will have a profound impact on deployment of advanced nuclear energy technology, resulting in a reduction in development timelines, reduced investment risk, shorter time to market, and deployment of new technology by the commercial nuclear sector.

2.1.2 Materials and Fuels Complex Research and Development Focus Areas

Along with MFC's physical research and production capabilities described in Section 2.1.1, personnel expertise, material assets, and historical missions have resulted in capabilities and expertise in six key areas in support of development and deployment of advanced nuclear energy technology. These six areas provide the technological basis for advancing and protecting the nuclear fuel cycle, addressing a significant portion of current reactor economic issues, improving safety performance, and establishing a basis for potential technological breakthroughs. MFC will continue to focus on and develop capability in the following focus areas:

1. Nuclear fuels – Continuing advances in light water reactor (LWR) fuel technology have been critical to increasing performance of the current fleet and may increase tolerance to severe accidents. Developing advanced nuclear fuels is central to deploying advanced nuclear systems that have significant advantages over LWRs in terms of efficiency, waste generation, safety, and proliferation resistance; advanced reactors cannot function without advanced fuels. MFC currently has the capability to produce nearly any fuel type on a research scale. MFC has previously operated production-scale fuel fabrication capabilities (i.e., FMF) in support of EBR-II.

2. Radiation-tolerant materials – The life-limiting factors in both fuel and reactor operating lifetime are cladding and structural materials. Understanding and overcoming the effects of high radiation damage levels is instrumental in maintaining the current fleet and developing advanced reactors. MFC capabilities for sample storage, preparation, and characterization on the nano and atomic scales are key to this research. SPL is an important part of the strategy for enabling access of material samples and research capability to the broader nuclear energy research community.

3. Fuel recycling – Nuclear fuel cycles that increase uranium resource utilization and reduce nuclear waste are required to reduce long-term risk of waste disposition, support a greater level of public acceptance of nuclear power, and support a more economical closed fuel cycle. MFC capabilities and expertise include engineering-scale capabilities for pyroprocessing, bench-scale capability for development of aqueous processes, and potential to expand the FCF mission or utilize RAL for fuel cycle demonstrations if appropriate.

4. Focused basic research – Focused basic research sets the stage for advances in technology through advances in the fundamental understanding of the underlying physics and chemistry of material behavior in the nuclear environment. DOE investment in IMCL as a user facility sets the stage for increased work in this important area. Completion of SPL will support sample preparation, enabling broader access to Basic Energy Sciences user facility partners (such as the National Synchrotron Light Source–II at Brookhaven National Laboratory and the Advanced Photon Source at Argonne National Laboratory) that can handle only very small quantities of material with low levels of alpha contamination.

5. Nuclear nonproliferation and nuclear forensics – Critical initiatives in this area include safeguards by design, addressing proliferation threats from rogue organizations and governments, support for nuclear forensics, materials protection, and control and accountability for protecting current and future reactors and nuclear fuel cycle facilities world-wide. MFC's inventory of strategic materials is used to conduct R&D on detection and characterization for DOE-NE, NNSA, the U.S. Department of

Defense, and the Department of Homeland Security, often acting in the manner of a collaborative user facility. This capability should be extended to develop and demonstrate safeguards technology appropriate for inclusion in new facility design.

6. Space nuclear power and isotope technologies – Production of RPS has been an ongoing endeavor for DOE and its predecessor agencies for the past five decades. The overall mission of the RPS Program is to develop, demonstrate, and deliver compact, safe nuclear power systems and related technologies for use in remote, harsh environments (such as space), where it is impractical to provide the fuel and maintenance that more conventional electrical power sources require.

Continuing to build on these strengths provides increased capability for the critical aspects of the nuclear test bed and demonstration platform. These focus areas align with two primary core capabilities defined by the DOE-NE Core Capability Definitions. Focus Areas 1 through 5 group largely under the Nuclear and Radiochemistry and the Nuclear Engineering core competency categories. Focus Area 6 is more closely associated with the Applied Nuclear Science and Technology core competency category.

2.2 Accessing the U.S. Department of Energy Office of Nuclear Energy's Nuclear Science User Facilities Extended Research Capability

INL was recently identified as the integrating laboratory for the GAIN Initiative. In some cases, MFC research capability, personnel expertise, or capacity may not be appropriate to complete an R&D task. INL, which includes MFC, provides a link to DOE-NE's extended research capability through the NSUF, which is shown in Figure 2-3. Current NSUF partner facilities include the following:

- Center for Advanced Energy Studies
- Argonne National Laboratory (Illinois Institute of Technology's Advanced Photon Source)
- Massachusetts Institute of Technology
- North Carolina State University
- ORNL
- Pacific Northwest National Laboratory
- Purdue University
- University of California – Berkeley
- University of Michigan
- University of Nevada – Las Vegas
- University of Wisconsin
- Westinghouse Nuclear.

The specific capabilities offered by each of these NSUF partner facilities can be accessed through the NSUF website.[e]

International partners already established through ongoing cooperative DOE-NE and NNSA programs also have significant interest in accessing advanced nuclear research capability at MFC. Further enhancing DOE-NE's research capability will strengthen international nuclear energy cooperation by enabling international research exchanges. SPL, when completed, will provide a central hub for accessing

[e] www.atrnsuf.inl.gov

this extended research capability by providing high-quality, alpha-free samples to partner facilities, both domestically and internationally, and by providing an increase in user-accessible capabilities at MFC.

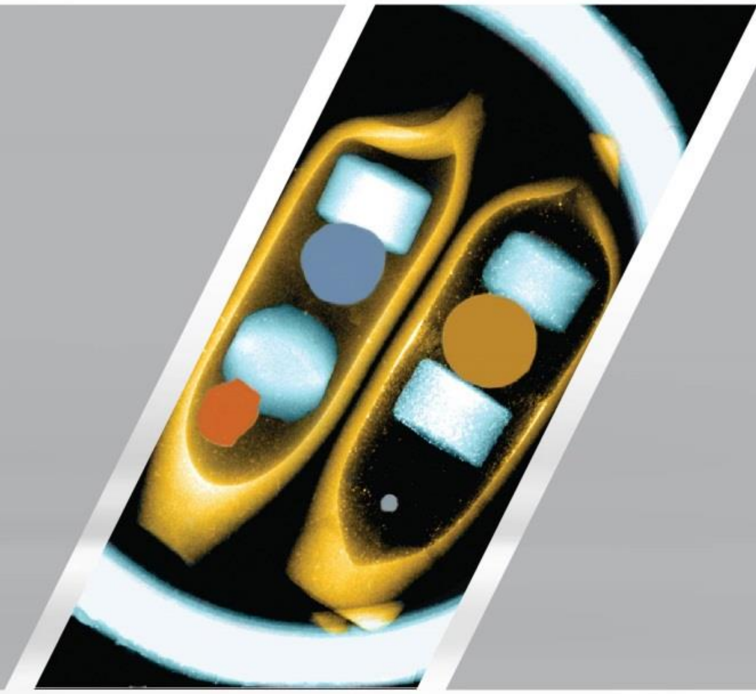
Figure 2-3. NSUF partner facilities and user institutions.

2.3 Materials and Fuels Complex Capabilities that Support Demonstration of Nuclear Technology

Requirements for demonstrating and deploying first-of-a-kind nuclear systems include the following:

- A well-characterized DOE site:
  - National Environmental Policy Act coverage
  - External hazards risk data and assessment
  - Buffer zone
  - Emergency planning
- Safeguards and security infrastructure
- Connections to grid and/or process heat applications infrastructure
- Civil engineering infrastructure:
  - Roads and transportation access
  - Utilities and water rights.

The INL Site has a long history of functioning as a nuclear demonstration platform. Founded by the Atomic Energy Commission as the National Reactor Testing Station, 52 reactors have been designed, built, and operated on the INL Site by entities ranging from the U.S. Army and Navy to Argonne National Laboratory and General Electric. MFC hosted one of the longest running reactor demonstration programs. EBR-II was a successful demonstration of sodium-cooled fast reactor technology that produced nearly half of the electricity needed for INL Site operations. EBR-II and the nearby FCF proved the concepts of fuel recycling and passive reactor safety characteristics, as well as demonstrated closure of the fuel cycle. During this period, MFC operated as a self-contained site, with all infrastructure required to support fueling, operations, and experiments associated with EBR-II. These capabilities are still used today as a critical component of DOE's nuclear research infrastructure.



IMPLEMENTING A NUCLEAR ENERGY RESEARCH, DEVELOPMENT, AND DEPLOYMENT TEST BED AT THE MATERIALS AND FUELS COMPLEX

Picture on the front depicts: Scientists need highly specialized instruments to determine how materials withstand the extreme environment inside a nuclear reactor core. This device will indicate the temperature at which different materials melt. Here, engineers evaluated how well quartz spacers (white squares) kept lead, aluminum, gold and silver wires (colored circles) separated when the pack was heated to 1475°C (2687°F).

3. IMPLEMENTING A NUCLEAR ENERGY RESEARCH, DEVELOPMENT, AND DEPLOYMENT TEST BED AT THE MATERIALS AND FUELS COMPLEX

Reestablishing MFC as a national nuclear test bed provides an effective and efficient method for meeting DOE goals for nuclear energy technology development.. DOE-NE has made significant investments in MFC over the last decade, including current funding for research capability in IMCL, HFEF, TREAT, and SPL. This investment forms the foundation for meeting nuclear R&D needs using both MFC and DOE-NE's broader research network.

3.1 Attributes of a Nuclear Research and Development Test Bed

Driving advanced technology to the market requires addressing the primary barriers to innovation while understanding funding and resource constraints. Addressing the technological (i.e., first) barrier to innovation requires implementation of a research capability that quickly and efficiently provides answers to technological questions.

In the non-nuclear world, development of advanced technology occurs rapidly because it is supported by abundant and easily accessible research capability. Accelerating nuclear innovation requires similar availability to research capability, thus increased availability to research capability is key to shortening the R&D cycle. Nuclear research facilities are high-hazard facilities that are heavily regulated and are expensive to acquire and maintain. Few of these facilities are currently operable in the United States and abroad. Because the number of these R&D facilities is limited, it is important that the available facilities be utilized to the greatest extent possible. This document presents a strategy for increasing nuclear R&D throughput and shortening the nuclear experiment lifecycle, which requires the following:

- Reliable and available research facilities
- State-of-the-art research instruments
- A dedicated cadre of world-class scientists, engineers, technicians, and support staff
- Planning and funding processes that maximize the use of instruments and generation of research data.

With sound planning and appropriate investment, existing MFC facilities can nearly quadruple their utilization and support capacity by moving from a 4-day, 40-hour work week to a 7-day-a-week schedule, consistent with the majority of world-class science user facilities. Most MFC research facilities, although fundamentally sound, are now four or five decades old. During the mid-1990s, maintenance of these facilities was limited. Recent DOE-NE investment has considerably improved facility reliability. A proposal for managing acquisition, improvement, and maintenance of research facilities that proactively meets the needs of the nuclear innovation community is presented in Section 5 of this strategy. In addition to increased operating hours, the operational efficiency of these facilities must be increased through improvements in the MFC operational model.

The type, quality, and performance of the instrumentation available to advanced nuclear development teams is critical for ensuring generation of relevant, high-quality information sufficient to overcome technological hurdles. The quality and performance of the instrumentation available to researchers is critical to ensuring the right data are generated to support nuclear R&D teams. Instruments used in nuclear research require special modifications for radiological materials, increased attention to maintenance and replacement, and the ability to respond to requests for new types of data, higher resolution, and improved analysis methods. The data associated with a nuclear experiment can encompass dozens of data streams, including hundreds of millions of data points and hundreds of gigabytes of data. As three-dimensional data acquisition becomes more prevalent and new instruments and methods are adopted for nuclear research, the amount of data will continue to increase. Data without analysis has little value. Information is necessary to drive nuclear innovation and information comes only after in-depth analysis. Tools required for the correct and efficient analysis of data are critical to driving nuclear innovation. Data management and instrument and analysis capabilities must be proactively managed to ensure the right capabilities are in place to produce the right information. Research capability needs are discussed in Section 6 of this strategy.

A dedicated cadre of scientists, engineering technicians, and support staff is also critical to ensuring the efficient generation of high-quality information that moves innovative concepts up the scale of technology readiness. Instrument scientists and engineers are responsible for ensuring that each research tool is performing at its peak level and for continuously improving research capabilities through innovations in data analysis and instrument hardware. These scientists, engineers, and technicians require a specific skill set to operate sophisticated research instruments, interpret data, and safely and effectively conduct research in a nuclear facility. These skills are acquired and honed by training and experience over several years. As MFC research facilities extend capabilities and operating hours to meet user requests, additional instrument scientists and support staff will be required. In order to be effective in helping drive innovation, these staff must be able to focus in a manner that allows them to be world-leading experts. Growth in research requests over the next 5 years will exceed the existing staff's ability to support additional work under the current operating model. A user-facility like model for developing personnel must be cultivated that allows both hiring in advance of need and more efficiently and effectively increasing, introducing, and reinforcing the core principals and critical skills required to build competence. Human capital needs are discussed in Section 7 of this strategy.

Improvements to the MFC operational model are discussed in Section 3.2. A user-facility like model that allows building, improving, and sustaining this critical national nuclear R&D capability is proposed in Section 3.3.

3.2 Improving Operational Effectiveness

Delivery of information to nuclear innovators that is timely, cost effective, and of high quality is critical to shortening the nuclear development cycle and essential to the success of a nuclear energy test bed. Several initiatives are being implemented at MFC that emphasize reliable and efficient R&D operations, increased safety performance, and increased access to capabilities, including the following:

- Enhanced safety culture and use of human performance improvement tools
- Integrated work planning
- Facility reliability plant health investments.

About 80% of all safety events are attributed to human error.[f] Human error is universal and cannot be prevented. Despite the inevitability of human error, in general, specific errors are preventable through an emphasis on human performance improvement. Using human performance improvement tools, error-likely situations can be predicted, managed, and prevented. Recognizing error traps and actively communicating and managing these hazards proactively manages situations and prevents the likelihood of error. Individual performance is improved by addressing underlying organizational processes, culture, and management planning and control systems that contribute to most causes of human performance problems and resulting facility events. People achieve higher levels of performance through implementation of a 'just culture' that provides positive reinforcement of good behavior from leaders, peers, and subordinates and consequences for unsatisfactory behavior.

Practical implementation of human performance improvement requires providing personnel with a set of tools that are easily implementable and reinforced on a daily basis. These tools are described in Figure 3-1. Reinforcement of the use of these tools is provided through interactive training and regular management presence in the field.

[f] DOE-HDBK-1028-2009, "Human Performance Improvement Handbook," June 2009.

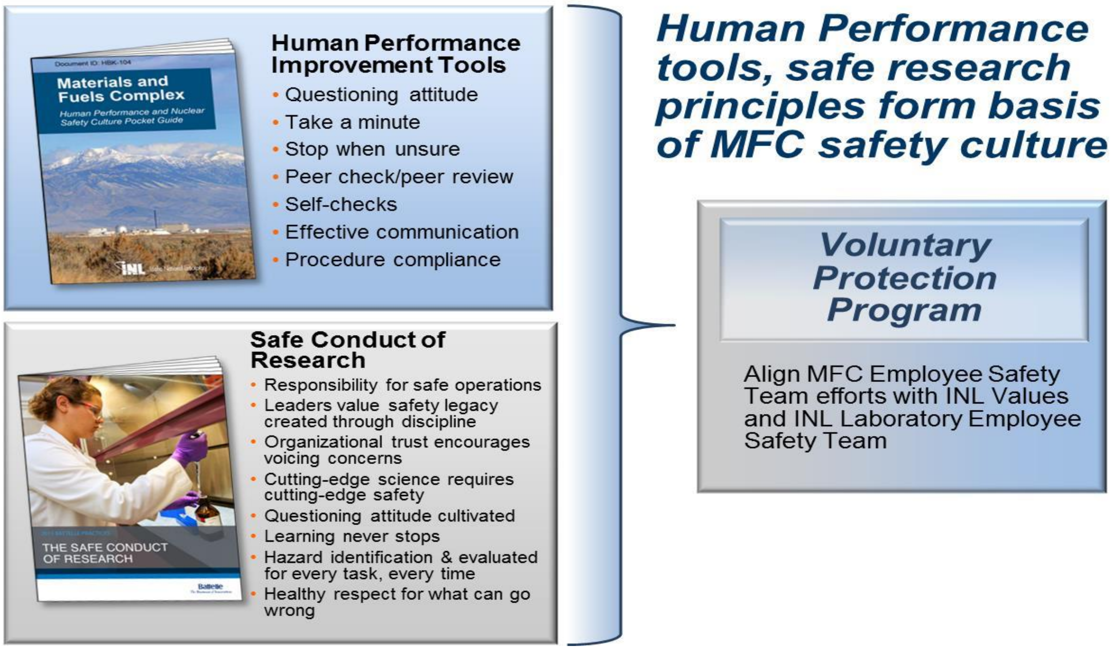


Figure 3-1. MFC safety culture overview.

Human performance improvement requires a combination of both proactive and reactive approaches to manage issues. Traditionally, improvement in human performance has resulted from corrective actions derived from an analysis of facility events and problem reports, which is a method that reacts to what happened in the past. Anticipating how an event or error can be prevented is proactive and is a more cost-effective means of preventing events and problems from developing. Proactive management of issues through development and execution of a structured improvement agenda is an important tool for improving performance. Management of issues that do occur is conducted with an understanding of the extent of the conditions that effectively address the issue, while reducing the impact to site-wide operations.

Integrated work planning is an important performance improvement tool and will be implemented at MFC beginning in FY 2017. Goals for integrated work planning include the following:

- Improvement in cost and schedule performance by ensuring people, processes, and equipment are ready to conduct the planned work scope
- Improvement in safety performance by ensuring field work is planned and vetted appropriately
- Ensuring staffing, processes, facilities, and specific research capabilities are available in advance of need
- Obtaining a clear understanding of the cost of conducting specific activities
- Developing the trust and confidence of DOE, industry, and university collaborators enables the development and deployment of advanced nuclear technology.

Figure 3-2 provides an example flow chart that is used to clearly map and communicate work scope to facilities and equipment (and by extension to staffing and procedural needs). Understanding exactly what instrument is needed in which facility and at what time allows MFC to optimize facility and instrument use.

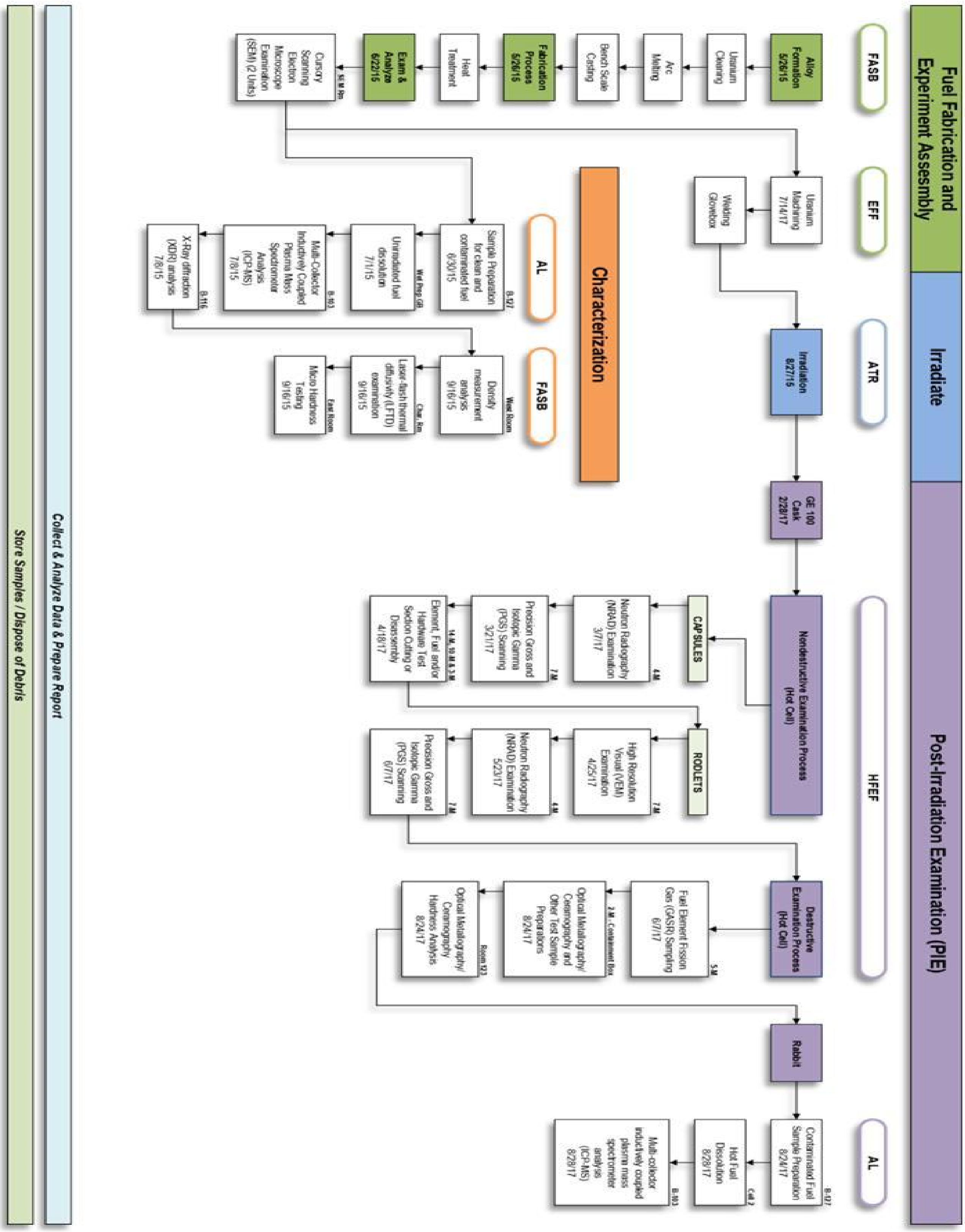


Figure 3-2. Example of experiment process flow.

Plant health investments in MFC assets ensure that facility availability is increased to the maximum extent possible. R&D activities, execution of maintenance to ensure facility reliability, and upgrades to research capability are planned together and balanced with the objective of optimizing research output over both the short-term and long-term. A detailed plant health investment strategy has been developed and compliments this science strategy. This plant health strategy identifies near-term (i.e., FY 2018 to FY 2022) and longer-term (i.e., FY 2023 to FY 2027) opportunities to increase the output of information from the MFC R&D capability. In general, as current facility reliability issues are addressed, the focus of life-cycle funding will shift to development of the R&D capability required to support generation of specific information that drives development of advanced nuclear technology.

3.3 Proposed Nuclear Research and Development Test Bed Funding Model

Implementing a sustainable and reliable nuclear R&D test bed requires a user-facility like model that supports effective plant health investments in assets critical to execution of the current DOE-NE research portfolio and in support of GAIN. A modified funding model is proposed to support building the DOE-NE RD&D capability required to support the test bed concept. The current funding model is not designed to simultaneously support the proactive management of infrastructure, research capability, and scientific and support staff needed for a nuclear test bed. The proposed user facility-like model provides the foundation for a comprehensive, reliable, and sustained research capability and also supports a stable environment for acquiring, training, and improving the expertise of the scientific and support work force, implements and continually improves capabilities that support the nuclear R&D test bed, and increases cost-effectiveness and reliability of operations. Building on this foundation will increase the output of technological information critical to bridging the barriers to innovation that currently limit deployment of advanced nuclear technology.

The proposed user-facility like model uses a consistent and simplified approach to funding (Figure 3-3) that aligns with the operation of MFC as an R&D test bed. It draws from the funding models used for successful operation of other national user facilities. The proposed funding model accounts for three key assets: (1) MFC Facility Base Operations and Facility Mission Enablement, (2) MFC Instrument Mission Enablement, and (3) MFC Experiment Infrastructure.

- MFC Facility Base Operations and Facility Mission Enablement includes base funding to support research facility operations and maintenance; reactor and hot cell fully qualified staff to operate, engineer, maintain, and support mission execution; and maintenance, operation, and engineering of nuclear research facilities and support systems such as maintaining the facility safety basis, inert gas, manipulators, windows, gloveboxes, and lighting to ensure safety and reliable performance. This includes MFC 5-year plant health investments for maintaining and improving facility reliability and availability.
- MFC RD&D Mission Enablement includes maintaining the technical and operational readiness of existing R&D capabilities and future support of a full spectrum of RD&D from basic research to preparation for deployment; RD&D instrument operations and maintenance to ensure a mission-ready capability, instrument performance specifications, and instrument service contracts; and existing support infrastructure such as test loops and associated instrumentation, safety basis, and procedures.
- MFC Experiment Infrastructure includes fully qualified scientists to perform science, ensure the laboratory has subject matter expertise, develop instruments and techniques, and collaborate with and grow the user community. This is also the key area where new RD&D techniques and capabilities are developed and deployed.

Details of proposed investments in facility and instrument infrastructure are available in the MFC Five-Year Plant Health Investment Strategy. This document accompanies this science strategy to provide scope recommendations and funding levels necessary for supporting revitalization of the nuclear energy test bed at MFC.

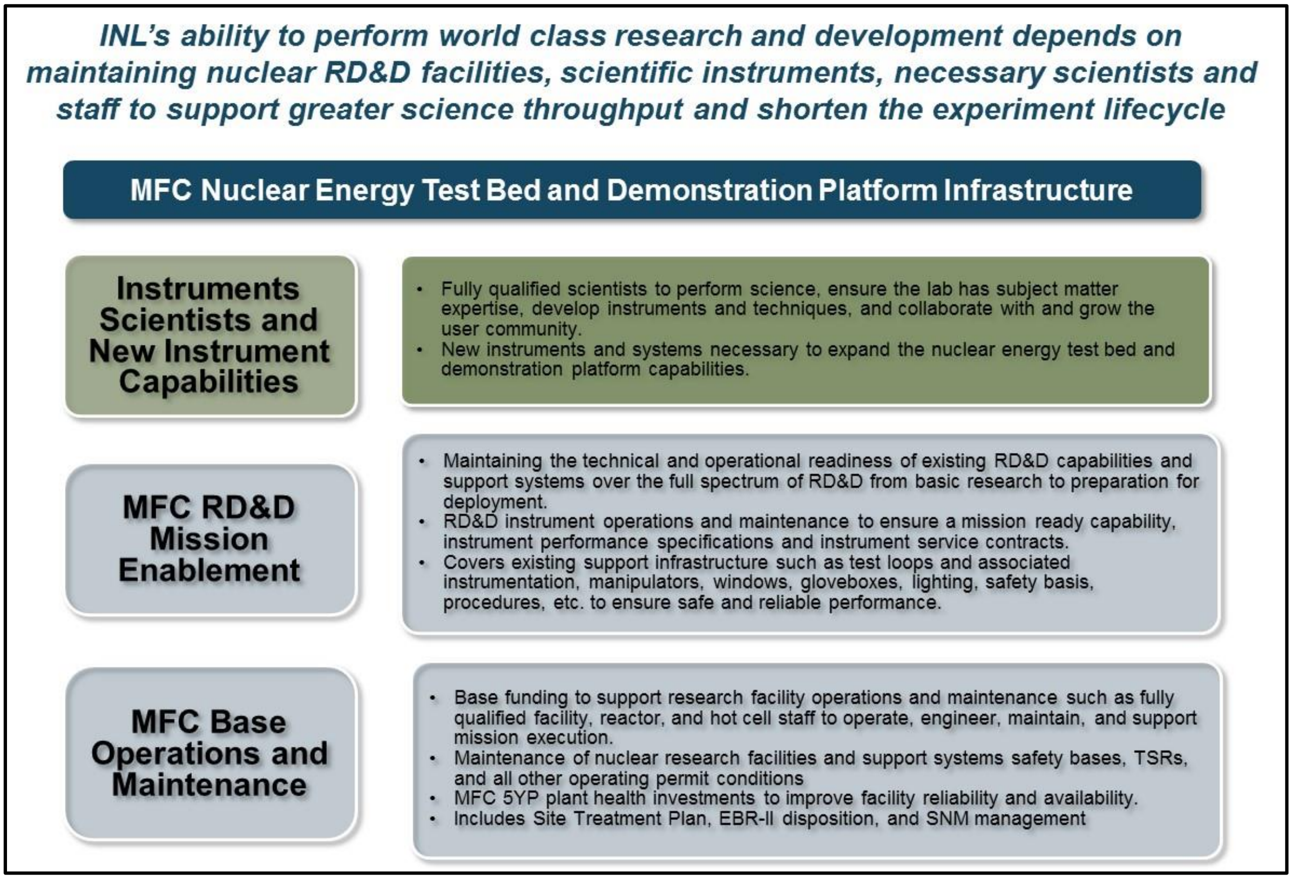


Figure 3-3. Proposed MFC funding model. INL's ability to perform world-class R&D depends on maintaining facilities, experiment infrastructure, scientists, and staff ready to support quality and efficient work.

Implementing a user-facility like model ensures that facilities, instruments, and personnel maintain readiness to support the increasingly complex and varied demands on MFC as DOE-NE's research mission expands in support of streamlined commercialization of advanced nuclear energy technology. Proactive management of R&D assets will increase research output, will be more cost effective, and will ensure that MFC is positioned to drive collaboration within the nuclear R&D community, increasing the generation of information and decreasing the length of the R&D cycle. A shortened and more efficient R&D cycle will result in a fundamental change in DOE-NE's ability to impact advanced nuclear energy. DOE-NE will drive international and industry collaboration that will be instrumental in reestablishing U.S. leadership in advanced nuclear energy, allowing the U.S. to realize the benefits of these technologies.

MATERIALS AND FUELS COMPLEX RESEARCH AND DEVELOPMENT PRIORITIES

Picture on the front depicts: INL researchers were the first in U.S. to perform the "Focused Ion Beam In-Situ Lift-Out" process on irradiated material. Here, they carved a tiny sample of irradiated nuclear fuel (gold) topped with a layer of platinum (blue) to protect the surface for examination.

4. MATERIALS AND FUELS COMPLEX RESEARCH, DEVELOPMENT, AND DEPLOYMENT FOCUS AREAS AND GOALS AND OTHER PRIORITIES

MFC was developed as a self-contained site that supports large research and demonstration projects, including EBR-II, FCF, TREAT, and ZPPR. The capabilities established by these programs now enable a wide range of research, development, and pilot-scale demonstration activities. These activities generate information on the performance of nuclear fuels and materials, the feasibility and efficiency of chemical processes, basic radiation damage processes, and nuclear nonproliferation.

MFC facility infrastructure, research capabilities, nuclear material inventory, and personnel have evolved over 50 years to support deployment of innovative nuclear energy technology in the following six key research areas:

1. Nuclear fuels
2. Radiation damage in cladding and in-core structural materials
3. Fuel recycling
4. Focused basic research
5. Nuclear nonproliferation and nuclear forensics
6. Space nuclear power and isotope technologies.

Tremendous opportunities exist in these areas to sustain the current reactor fleet and overcome the barriers that limit deployment of advanced nuclear technology. These opportunities include closing the fuel cycle and minimizing nuclear waste, incorporating safeguards instruments and methods into reactor and nuclear facility designs, improving reactor safety, and reducing nuclear energy life-cycle cost. These opportunities can be realized by shortening the nuclear technology development cycle to a timeframe that is consistent with commercial capital investment timelines and risk tolerance. Collaboration with universities, domestic and foreign national laboratories, national user facilities, small businesses, and the established nuclear industry further leverage MFC capabilities by bringing together a broader cross-section of nuclear energy expertise and capabilities to address important technical issues. Resolution of these issues decreases the technical, regulatory, and operational risks associated with commercialization of the next generation of nuclear technology.

These opportunities can be realized through a combination of improved utilization of DOE-NE's research network, continually improving R&D capability and facility reliability, and implementation of a methodology for more efficient management and analysis of the ever-increasing quantity of data produced.

4.1 Nuclear Fuels

The UO_2-zircaloy fuel system utilized today in commercial nuclear reactors has been in use throughout the history of commercial nuclear power. Incremental improvements in the basic design have been made over many decades to increase fuel lifetime and reliability. UO_2-zircaloy fuel has an excellent performance history; however, it is limited to use in LWR systems.

Developing advanced nuclear fuels is central to deploying advanced nuclear systems that have significant advantages over LWRs in terms of efficiency, waste generation, proliferation resistance, and safety; advanced reactors cannot function without advanced fuels. Knowledge of advanced fuel performance in advanced reactors is critical to demonstrating and deploying these systems.

MFC has the capability, experience, feedstock, and facility licensing that allows development of a wide breadth of fuel types that will significantly expand the range of technologies available to power nuclear reactors. MFC has been critical in positioning INL as a leader in the development of accident-tolerant fuels, including development of an U_3Si_2 fabrication process and processes for joining difficult-to-weld cladding alloys. MFC has been largely responsible for development work with plate-type research reactor fuels that has led to high-density uranium fuel meats and cladding systems that are currently being qualified. In addition, MFC and INL retain most of the world's expertise in fast reactor metal fuel.

Research on these fuel systems presents a number of scientific and engineering challenges that are discussed in the following subsections.

4.1.1 Fuel Research and Development Focus Areas

4.1.1.1 Accident-Tolerant Fuels. Fuels with enhanced accident tolerance are those that, in comparison with the UO_2-zircaloy system currently used by the nuclear industry, can tolerate loss of active cooling in the reactor core for a considerably longer time period (Figure 4-1). This performance must be maintained during normal operations, operational transients, and design-basis and beyond-design-basis events. Fuel system design objectives that are potentially important for improving accident tolerance include reduced hydrogen generation, improved fission product retention, improved cladding reaction to high-temperature steam, and improved fuel cladding interaction for performance under extreme conditions. Challenges specific to developing accident-tolerant fuels include fabricating new fuel types, determining behavior during transient irradiation conditions, and out-of-pile safety testing.

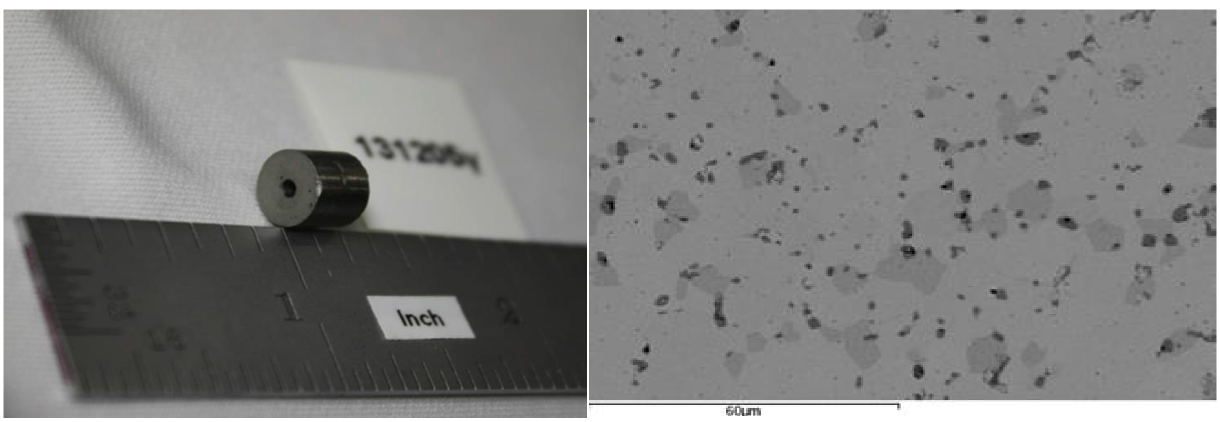


Figure 4-1. Sintered high-density U_3Si_2 pellets (left) and U_3Si_2 microstructure (right).[g]

4.1.1.2 Transmutation Fuels. Sustainable fuel cycle options improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk. These fuel cycle options focus heavily on advanced fuels containing TRU elements (e.g., neptunium, plutonium, americium, and curium), with second tier options involving thorium. The greatest challenge associated with these fuels is in acquiring the ability to understand and predict the broad range of nuclear, chemical, and thermo-mechanical phenomena that synergistically interact to dictate fuel behavior over a wide range of fuel chemical compositions and operating conditions. An important obstacle in demonstrating the feasibility of candidate advanced fast-spectrum fuels that support these fuel cycles is the absence of an available fast-spectrum test facility. Overcoming this challenge requires that revolutionary advances in electronic structure theory, computational thermodynamics, and innovative, science-driven experiments be integrated to obtain the required understanding of nuclear materials and their behavior. The knowledge gained from combining thermal-spectrum reactor irradiations, past fast-spectrum irradiation experiments on cladding materials, and modeling and

[g] Jason M. Harp, Paul A. Lessing, Rita E. Hoggan, 2015, "Uranium silicide pellet fabrication by powder metallurgy for accident tolerant fuel evaluation and irradiation," *Journal for Nuclear Materials*.

simulation can be used to show the feasibility of candidate transmutation fuel/cladding systems. Fast-spectrum irradiation testing is required to demonstrate performance at scale in the design environment.

Most sustainable fuel cycle scenarios require that fuel be fabricated remotely in shielded facilities because of gamma ray emission from TRU elements and fission product carryover from recycling. The difficulty in remote fabrication is compounded by the necessity to reduce TRU material loss to ensure the maximum benefit to a geological repository. The highest potential for material loss occurs during fuel recycling and fuel fabrication. Extending the fuel burn-up lifetime reduces the number of fuel processing cycles and is one method of reducing these fabrication losses (Figure 4-2). Design of efficient, low-loss fabrication processes is essential for success.

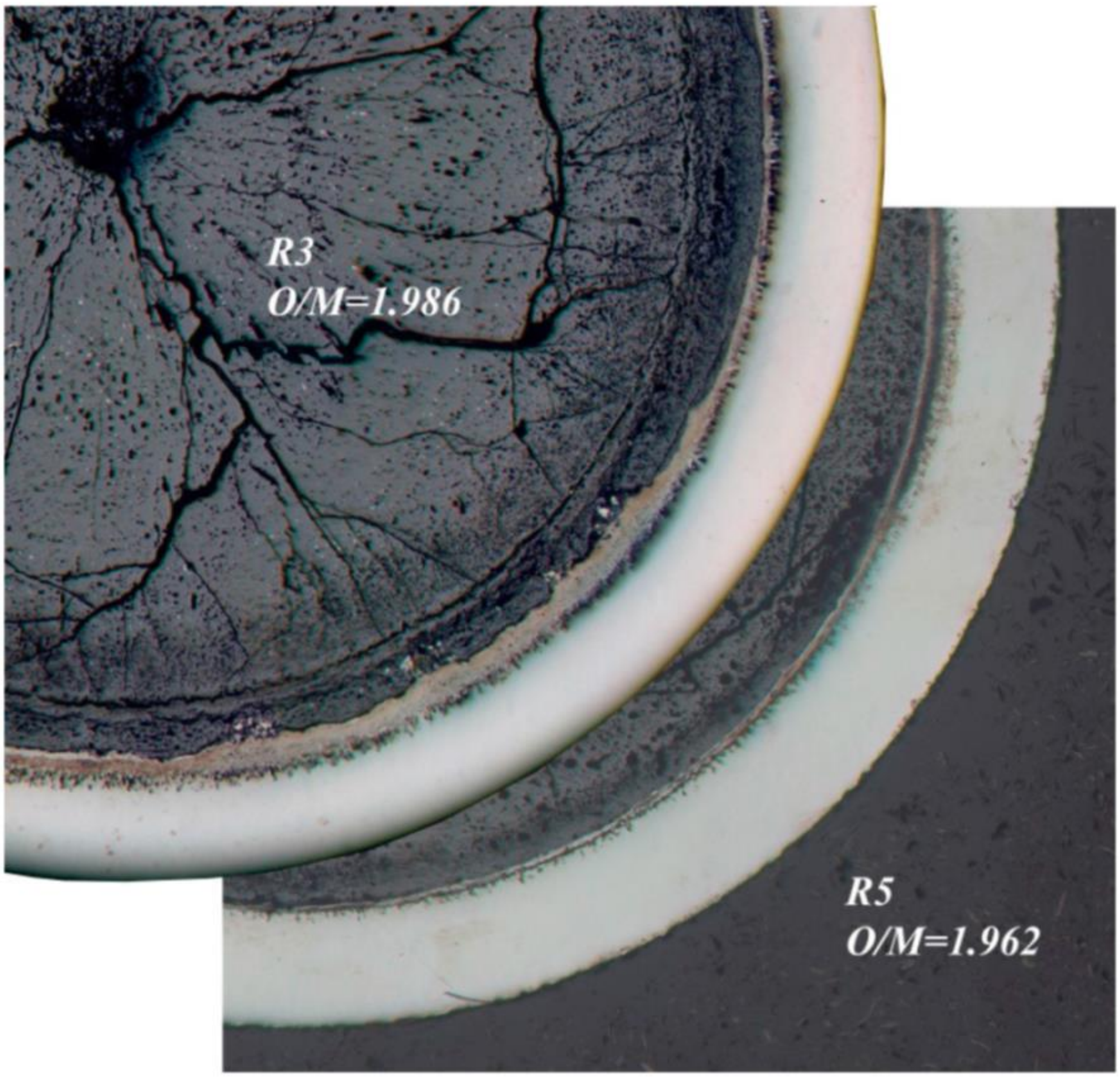


Figure 4-2. Comparison of the effect of the oxygen-to-metal ratio (i.e., O/M) in minor actinide mixed oxide fuel. A lower oxygen-to-metal ratio results in reduced fuel-cladding chemical interaction.

4.1.1.3 Used Fuel Disposition. Understanding the behavior of used nuclear fuel during interim storage is required to extend the dry storage period while a permanent repository is being developed. Additionally, as commercial utilities pursue higher fuel burnup, information about the impact to storage must be provided to the Nuclear Regulatory Commission to allow storage licenses to be considered. Understanding the performance of fuel, fuel cladding, assembly components, and cask material degradation as a function of time and environment is essential to development of predictive models that will be used to analyze performance during long-term dry storage with confidence. Detailed fuel examination and testing required to characterize the fuel and support a science-based approach are intended to reduce the cost and schedule required to obtain data necessary to extend the licensed, interim, dry storage period. Conducting this important long-term research program requires that current barriers to bringing research quantities of used commercial nuclear fuel into the State of Idaho be resolved as soon as possible.

4.1.1.4 High-Temperature Gas Reactor Fuel. High-temperature gas reactor concepts are based on tristructural isotropic (TRISO)-coated particle fuels (Figure 4-3). The silicon carbide and pyrocarbon layers in the TRISO particles provide excellent retention of fission products during normal operation and during accident conditions. Fuel performance is closely tied to the fabrication process in this highly engineered system. A number of known degradation mechanisms that are temperature and burnup dependent have the potential to affect TRISO fuel performance. These include the thermomechanical response of pyrocarbon layers, fission gas release and carbon monoxide production, the ‘amoeba’ effect (i.e., migration of the kernel due to chemical reactions in a thermal gradient), and palladium attack of the silicon carbide layer. The ties between the fabrication process, resulting particle structure, microstructure, chemical composition, and performance must be well understood to define a fabrication process and set control limits that ensure fuel performance. Qualifying fuel for use in a licensed reactor involves experiments and examinations to gain an understanding of the behavior of the TRISO fuel under the radiation and temperature environment expected in a high-temperature gas reactor. It also involves experiments to allow for understanding how well the fission products (i.e., the elements produced when uranium fissions) stay inside or move outside the coated fuel particles and through the graphite reactor core. Testing involves identification and sorting of a very small fraction of failed test fuel particles and detailed investigation of the failure modes. Validation through experimentation of modeling and simulation tools that analyze and predict behavior is also vital.

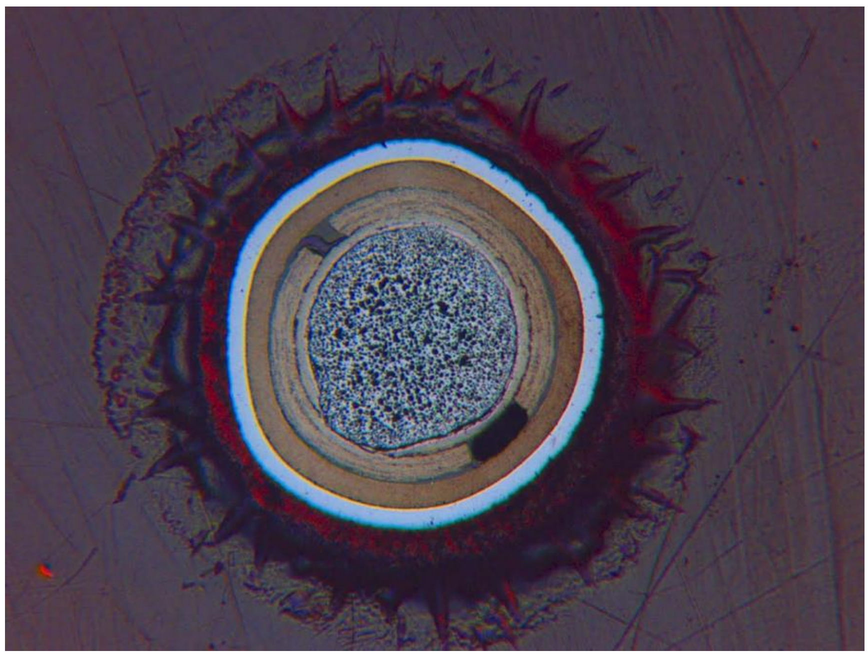


Figure 4-3. Next-generation nuclear reactor fuels are designed to be more efficient and resistant to accident conditions. TRISO fuel contains a layer of silicon carbide that serves as the primary containment for radioactive material (center). Researchers have subjected TRISO fuel to extreme temperatures well above postulated accident conditions and found that most fission products remained inside the fuel particles.

4.1.1.5 Support for the U.S. Commercial Reactor Fleet. It is vital to the economic competitiveness and well-being of the United States that the commercial LWR fleet continue to produce electricity at its current high level of reliability. Fuel vendors continue to improve fuel performance and lifetime through use of fuel assembly design changes, fuel pellet additives, and improved cladding materials; however, the nuclear industry no longer has the capability to perform the PIE necessary to confirm performance or understand the cause of failure. Conversely, DOE does not have capabilities for full-scale demonstration of fuels in a representative LWR environment and requires cooperation with industry for demonstration testing. Developing close, mutually beneficial relationships between national laboratories and nuclear industry provides opportunities for injecting innovative technologies into the commercial marketplace. Securing INL's role as a partner to the commercial industry requires resolving current issues with bringing research quantities of used commercial nuclear fuel into the State of Idaho. Rapid turnaround on fuel examinations that produce high-quality data using a sustainable cost model are required to meet industry needs.

4.1.1.6 Low-Enriched Research Reactor Fuels. Research reactor fuels are the largest remaining source of civilian commerce in highly enriched uranium. Many reactors have converted to low-enriched uranium using conventional dispersion fuels. The remaining high-power reactors, which by far consume the most highly enriched uranium, require a new type of very-high-density fuel to allow for their conversion. Equally important to the nuclear research community is ensuring low-enriched fuels are available for use in future high-power density research and test reactors. Because this fuel attains extremely high fission density, it undergoes a series of transitions in behavior that are linked to the starting microstructure and its evolution (Figure 4-4). Defining the linkage between fabrication process parameters, microstructure, performance, and, ultimately, failure as the fuel achieves increasingly higher burnup is an important challenge for development of this fuel system. Because it is a plate-type fuel and has very different failure mechanisms than rod-type or particle fuels, identifying these linkages requires specialized instrumentation installed in a hot cell. Additionally, geometry and failure mode-specific methods need to be developed to measure fuel performance parameters.

Figure 4-4. An optical micrograph of an irradiated low-enriched uranium monolithic fuel plate showing laminated fuel structure (top) and fuel microstructure (bottom) after irradiation to a fission density in excess of 4.1×10^{21} fissions/cm^3, showing fission-gas bubbles within recrystallized regions, remnants of original grains, and precipitates.

The U.S. High Performance Research Reactor Program is working to increase PIE capability to meet these specific needs in FY 2016 through FY 2018. In FY 2019, examination of the MP-1 irradiation test will require a significant fraction of HFEF PIE capacity. This test is critical to the selection of a fabrication process for low-enriched uranium research reactor fuel. Accommodating the needs of all HFEF users will require consideration of additional operating shifts and a consequent increase in staffing during this period.

In addition to development of new low-enriched uranium fuels, a gap in production of existing low-enriched uranium TRIGA reactor fuel exists. TRIGA reactors are the single most widely deployed research reactor in the world and support a wide range of research, training, and isotope production activities. INL is exploring the possibility of production of these fuels to meet the needs of the nuclear community.

4.1.1.7 New Fuel Concepts. Many concepts for new fuels that may have economic, performance, and/or safety advantages or that are required to enable new reactor concepts are generated by universities, small businesses, and industry. Fundamental research on fuel behavior is of great interest to the scientific research community and is used to validate specific fuel behavior models through separate effects testing. NSUF provides opportunities for a broad range of researchers to conduct scoping testing of novel fuels and fundamental research by providing support for fuel fabrication, irradiation testing, and PIE. Developing new fabrication processes is often required and PIE instruments and techniques may need to be modified.

4.1.2 Nuclear Fuel Development Research, Development, and Demonstration Goals

Historically, nuclear fuel development has been empirical. The massive amount of atomic displacement damage the fuel microstructure sustains, along with change in chemical composition during fission, makes it difficult to track microstructural evolution, understand the interaction between radiation damage processes, and formulate general models that accurately predict the evolution of microstructure and associated physical properties. These limitations make it difficult to understand fuel behavior and apply a systemic approach to fuel design. As a result, the experimental cycle for fuel development is currently long and expensive. The following opportunities exist, decreasing fuel development time and expense:

- Develop flexible fabrication capabilities that increase the ability to develop fabrication processes and produce unique experimental fuel test specimens.
- Implement modern non-contact measurement tools in hot cells and in-canal examination instrumentation to acquire engineering-scale irradiation performance data more rapidly and in three dimensions.
- Increase the scientific understanding of fuel behavior through detailed microstructural examinations, chemical and isotopic analysis, and property measurements essential to the more fundamental understanding of fuel behavior required for modeling and simulation.
- Integration of experimental and modeling and simulation activities to ensure experimental measurements support development and validation of computational models and modeling and simulation are used to inform and focus experimental measurements.
- Implement a transient testing capability to demonstrate fuel behavior during off-normal occurrences for both research and licensing purposes.

Achieving these goals, coincident with development of robust modeling and simulation tools, will provide the information required to move away from lengthy and costly empirical approaches to fuel development and qualification, decreasing the time to market for new or improved fuels.

4.1.2.1 Fabrication Development. The importance of a thorough and disciplined approach to fuel fabrication process development is often overlooked. Fabrication is one of the most important aspects of the development cycle for advanced fuels and, as such, has high potential to enable compression of the nuclear development cycle. MFC has broad experience with fuel fabrication development. FCF was used to demonstrate remote fuel fabrication of recycled metal fuel to close the fuel cycle. FMF and the AL Casting Laboratory produced the U-Zr driver fuel and experimental U-Pu-Zr fuel required to fuel EBR-II. Refocusing these production facilities and development of additional R&D capability in FASB and EFF has allowed development and fabrication of many first-of-a-kind fuels, including transmutation fuels (containing plutonium, neptunium, americium, and curium), accident-tolerant fuels for commercial LWRs, extruded metallic fuels, annular fuels, dispersion fuels, and uranium-molybdenum monolithic fuel.

Fuels that are different from those currently in commercial use drive the need for new fuel fabrication technology. Fabrication development of fuels historically has relied on a trial-and-error approach. Past experience is used to establish a recipe that provides a consistent and reproducible product. Parametric irradiation testing leads to a limited understanding about the effects of process variables on performance. Operational experience feeds into the fabrication process, allowing incremental improvements in performance. For example, over the last five decades, this process has resulted in a highly reliable LWR fuel system. A shift to using modeling and simulation tools to design fabrication equipment and processes, development of flexible fuel fabrication capability, and real-time feedback on the relationship between fabrication and microstructure during process development will provide more rapid development of fuels with specified and well-defined microstructures.

4.1.2.1.1 Modeling and Simulation of Fabrication Processes—Modern modeling and simulation tools, with additional development and validation over a broader range of fuel systems, will soon provide the ability to model changes in fuel behavior as a function of changes in microstructural parameters. Fabrication process models have the ability to design process components (such as casting molds) and fabrication process parameters (such as thermal cycles) to efficiently lead fabricators to a viable laboratory-scale fabrication process and bridge the gap between laboratory-scale and commercial production processes (Figure 4-5). Process models also have the possibility of predicting microstructural evolution as a function of discrete process steps (such as solidification and rolling). Mesoscale microstructure/performance models that specify the desired microstructure, combined with process models that aid in design of fabrication process equipment, and parameters have the potential to significantly reduce the number of iterations in the fuel development cycle.

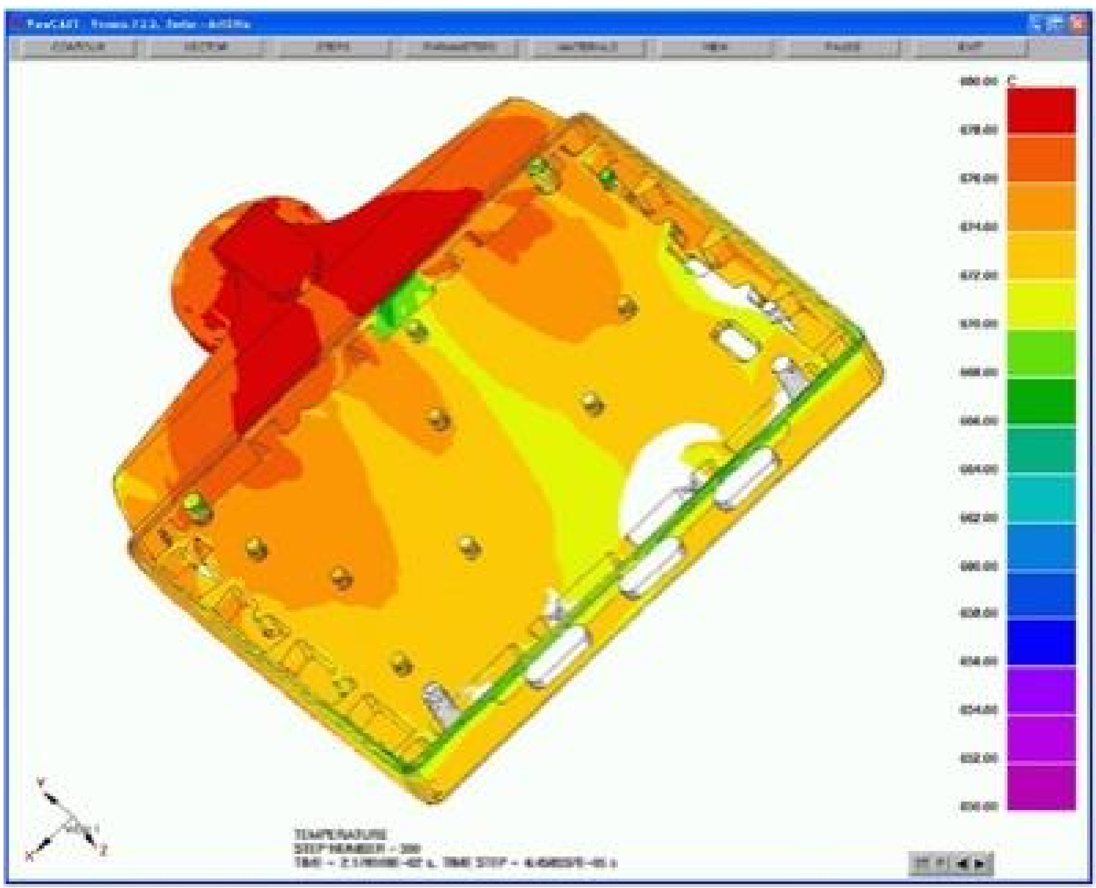


Figure 4-5. Fabrication process modeling can be used to determine optimum casting mold geometry and thermal conditions, reducing time for development of advanced fuel fabrication technology.

4.1.2.1.2 Flexible Fabrication Capability—MFC fabricates a wide range of fuels for research, ranging from pin-type metallic fuels containing minor actinides, to research reactor fuels, to accident-tolerant LWR fuels. Each of these fuels requires specific fabrication capabilities. These capabilities are normally housed in gloveboxes or hoods and, once installed, are largely static because of the difficulty in modifying contaminated equipment. This capability gap often results in fuel fabrication processes being adapted to installed process equipment rather than equipment being adapted to meet fuel requirements. A relatively wide range of equipment that operates over a wide range of parameters is required to remain responsive to R&D needs as they evolve.

Additive manufacturing technology[h] is currently being developed in other major technology sectors (Figure 4-6).[i] This technology, when appropriately modified and applied as part of the nuclear fuel fabrication process, has high potential to meet needs for fabrication of fuel test specimens with unique geometry, microstructural features, and chemical composition. This technology is already being developed by DOE-NE for application to nuclear components[j,k] and fuels.[l] NNSA is also exploring the use of this technology for fabrication of low-enriched conversion fuel for the TREAT reactor.

Figure 4-6. Laser additive manufacturing is being developed and applied for use in the manufacturing of advanced materials, for example, turbine engine components. The method will be applied to the development of advanced nuclear fuels at MFC.

Additional configurable fabrication space will be made available for testing and optimization of the new processes required for new fuels as DOE-NE's R&D needs evolve. For example, conversion of the TREAT Warehouse to support low-enriched fuel fabrication for TREAT is currently being planned. Space will be made available over the next 5 years through strategic reconfiguration of current fuel fabrication facilities (i.e., FMF, TREAT Warehouse, FASB, EFF, and AL) to remove unused equipment and gloveboxes and transfer characterization equipment to new facilities (i.e., IMCL and SPL).

More than 70 TRIGA reactors are in operation worldwide, including the Neutron Radiography Reactor at the MFC site and 17 others in the United States. These reactors are a staple for university and

[h] Ian Gibson, David Rosen, and Brent Stucker, 2015, "Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing," second edition, Springer.

[i] For example, http://www.geaviation.com/company/additive-manufacturing.html.

[j] SBIR contract DE-SC0011874, 2014, "Additive Manufacturing of Nuclear Grade Components," *Physical Sciences Inc.*

[k] SBIR contract DE-SC0011826, 2014, "Development of nuclear quality components using metal additive manufacturing," *RadiaBeam Systems*.

[l] SBIR contract DE-SC0011954, 2014, "An additive manufacturing technology for the fabrication and characterization of nuclear reactor fuel," *Free Form Fibers*.

government nuclear research programs worldwide. Each reactor requires a relatively small quantity of new fuel (i.e., a few pins) on an annual basis to continue operation. The current manufacturer of TRIGA fuel has shut down its facilities in France, pending seismic upgrades, and is requesting investment from the U.S. government to upgrade the facility and resume production. As a long-term alternative, MFC will explore the possibility of assuming production of TRIGA fuel to supply the nuclear R&D community.

4.1.2.2 Engineering-Scale Examination of Irradiated Fuels. Measuring the irradiation-induced response of fuels on the engineering scale is critical in determining the feasibility of new fuel concepts, establishing a licensing basis for fuels under development, and extending the operating envelope of existing fuels. Characterization at this scale is essential for quantifying fuel swelling response, corrosion behavior, fission product transport, and identifying failure locations and failure modes. Measurements of fuel performance parameters have traditionally been made serially, in two dimensions, using contact measurements. Traditional measurements include visual examination, radiography, gamma scanning, corrosion layer thickness measurement, dimensional measurement, geometrical changes (e.g., bowing and blistering), and gas pressure measurement and analysis; these are conducted in HFEF. Significant increases in data quality and throughput can be made by implementing currently available noncontact measurement technology and expanding PIE capability to the ATR canal. Additional capability is also required to accommodate PIE on transient tests conducted in the TREAT reactor.

4.1.2.2.1 Advanced Nondestructive Examination—Current commercially available non-contact measurement technology and advances in tomographic data acquisition and image processing provide the opportunity to transition to new nondestructive examination methods that use parallel acquisition of multiple data types in three dimensions. Data acquired simultaneously from multiple sensors (e.g., visual, dimensional, and gamma tomography) can provide greatly increased data acquisition rates, reducing the time required to conduct a complete examination and providing higher fidelity data. Measurements in three dimensions provide a much richer data stream for visualization and for use in validating models. Noncontact methods do not require use of geometry-specific measurement systems; plates, rods, and cylinders can be measured with no change in configuration. Acquisition of three-dimensional nondestructive examination data will provide more precise information for directing the collection of follow-up samples supporting metallography, radiochemistry, and other types of measurements, removing random chance in the process of identifying and studying stochastic and non-stochastic phenomena in fuel and fuel-cladding systems. It can also extend to chemical analysis using techniques such as laser-induced breakdown spectroscopy.

PIE capability can also be extended to the ATR canal. Use of the canal provides capability for interim examination between irradiation cycles and may be used to perform a complete nondestructive examination in some cases. This will decrease the burden on HFEF and increase overall PIE throughput. The ATR canal currently provides capability for visual inspection, ultrasonic examination of fuel plates to determine swelling and detect delamination, and capability for precision dimensional measurement of coolant channel gap width. Experiment disassembly is performed on some experiment configurations. The feasibility of gamma-ray scanning has also been demonstrated[m] and radiographic tomographic visualization is also possible. Installation of a single PIE examination station in the ATR canal would optimize use of limited canal space and provide the most efficient and cost-effective method for conducting these examinations.

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[m] J. Navarro, 2013, *A Feasibility and Optimization Study to Determine Cooling Time and Burnup of Advanced Test Reactor Fuels Using a Nondestructive Technique*, INL-EXT-29997.

4.1.2.3 Scientific Understanding of Fuel Behavior. Fuel performance originates in events that occur at the atomic scale and it is important that atomic-scale damage processes be well understood. This understanding translates to control of the fuel microstructure, composition, fine-scale geometry, and interfaces to optimize the local response of fuel to the fission environment. It is further applied to the engineering-scale design of fuel elements and assemblies to compensate for material changes. For example, examination of the microstructure of U-10Mo fuel indicates that a stable nanoscale superlattice of fission gas bubbles forms during irradiation and remains stable to very high fission densities (Figure 4-7). This superlattice provides an extremely efficient method for storing fission gas and controlling fuel swelling. If the formation mechanism can be understood, it may be applicable to other fuel systems.

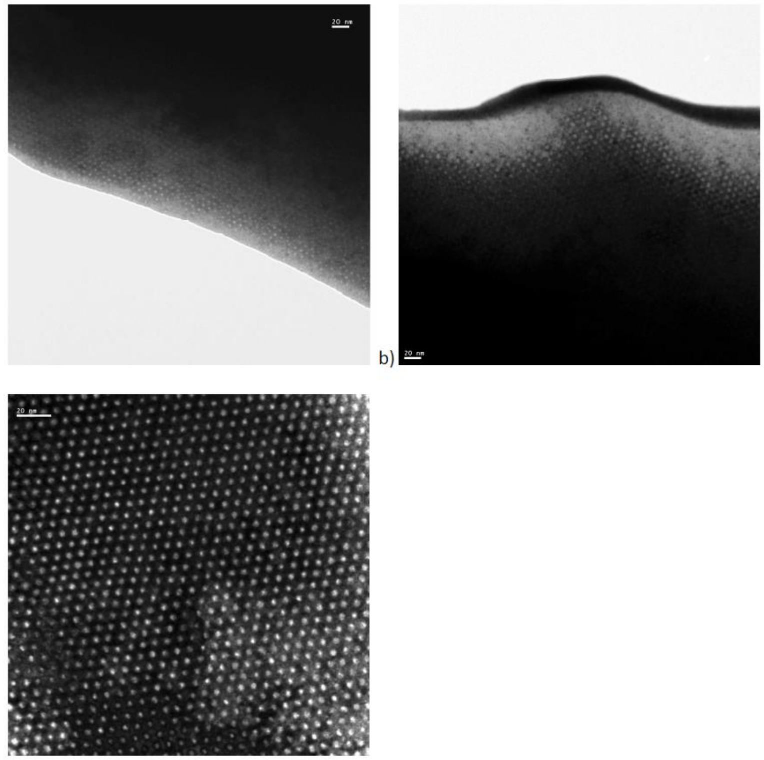

Figure 4-7. Transmission electron microscopy images of an ordered array of fission gas bubbles in U-Mo fuel at high burnup. The ordered array of high-pressure gas bubbles provides a stable and efficient mechanism for storing fission gas (INL/EXT-10-20466).

Scientific understanding of fuel behavior requires that microstructural evolution be understood as a function of service conditions, that fuel properties are understood at the mesoscale in terms of nanostructure, and that engineering-scale properties can be derived from mesoscale quantities. This requires that properties be understood at both the mesoscale and engineering scale and that microstructural features be quantified from the nanoscale to the mesoscale. Close coupling of experimental data with computational models is critical to achieving this understanding.

4.1.2.3.1 Fuel Properties—A detailed understanding of the properties of nuclear fuels is necessary to formulate a detailed understanding of fuel performance and underlying fuel behaviors. Thermal properties of nuclear fuels and cladding materials are critically important because these properties determine the temperature, temperature gradients, and thermal response of the fuel system during operation. Important fuel behaviors (such as fission product transport, phase equilibria, and swelling) are universally temperature dependent. Properties, in turn, are heavily dependent on microstructure and material chemistry. As fuel fissions, it undergoes displacement damage and compositional changes that generally degrade these properties, potentially affecting margin to failure.

Mechanical properties as a function of fission density and temperature over a wide range of variables are important in determining failure modes, safety of storage and transportation, and accident response.

With the advent of modern laser-based methods for measurement of thermal and mechanical properties, opportunities exist to conduct these measurements at the mesoscale and connect them to the engineering-scale response. Combining these measurements, along with lower-length-scale microstructural characterization data, allows elucidation of the effects of specific microstructural features on mechanical and thermal properties (Figure 4-8). This knowledge allows development and validation of models that accurately predict local thermal conditions and mechanical properties throughout the fuel's life cycle.

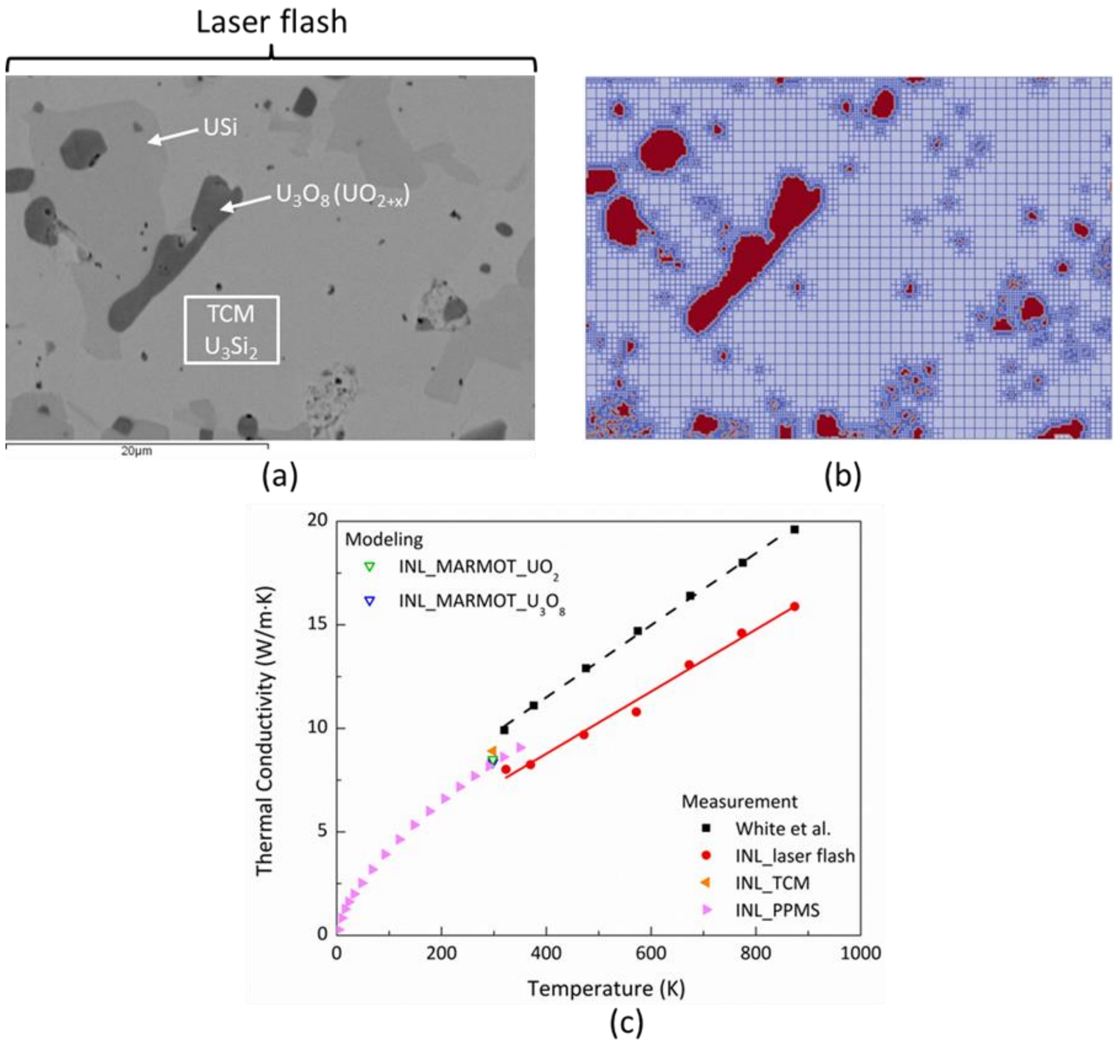

Figure 4-8. Thermal conductivity measurements of U_3Si_2 using several methods comparing different length scales and a wide range of temperatures. (a) Scanning electron microscopy image of an U_3Si_2 sample, (b) reconstructed microstructure and mesh in MOOSE for MARMOT calculations, and (c) thermal conductivity of U_3Si_2 as a function of temperature. The solids symbols are experimental measurements from literature and INL. TCM (i.e., thermal conductivity microscope) and PPMS (i.e., physical property measurement system) results are shown as the solid triangles. The MARMOT results, based on the reconstructed mesh, are represented by the open triangles.

4.1.2.3.2 Microstructural Characterization—The engineering-scale response of fuel depends on its response to high-energy damage processes and chemical evolution that occur at the atomic scale. Neutrons and fission fragments displace atoms from their lattice sites, creating defect structures that have both direct short-term impacts on properties and drive longer-term microstructural evolution. Chemical composition changes dramatically as fissile atoms are split, forming both solid and gaseous fission products. Increased populations of irradiation-produced defects allow rapid chemical diffusion to occur in response to chemical potential gradients driven by steep thermal gradients and dissimilar material interfaces. These atomic-scale processes change the mesoscale structure of the fuel materials, generally degrading properties and sometimes causing unpredicted material responses.

Revolutionary advances in materials characterization tools over the last decade now allow probing of the microstructure and materials chemistry at the atomic scale. These advances include routine atom probe tomography, aberration-corrected transmission electron microscopy, nanoscale measurement of grain orientation, nano and pico-indentation, and high-resolution x-ray tomography. Close coupling of data from these characterization tools with multiscale modeling and simulation will allow scientific discovery of the mechanisms that promote fuel stability and application to other fuel systems. Work at INL is establishing possible links between fabrication conditions, microstructure, and fission product transport behavior. Figure 4-9 is an example of nanoscale analysis from a neutron-irradiated TRISO particle that was fabricated with different conditions to achieve smaller grain sizes in the silicon carbide layer. This is an analysis of the orientation of individual silicon carbide grains using scanning transmission electron microscopy energy dispersive spectroscopy and ASTAR (grain orientation mapping in transmission electron microscopy) by MFC staff at the Center for Advanced Energy Studies MaCs Lab (INL-owned instruments). Analysis on this scale is essential to understanding fuel behavior.

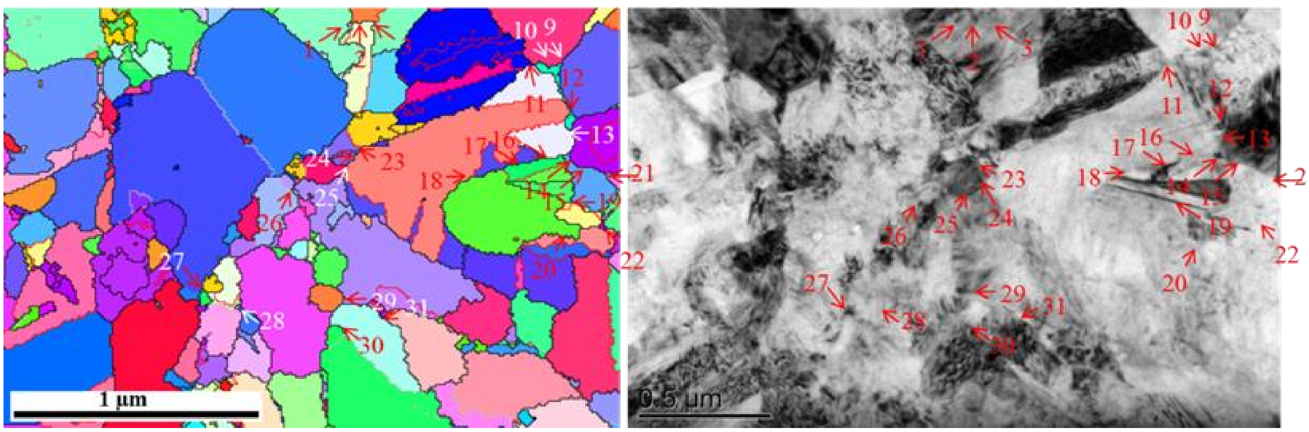

Figure 4-9. Silver transport through the silicon carbide layer in TRISO fuel has been a known issue for more than four decades, but has not been understood. Analysis using advanced PIE in HFEF, AL, and ORNL, coupled with high-resolution transmission electron microscopy is now helping to identify transport paths and understand the mechanism.

Neutron and photon-based scattering methods that probe the atomic structure of matter are key materials science tools. These methods are commonly used to elucidate crystal structure, phase array, orientation, and strain, which are important parameters for understanding response to irradiation. Major national user facilities such as the Spallation Neutron Source, High-Flux Isotope Reactor, and National Institute of Standards and Technology Center for Neutron Research provide specialized and highly subscribed neutron beam lines. The Advanced Photon Source, National Synchrotron Light Source–II, and facilities at Stanford National Accelerator Laboratory provide top-level capabilities for x-ray scattering and imaging.

The Advanced Photon Source (Figure 4-10) currently accepts small (i.e., less than 0.08-mm^3) samples of irradiated fuel produced using focused ion beam techniques. The National Synchrotron Light Source–II has developed an automated sample loading capability using DOE Nuclear Energy Enabling Technology funding for use on low activity materials. The use of national neutron and photon scattering facilities has the potential to provide higher quality data, but on small samples and with the added complexity of shipping. Development of neutron and/or x-ray scattering capabilities at MFC would provide basic, but very useful, information on larger specimens.

A two-tiered approach will be pursued to develop this capability:

- Explore a partnership with a national user facility to develop the capability to routinely accept high-activity samples. For example, both the National Synchrotron Light Source-II[n] and Advanced Photon Source[o] have proposed beamlines that may be able to accept higher activity fuel samples. These capabilities are most applicable to high-resolution measurements using advanced techniques on smaller, lower activity samples.
- Develop and test concepts for x-ray and neutron scattering capability at MFC. Evaluation of neutron scattering would include the Neutron Radiography Reactor and TREAT reactors as potential neutron sources. The Neutron Radiography Reactor at MFC has a second beam line that may be suitable for neutron diffraction. Evaluation of neutron scattering using the Neutron Radiography Reactor and TREAT reactor will be conducted in consultation with experts from ORNL and universities. Evaluation of x-ray scattering as an alternative will explore the use of a high-intensity laboratory x-ray source. These MFC capabilities are most suitable for providing basic, but very important, information on crystal structure and phases present in larger, highly active materials.

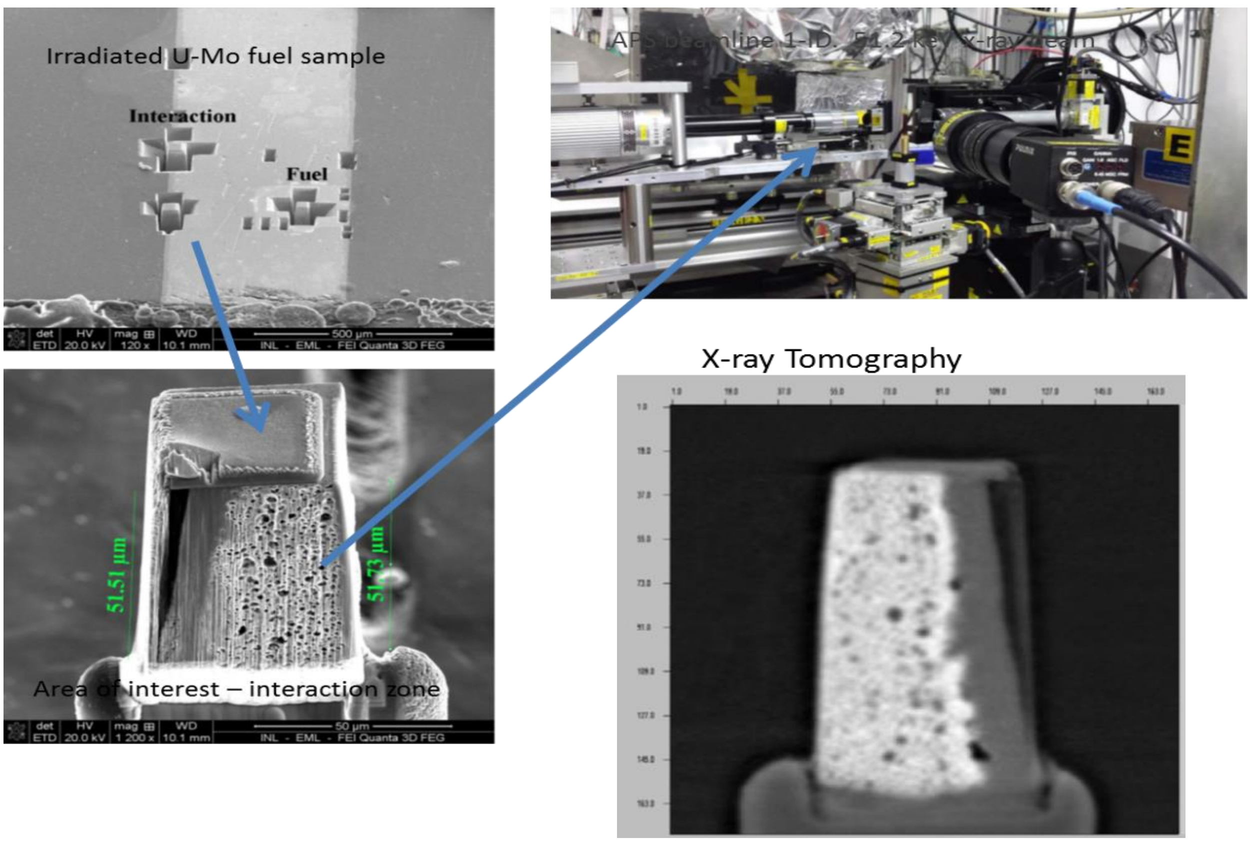

Figure 4-10. Focused ion beam sample preparation at MFC allows INL staff to conduct fuel experiments at other national user faculties. An irradiated U-Mo fuel sample was prepared for characterization at the Advanced Photon Source at Argonne National Laboratory. Access to Advanced Photon Source beam lines provides a combination of three-dimensional data on fuel behavior that is not otherwise available, such as three-dimensional phase analysis, three-dimensional grain size analysis, grain orientation, lattice parameters, microstrain, dislocation density, and pores, cracks, and bubbles.

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[n] https://www.bnl.gov/radbeam/.

[o] http://www.ne.anl.gov/mmsnf/presentations/Li.pdf.

4.1.2.4 Transient Testing. A major shortfall currently hindering the ability to advance the state of nuclear energy science and technology is the ability to conduct state-of-the-art in-pile transient tests that are required to evaluate the behavior of fuel during off-normal conditions (Figure 4-11). These evaluations are central to the development and eventual qualification of advanced fuel designs and the licensing and regulation of reactors to operate with them. Transient testing occurs in parallel with the rest of the fuel development cycle through the research, development, and qualification/demonstration phases:

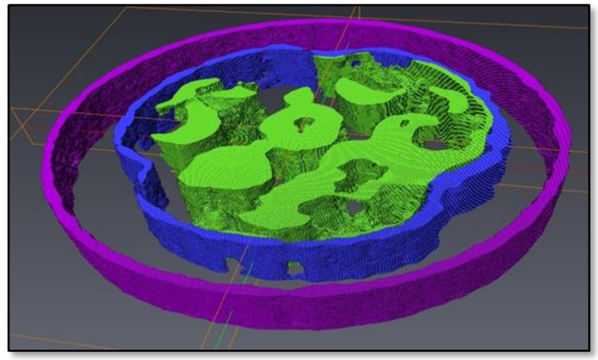

Figure 4-11. Tomographic reconstruction of archived neutron radiography reactor images taken from TREAT experiments provides an efficient and comprehensive method for assessment of fuel performance. The reconstruction can also be used with a three-dimensional printer to make a physical model of the disrupted fuel (TREAT Experiment L05).

- Application of the goal-oriented, science-based approach to R&D initially requires a set of transient testing capabilities designed to isolate specific phenomena that occur in individual materials or at their interfaces.
- Development of advanced fuel technology requires a wide range of testing under a variety of conditions, ranging from benign to extreme, in order to properly screen fuel designs and select materials used in them. These tests are used to identify a range of fuel performance features that may be used to guide fuel design and advanced reactor design.
- Prior to design of a new reactor system that will utilize a given fuel system, a qualification program is conducted to establish the fuel system's operating parameters and performance limits. These parameters and limits become the basis for design criteria and regulatory assessment of a particular reactor design.
- In addition to supporting the specific missions of DOE-NE, the capabilities resident in the transient testing capability support forensics, nuclear attribution, and fuel development for NNSA, National and Homeland Security, the U.S. Nuclear Regulatory Commission, nuclear vendors, the Electric Power Research Institute, domestic and foreign regulators, and nuclear power generating companies.

4.1.2.4.1 Transient Experiment Test Facility Post-Irradiation Examination Capability—Transient testing of irradiated fuel requires a station to assemble highly irradiated fuel into an experiment assembly prior to transport to TREAT. Interpreting results of transient testing requires the capability to disassemble TREAT test vehicles, extract the fuel, and introduce it into the HFEF PIE line. Preparing, operating, and dispositioning test loops with appreciable quantities of contaminated sodium and pressurized water is a key part of DOE's transient testing capability. A description of the transient testing PIE capability needed to support basic and complex transient testing is provided in INL/LTD-14-33324, *Ten Year Plan for Implementation of Transient Testing Capability in the United States (FY 2014 to FY 2023)*.

4.2 Radiation Damage in Cladding and In-Core Structural Materials

The limiting factors in both fuel and reactor operating lifetime are cladding[p] and structural materials. Research for developing the scientific basis for understanding and predicting the response of materials to

[p] Although fuel cladding materials are integral and essential to fuel performance and are normally grouped with fuels, initial development of new cladding materials that meet basic requirements (i.e., strength, creep resistance, fabrication, and joining) primarily requires consideration of high dose material irradiation damage mechanisms and are included here.

the nuclear environment allows deliberate design of materials better suited to the in-core nuclear operating environment than current off-the-shelf materials. Critical to success in this area is the availability of materials for study by the nuclear energy research community, including the ability to fabricate standard test samples from irradiated materials mined from current reactors and the ability to transport materials to and from GAIN/NSUF partner facilities as appropriate.

4.2.1 Cladding and In-Core Structural Materials Research, Development, and Demonstration Focus Areas

Damage processes in materials are driven by neutron damage cascades and, in principle, are easier to understand at a fundamental level in materials than in fuels. Structural materials research provides a fertile basis for collaborative scientific investigation by INL, other national laboratories, and universities/ industry partners. Irradiated materials (i.e., non-fueled and non-alpha-contaminated) can be more easily handled than fuels at universities, national user facilities, and low-level radiological facilities at other national laboratories, allowing more diverse data streams and enabling a broader collaborative approach (Figure 4-12).

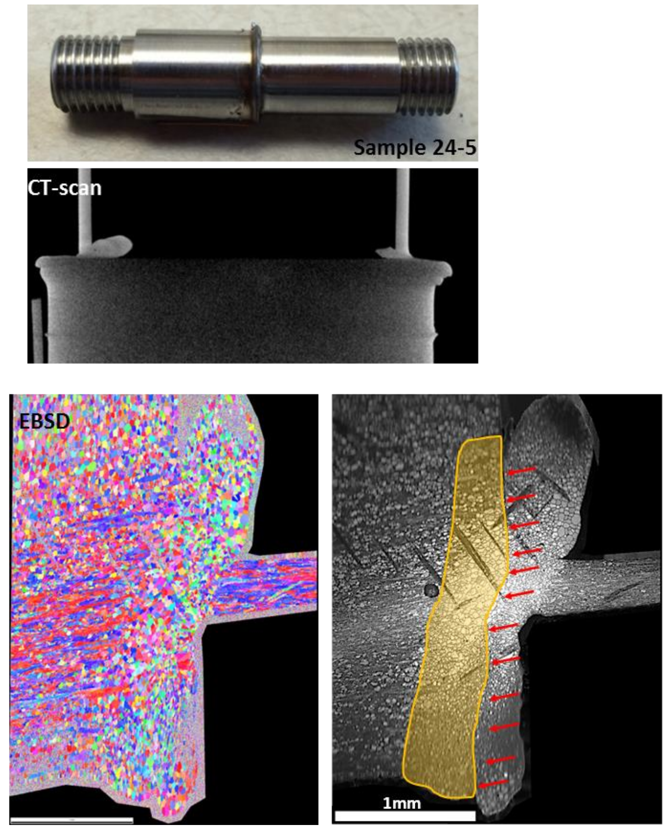

Figure 4-12. Thin-walled tubing is being developed as an alternative to zircaloy cladding for use in LWRs.

4.2.2 Cladding and In-Core Structural Materials Research, Development, and Demonstration Goals

4.2.2.1 Radiation-Tolerant Cladding Materials. Developing accident-tolerant fuel concepts revolves around replacing current zircaloy cladding materials with steel or ceramic materials or increasing the high-temperature corrosion and oxidation resistance of zircaloy cladding through the use of coatings or surface modification. These cladding materials will be irradiated in ATR as part of the Accident-Tolerant Fuel Experiment series and configured in both gas-filled irradiation capsules and as loop tests in contact with water at pressurized water reactor temperature and chemistry conditions. Availability of these cladding materials at MFC after irradiation presents a unique opportunity for collaboration with other national laboratories, industry, and universities to understand the response of these materials in detail when integrated into a fuel system.

Development of cladding for fast-spectrum reactor systems has been focused on ferritic/martensitic steels. Ferritic/martensitic steels experimentally have been shown to exhibit radiation resistance to neutron doses as high as 200 displacements per atom. High creep rates and a significant decrease in tensile strength limit the operating temperature of ferritic/martensitic steels to less than 600°C. Certain reactor systems that propose extended core residence times can require that cladding materials perform to 400 displacements per atom or above. The introduction of nano features, typically Y-Ti-O particles, into the microstructure to form oxide dispersion strengthened alloys dramatically improves high-temperature creep resistance, strength, and radiation tolerance. To realize the potential of these materials, the relationship between microstructural characteristics of oxide dispersion-strengthened alloys and their irradiation performance must be understood and issues with fabrication and joining (i.e., welding) resolved. MFC's role in development of this important class of alloys is to collaborate broadly to facilitate progress through established research programs to make materials, instrumentation, and expertise available during analysis that result in advancement of this technology. MFC capabilities may also be used to develop new alloy systems and fabrication processes that result in materials that can be commercially deployed.

Many of these materials are difficult to join; alternatives to traditional fusion welding are being developed. Electron backscatter diffraction results from a pressure-resistance welded sample that encompasses the weld and sections of the tube and plug microstructures are shown in Figure 4-13 (lower left), along with a computed tomography image and photo of the weld joint (top). The results reveal the microstructure of the bond that developed in the weld because of rapid melting coupled with the mechanical load applied during welding. Equiaxed grains suggest that the redistributed material fully melted and re-solidified, with a resulting acceptable bond line.

So-called MAX phases are being considered for nuclear applications (e.g., high-temperature coating on zircaloy fuel rods for LWRs). The first analysis of the microstructural response of MAX phases to neutron irradiation at LWR accident temperatures and high dose is being conducted at INL. Analysis of the Ti_3SiC_2 MAX phase shows excellent radiation damage tolerance after ATR irradiation to 9 dpa and 1000°C. Figure 4-14 shows the nanostructure of the Ti_3SiC_2 MAX phase.

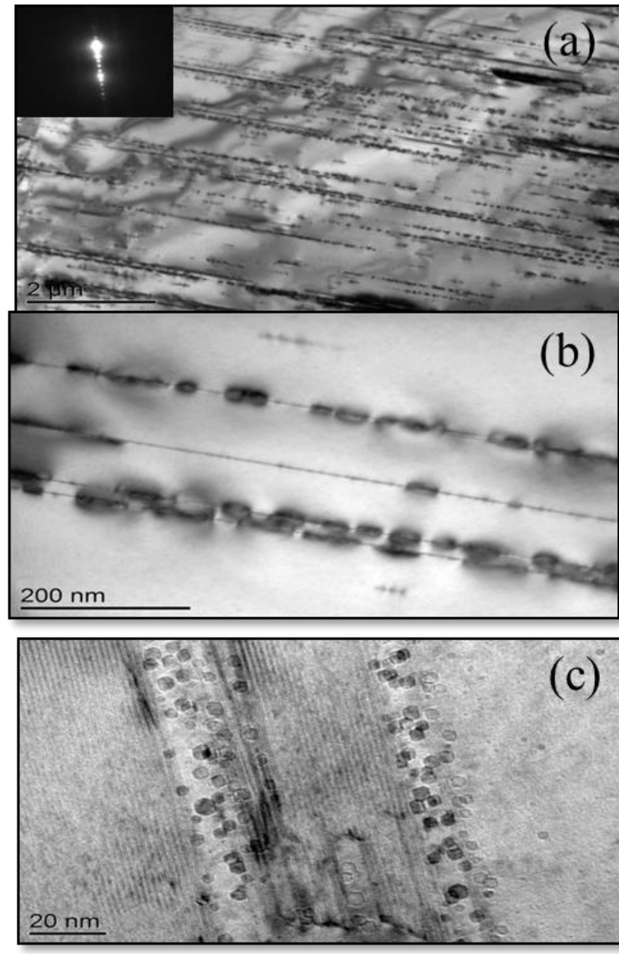

Figure 4-13. (a) and (b) show that dislocation loops mainly exist at the stacking faults in the structure. Nanochemical analysis shows that the stacking faults are TiC (titanium monocarbide). (c) Shows that the cavities that produce swelling mainly exist at the stacking faults. This work was part of an NSUF experiment with Drexel University.

4.2.2.2 Irradiation-Assisted Stress Corrosion Cracking and Fracture Toughness. There is a large environmental and economic benefit to extending current commercial nuclear plant lifetimes beyond 60 years. The key issue facing life-extension efforts for current reactors is radiation-induced degradation of materials. One of the most important issues facing further extension of reactor lifetimes is IASCC, where exposure to neutron irradiation increases the susceptibility of in-core structural stainless steels to stress corrosion cracking. IASCC is a complex phenomenon that involves simultaneous actions of irradiation, stress, and corrosion that, despite five decades of research, is not well understood. In recent years, as nuclear power plants have aged and irradiation dose increases, IASCC has become an increasingly important issue. Gaining a better understanding of IASCC in reactor materials is a high priority for the Electric Power Research Institute (representing nuclear industry research), the Nuclear Regulatory Commission, and DOE's LWR Sustainability Program. From an applied (i.e., industry) perspective, it is essential to measure and understand changes in crack growth rates and fracture toughness as a function of radiation fluence; therefore, when cracks are identified during outage inspections, quantitative decisions can be made as needed for component replacement. Capability at MFC (Figure 4-14) is used to make these measurements on materials with gamma dose rates up to 40,000 R.

Developing a scientific basis for understanding and predicting long-term degradation behavior and the operational limits of materials relies on detailed examination at the lower-length scales (i.e., micrometers to nanometers). Critical to this effort is the ability to generate high-dose materials by reconstituting material mined from commercial reactors for accumulation of additional dose in test reactors. These data are required to build accurate, predictive computational models useful for prediction of reactor service life.

Figure 4-14. IASCC test rigs for high-activity materials.

4.2.2.3 Improving Structural Material Performance. Improving the performance of structural materials can improve the life-cycle economics of advanced reactors by potentially allowing both higher operating temperatures (i.e., higher thermal efficiency and power output) and longer lifetimes. Advanced materials could have a significant impact on life-cycle costs, even if raw material costs are higher than the currently used stainless steels. Improved materials performance also improves safety performance through improved reliability and greater design margins. Requirements for advanced structural materials include dimensional stability, acceptable mechanical properties at high fluence, and good corrosion resistance. Considerable overlap exists between this area and development of advanced cladding materials. Understanding this issue and incorporating modified or alternative materials (Figure 4-15) into design of new reactors that further increase the operating lifetime would provide substantial benefit to the nuclear industry.

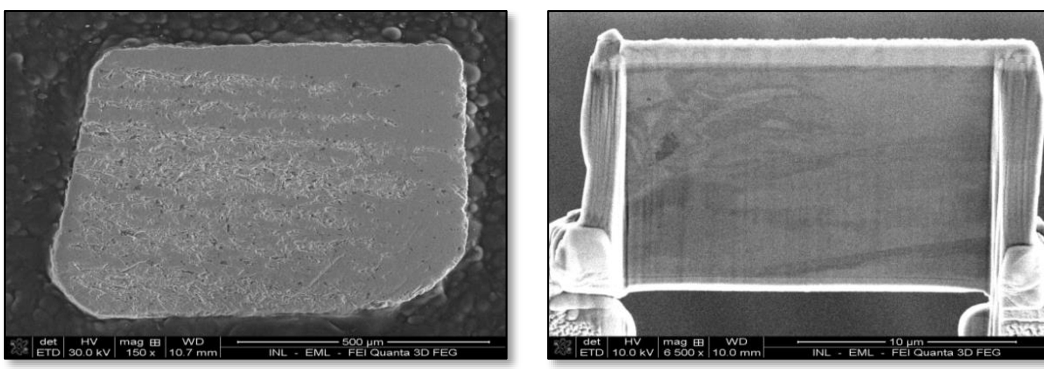

Figure 4-15. Irradiated X-750 nickel alloy specimens (left) were prepared by focused ion beam (right) for Atomic Energy Canada Limited. This joint work helps to address the root cause of a material performance issue in CANDU reactors and define improved material specifications.

4.3 Fuel Recycling

Nuclear fuel cycles that increase uranium resource utilization and reduce waste require a recycling strategy. In general, all actinides important for resource utilization and waste management can be recycled in thermal or fast-spectrum systems to reduce the decay heat and radiotoxicity of the waste placed in a geologic repository. Only those elements that are considered to be waste (i.e., select fission products) are interred in a repository for disposal. Recycling requires extensive use of separations technologies. Long-term radiotoxicity of waste decreases as more elements are separated and recycled, but this increases the complexity of the separation process. In the case of fast reactors, minor actinides will be transmuted, resulting in 8 to 12 times less high-level waste than the amounts of spent nuclear fuel processed and will require less repository capacity when compared to direct disposal.

Nuclear separations RD&D requires highly specialized facilities because many of the important species are radioactive and/or entail extensive safeguards and security. Outside INL, few laboratories exist in the United States that are capable of doing research in actinide separations chemistry. The skills and capabilities at MFC have been traditionally geared toward applied and developmental research in radiochemical separations for the nuclear fuel cycle.

Recycling of spent fuel today can be conducted using either aqueous chemical methods or electrochemical methods, typically using a molten salt electrolyte.

4.3.1 Aqueous Recycling Research, Development, and Demonstration Focus Areas and Goals

4.3.1.1 Aqueous Recycling Research Focus Areas. The current U.S. baseline for managing commercial used nuclear fuel is direct disposal in a geologic repository after a single burn in a reactor. This has the advantage of no processing of used nuclear fuel and reduced low-level waste generation. However, compared with the used fuel recycle, the disadvantages include increased mass and volume for geologic disposal, increased radiotoxicity associated with the waste (i.e., spent nuclear fuel), a less durable disposal waste form that requires more elaborate engineered barriers, higher demand for uranium ore, and higher long-term heat loading of the repository.

Although aqueous separations and waste forms technologies are not currently developed to the point necessary for commercially implementing a sustainable fuel cycle, preliminary results from the United States and abroad have demonstrated sufficient promise to be confident of success if sufficient technology development is performed. For this reason, there is an ongoing challenge in the area of nuclear separations involving the need to understand how actinide, lanthanide, and fission product extraction changes with differing solvents in the presence of a radioactive environment. The complex chemical properties of actinides are less explored and more difficult to model than other elements that present a unique challenge within separation science.

4.3.1.2 Aqueous Recycling Research Goals. Implementation of a sustainable fuel cycle requires a long-term investment in separations research. Technology developments must be made on a firm foundation of scientific understanding. This understanding will allow for application of technologies to changing potential flowsheets, will be more easily licensed and operated, and will support technology and fuel cycle options screening and demonstrations. Technologies developed for a fast reactor fuel cycle must also be amenable to commercial deployment. This demands a cost-effective, robust, and integrated process, where each individual technology or unit operation is integrated into an entire flowsheet. With these overriding principles in mind, two of the primary technological gaps for an aqueous fuel recycle flowsheet are as follows:

- Efficient separation of the actinides from the chemically similar lanthanides and, potentially, from each other in an aqueous reprocessing flowsheet. A better fundamental understanding of the chemistry of actinides and lanthanides in aqueous and organic solutions will greatly help in development of a more efficient and cost-effective recycling process. Once developed, the process will need to be scaled-up and integrated with the other required processes.

- Management of process off-gasses that meet U.S. regulatory constraints. The isotopes Kr-85, I-129, H-3, and, potentially, C-14 require capture and immobilization; however, several challenges remain. The first challenge is the very high decontamination efficiency required for iodine (plant-wide decontamination factor of 380 to 8,000) combined with data, suggesting that greater than 2% of the iodine remains in the aqueous stream, leaving the dissolver, and is emanated from virtually all vessel vent and process off-gas streams in small concentrations. A second challenge involves the capture of krypton, which requires cryogenic separations from a gas stream devoid of any gasses except for nitrogen and noble gasses. Although this is a relatively proven technology, it is expensive and typically captures xenon, which is non-radioactive and at a much higher concentrations than krypton.

To support these efforts, several areas of aqueous separations research are being performed at MFC, including the following:

- Evaluation of radiation effects and the resulting degradation products on the various solvents and extractants being developed for separation of uranium and TRU from dissolved used nuclear fuel
- Developing a better understanding of the thermodynamics and kinetics of actinides and lanthanides with various separations processes
- Understanding the impact of radiation on newly developed sorbents for the separation of krypton, xenon, and iodine from aqueous separations off-gas
- Developing an understanding of the behavior of technetium in the separation of uranium/ plutonium/neptunium utilizing tributyl phosphate-based separation processes that do not separate pure plutonium
- Utilizing data obtained from separations research to support development of predictive capabilities to inform future research and support, eventual scale up, and design of robust separation processes.

4.3.2 Pyroprocessing Research, Development, and Demonstration Focus Areas and Goals

4.3.2.1 Pyroprocessing Research Focus Areas. The term pyroprocessing refers to a family of technologies involving high-temperature chemical and electrochemical methods for separation, purification, and recovery of fissile elements from used nuclear fuel. Pyroprocessing technologies can be applied to oxide fuels and metallic fuels; however, the fissile elements are ultimately recovered as metals for fabrication of new fuels. Presently, pyroprocessing technologies are being actively researched by the United States, Japan, France, Republic of Korea, China, India, and Russia. Research in pyroprocessing aims not only at the challenges of implementing the technologies for commercial-scale applications, but at the challenges of safeguarding such facilities to the standards imposed by the International Atomic Energy Agency.

Pyroprocessing has some unique advantages as a reprocessing technology for used nuclear fuel. For example, molten salts are impervious to the radiolysis effects of used nuclear fuel, unlike aqueous organic solvents, allowing for the treatment of ‘fresh’ used nuclear fuel recently removed from a reactor core. Molten salt chemical systems allow for excellent separation capabilities of fission products from the useful actinide components with minimal waste generation. Pyroprocessing of used nuclear fuel has a much smaller facility footprint than traditional aqueous treatment facilities. Current MFC activities in this area include those mentioned in the following subsections.

4.3.2.1.1 Joint Fuel Cycle Study—MFC supports a pyroprocessing study with the Republic of Korea on the Joint Fuel Cycle Study’s Integrated Recycle Test. In this study, LWR fuel will be used as the feed for kilogram-scale pyroprocessing equipment that is being installed in the HFEF argon-atmosphere hot cell. Through electrochemical oxide reduction and electrorefining, the oxide fuel will be reduced to a metal and TRU will accumulate in the molten electrorefiner salt. When a sufficient quantity of TRU has accumulated, these metals will be recovered from the salt through application of a liquid cadmium cathode. The resulting uranium/TRU alloy will be used to make fuel samples for irradiation testing in ATR and subsequent PIE analyses in HFEF. This research will not occur without the receipt of commercial fuel as feedstock.

4.3.2.1.2 Experimental Breeder Reactor-II Driver Fuel Initiative—The Driver Fuel Initiative Program for treating the remaining inventory of EBR-II sodium-bonded metallic fuel is being performed in the FCF argon-atmosphere hot cell using the Mk-IV and Mk-V electrorefiners and cathode processor. Processing the EBR-II driver fuel is necessary to meet DOE obligations under the 1995 Settlement Agreement with Idaho, which will enable INL to maintain its role as a world leader in nuclear energy research.

A small fraction of the EBR-II irradiated fuel inventory is corroded (i.e., oxidized) as a result of decades of storage in hot cells and water pools. These corroded materials are not amenable to treatment by pyroprocessing equipment in FCF. Alternative disposition technologies and paths are being evaluated.

4.3.2.2 Pyroprocessing Research and Development Goals. Research in pyroprocessing focuses on development of fundamental process understanding, safeguards, commercial-scale flowsheets, and waste forms. Active research projects that are working toward the deployment of pyroprocessing supported by MFC include the following:

- Fundamental Chemistry and Theory of Pyroprocessing Operations – A primary area of interest is the technology for recovering TRU from molten salt that develop in the electrorefining cell. Research is being performed on methods (such as liquid cadmium cathode, solid cathode, chemical drawdown, and electrolysis) to determine the separation efficiency and applicability of these technologies to recycling used nuclear fuel.
- Modeling and Simulation of Pyroprocessing Operations – These theoretical-based efforts provide a means of assessing the performance of a process flowsheet with regards to the layout and performance of the various unit operations within the flowsheet. Verification of performance requires experimentation.
- Technology Development for Commercial-Scale Operations – Flowsheets are under development for pyroprocessing of oxide fuels and metallic fuels based on both U-235 and Pu-239 as the primary fissile element. The flowsheets are used to benchmark and reference the present state of technology development and identify those areas most deserving of the limited resources available for focused research.
- Technology Development for Safeguarding Commercial-Scale Operations – The international safeguards community is increasingly concerned as more countries begin to show interest in pursuing pyroprocessing technologies. Research is underway to determine a safeguards strategy for a declared pyroprocessing facility that will satisfy International Atomic Energy Agency standards. An understanding of signatures and observables is vital to the detection and surveillance of pyroprocessing facilities for safeguard and security applications.
- Waste Form Development – Characterization and assessment of pyroprocessing waste is a key component of determining the efficiency and viability of any proposed reprocessing scheme. Both the ceramic and metal waste forms were developed to immobilize high-level waste from the treatment of EBR-II used fuel and are recognized world-wide as the baseline pyroprocessing waste forms. MFC continues to lead in development of advanced pyroprocessing waste forms. Appendix E provides a more detailed strategy for development of disposition pathways for recovered uranium and envisioned salt and cladding waste streams.

4.4 Focused Basic Research

Focused basic research sets the stage for advances in technology through revolutionary advances in the fundamental understanding of the underlying physics and chemistry of material behavior in the nuclear environment. Effectively exploring the fundamental behavior of actinide elements requires that capabilities for the study of actinide materials be made available to a broad spectrum of the nuclear science and physics research community through NSUF or other collaborations (Figure 4-16).

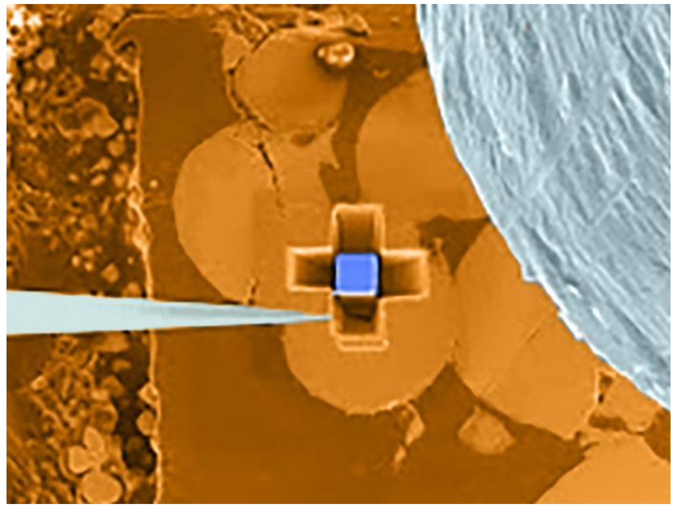

Figure 4-16. INL researchers have demonstrated a new sample preparation technique that makes it easier to examine irradiated fuel at the nanoscale. The new technique uses an ion beam to mill material sections that are just tens of nanometers thick. A platinum layer (i.e., the blue square) protects the surface and an Omniprobe needle (i.e., gray) is used to lift the tiny sample. The sample can then be used for a variety of characterization activities that probe fundamental properties.

4.4.1 Basic Research Challenges

Basic research priorities supporting an advanced nuclear energy system have been identified by DOE's Office of Science through a series of workshops on nuclear energy and related topics. Research priorities identified in a 2006 workshop, *Basic Research Needs for Advanced Nuclear Energy Systems*,[q] include the following:

- Nanoscale design of materials and interfaces that radically extend performance limits in extreme radiation environments
- Physics and chemistry of actinide-bearing materials and the 5f-electron challenge
- Microstructure and property stability under extreme conditions
- Mastering actinide and fission product chemistry under all chemical conditions
- Exploiting organization to achieve selectivity at multiple length scales
- Adaptive material environment interfaces for extreme chemical conditions
- Fundamental effects of radiation and radiolysis in chemical processes
- Fundamental thermodynamics and kinetic processes in multi-component systems for fuel fabrication and performance
- Predictive multiscale modeling of materials and chemical phenomena in multi-component systems under extreme conditions.

A Basic Energy Sciences workshop[r] on the broader topic of Materials in Extreme Environments identified the topic of *Design of Materials with Revolutionary Tolerance to Extreme Photon and Particle Fluxes* as a priority research direction, including the following three primary challenges:

1. Understanding the fundamental origins of the performance limits of materials under high flux environments

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[q] "Basic Research Needs for Advanced Energy Systems," Report of the Basic Energy Sciences Workshop on Basic Research Needs for Advanced Nuclear Energy Systems, Office of Basic Energy Sciences, U.S. Department of Energy (2006).

[r] "Basic Research Needs for Materials under Extreme Environments," Report of the Basic Energy Sciences Workshop for Materials under Extreme Environments, Office of Basic Energy Sciences Department of Energy (February 2008).

2. Understanding material response over the full range of time and length scales, from defect creation by atomic ionization or displacement in attoseconds or femtoseconds, to defect migration and assembly into large clusters over microseconds, and to macroscopic degradation of performance and eventual failure over years or millennia
3. Developing defect-free, defect-tolerant, or self-repairing materials for application in high flux environments.

MFC capabilities and expertise extend to the areas that are highlighted above, primarily through the use of advanced microstructural characterization, property measurement tools, and radiochemistry. MFC's capability to handle and process significant quantities of actinide materials in research user facilities, along with a sizable inventory of the actinide materials required for research, will lead to expansion of capabilities for investigating the physics and chemistry of 5f electron materials.

Figure 4-17 shows fuel areas at a fission density of 1.1×10^{22} f/cm^3. In low-enriched uranium fuel, all U-235 is consumed at 7.8×10^{21} f/cm^3. The fission gas bubble superlattice remains in some areas, along with a high concentration of small bubbles in the U-Mo matrix that remains at this burnup. The surprising stability of this fission gas structure spurred interest from Basic Energy Sciences, who requested a proposal to further investigate the formation and stability of this structure.

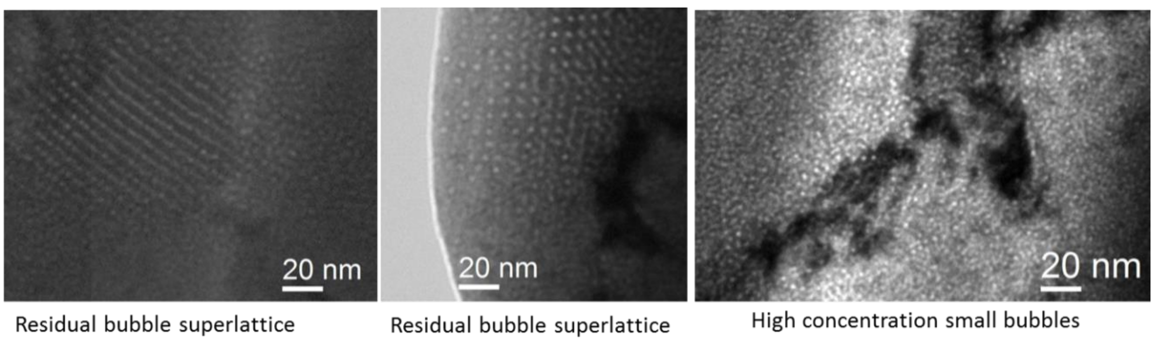


Figure 4-17. Examination using transmission electron microscopy shows that the unusual fission gas bubble superlattice that forms in U-Mo fuel during irradiation and is retained to ultra-high burnup.

4.4.2 Focused Basic Research Goals

The availability of new scientific tools and specialized facilities (IMCL and SPL) at MFC dedicated to nanoscale characterization of fuels and materials and open to the science community lays the groundwork for research leading to resolution of the challenges listed above. At a more fundamental level, the actinides (i.e., 5f electron elements) defy efforts to understand their unusual properties. These elements are among the most complex and display some of the most unusual behaviors of any series on the periodic table.

At the core of achieving a full understanding of advanced fuel behavior, a solid fundamental understanding of the physical properties of actinide materials, including transport, thermodynamics, and magnetism is required. The unusual thermal behavior of UO_2 is an example of the complexity of actinide materials. As a ceramic, thermal transport in UO_2 is mainly controlled by phonons. It has recently been suggested[s] that the unusually low thermal conductivity and its unique temperature dependence, which have been a mystery since the beginning of the nuclear era, is related to resonant spin-phonon interactions. These collective phenomena suppress the thermal conductivity and lead to many intriguing

[s] K. Gofryk, S. Du, C. R. Stanek, J. C. Lashley, X.-Y. Liu, R. K. Schulze, J. L. Smith, D. J. Safarik, D. D. Byler, K. J. McClellan, B. P. Uberuaga, B. L. Scott, and D. A. Andersson, 2014, "Anisotropic thermal conductivity in uranium dioxide," *Nature Communications* 5: 4551.

transport and thermal behaviors. The majority of the unique properties is related to strong electronic correlations and interplays with complex magneto-phonon interactions, the understanding of which is necessary to describe and predict the physical properties of this material and other actinides.

Exploring the fundamental nature of actinides, especially TRU elements and compounds at this level, requires that additional research tools be brought online in existing (i.e., IMCL) or planned (i.e., SPL) nuclear and radiological research facilities. These tools include methods such as detailed transport, thermodynamic and thermal properties measurements performed at low and moderate temperatures, and extreme conditions such as pressure and magnetic field. While nuclear fuel operates at high temperatures, thermal conductivity and other materials properties provide the richest fundamental information on actinide material behavior at low temperatures. Properties measured at low to moderate temperature have more variation in properties with high temperature, have less uncertainty, and have larger differences in properties for different materials. These variations need to be characterized, because if these property variations can be captured with high fidelity, they will afford the highest predictive capability in modeling and the best assurances for validation and verification at all temperatures. On the other hand, changing distances between atoms by amplification of pressure affects the collective vibrational properties and the way phonons interact with other quasiparticles. Transport, thermodynamic, and spectroscopic measurements under pressure can be used to probe coupling between these states. By proving the dependence of thermal transport in actinide materials on the quasiparticle scattering and excitations and on coupling between lattice vibrations and magnetism, work in this area will shed unprecedented light on the physical, especially thermal, properties of these unique materials.

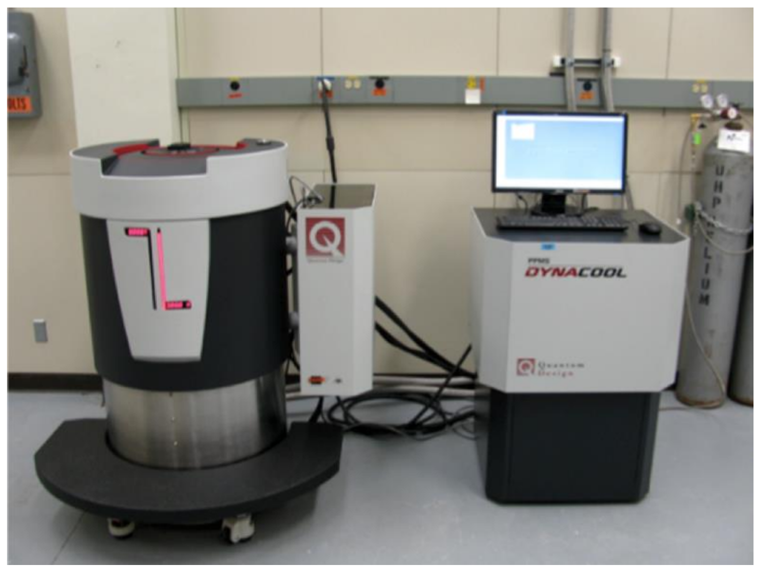


Figure 4-18. Physical Property Measurement System (DynaCool-9, currently installed at the INL Idaho Research Center). Availability of this capability in IMCL will result in unique capability for understanding the fundamental properties of the actinides and actinide-bearing ceramics and alloys.

Because actinides are difficult to handle in normal laboratory environments, substantial progress in understanding actinide materials will require adapting scientific instruments that are not currently available for use with higher actinides (such as the Physical Properties Measurement System; see Figure 4-18) to handle high-activity radiological materials and incorporating these instruments into a nuclear research facility. The results obtained from research conducted using this capability will provide fundamental understanding of nuclear materials and fill in missing critical parameters for advanced modeling and simulations crucial for model validation and development.

This measurement platform allows a variety of transport and thermodynamic measurements of nuclear materials in wide temperature (near 0 K) and magnetic field ranges. A similar system able to perform measurements of minor actinide materials, in conjunction with microstructural characterization, will provide deep insight into the unique properties related to strong electronic correlations and their interplay with complex magneto-phonon interactions.

4.5 Nuclear Nonproliferation and Nuclear Forensics

For nuclear power to continue to be a viable energy option in any country, including the United States, nuclear security, material protection control and accountancy, and safeguards must be maintained at a high level. A key approach to increasing the proliferation resistance of nuclear facilities and processes is the development of improved technologies to track and account for fissile material in nuclear systems. By making a nuclear system more transparent for material accountancy and process monitoring, it becomes easier to safeguard and improve proliferation resistance. These technologies cover the full spectrum of the nuclear fuel cycle, including uranium enrichment, fuel fabrication, reactor operations, fuel recycling, used fuel storage, transportation, and disposal. Safeguards technologies and integrated systems must be developed for current and potential future domestic and international fuel cycle options. INL researchers from the nuclear nonproliferation directorate are currently leading research activities in the following areas:

- Study and development of new approaches and methodologies for addressing nuclear cyber security threats at nuclear reactors and facilities
- Understanding how safeguards- by-design approaches can and should be applied for small modular reactors
- Invention of wholly new methods for safeguarding pyroprocessing technology
- Development of new instruments for assaying the uranium content of advanced LWR fuels for current generation nuclear reactors
- Offering world-class training courses for domestic and international students to learn about the nuclear fuel cycle and methods and best practices for safeguards.

These activities include work funded by multiple U.S. government agencies and involve partnerships with other U.S. national laboratories, foreign national laboratories, universities, the IAEA, and companies, including small businesses, large businesses, and a potential small modular reactor vendor.

The need for adaptive approaches to the physical and cyber security of nuclear facilities is needed in conjunction with the development of instruments and methods to support safeguards and material accountancy. MFC (and other fuel-cycle facilities at INL, including ATR and INTEC) presents unique capabilities for performing R&D in these areas.

Because of INL's legacy activities related to nuclear energy R&D and its current hands-on experimental activities related to handling nuclear and radiological materials, the laboratory also plays a key role in support of important U.S. National Technical Nuclear Forensics programmatic activities. This work takes advantage of many facilities at MFC, including AL, Radiochemistry Laboratory (RCL), EFF, FASB, FCF, FMF, HFEF, and the ZPPR. INL work in this area also strongly leverages the MFC workforce and the cadre of uniquely trained personnel with key skills related to handling and safely working with radioactive and nuclear materials.

4.5.1 Nuclear Nonproliferation and Nuclear Forensics Research, Development, and Demonstration Focus Areas

New challenges are evolving in the area of nuclear nonproliferation and nuclear forensics research due to the continued spread of nuclear technology throughout the world, the international expansion of nuclear energy, changes in the nature of physical threats against nuclear facilities and materials, and the constantly changing nature of cyber threats. Specific scientific challenges exist in relation to understanding and characterizing the materials and processes taking place in nuclear facilities, especially hot cells; working with complicated actinide-bearing materials to perform uranium and plutonium accountancy; developing methods and protocols for understanding current cyber security vulnerabilities at nuclear facilities and predicting future threat pathways and how they might develop at these facilities; and developing faster and more sensitive analytical methods for nuclear forensics. Examples in these areas include the following:

- Developing assay methods for quantifying uranium and plutonium in traditional and non-traditional matrices containing higher-order actinides. Examples in this category include the need for the ability to assay plutonium in advanced transmutation fuels and the need to assay U-235 in advanced LWR fuel assemblies containing high levels of burnable gadolinium (and potentially hafnium) poisons.
- Developing real-time measurement methods for quantifying plutonium within hot cells.
- Developing advanced process monitoring approaches for monitoring activities within hot cells.
- Developing real-time process monitoring methods for assaying electrorefiner salts to quantify plutonium concentration and total mass.
- Developing advanced safeguards methods for characterizing and monitoring plutonium and uranium within used nuclear fuel stored in cooling ponds and dry-cask storage containers.
- Developing approaches to improve the physical security of nuclear facilities and developing methods to assess the performance of these approaches.
- Developing approaches to improve the cyber security of nuclear facilities and developing methods to assess the performance of these approaches.
- Improving our understanding of the physical and chemical characteristics of radiological and nuclear materials found throughout the nuclear fuel cycle, the radiation signatures emitted from materials, and using this information to support nuclear forensics.

4.5.2 Nuclear Nonproliferation and Nuclear Forensics Research, Demonstration, and Development Goals

Many advanced fuel cycle processes (such as advanced aqueous reprocessing, electrochemical separations, and recycled fuel fabrication) pose new challenges for safeguards and nuclear material management. Similarly, new small modular reactor designs require comprehensive safeguards-by-design evaluations to ensure they can economically and practically meet international safeguards implementation requirements. Early integration of safeguards concepts into nuclear facility design (i.e., the safeguards-by-design concept [developed at INL]) is optimal for meeting U.S. and international standards with a minimal impact on operations. This requires developing a solid understanding about how nuclear facilities are built and operated together with support for development of advanced technology so that it is ready for deployment during the design process. State-of-the-art will be advanced through a developmental program to improve the precision, speed, sampling methods, scope of nuclear process monitoring and accountancy measurements, and innovative approaches for containment and surveillance.

Multiple opportunities exist for INL to take advantage of the unique, diverse special nuclear materials inventoried at MFC to facilitate this research. Similarly, the nuclear facilities operated at MFC present fertile testing grounds for developing and evaluating new technologies across the spectrum of nuclear security R&D. For INL to fully realize the DOE-NE goals to understand and minimize the risks of nuclear proliferation and terrorism, continued progress must be made to integrate nuclear nonproliferation and nuclear forensics activities into nuclear fuel, fuel recycling, and focused basic research activities at MFC. Projected developments and R&D activities at AL, EFF, HFEF, IMCL, FCF, FMF, RCL, SPL, and ZPPR all provide opportunities for future nuclear nonproliferation and nuclear forensics programmatic activities.

Potential growth areas include the following:

- Domestic and international safeguards and emergency response research, development, and training focused on developing and testing instruments and methods for safeguarding current LWRs and training for nuclear nonproliferation and international safeguards inspectors.

- Safeguards by design outreach activities at INL, including ongoing engagement with a leading small modular reactor developer.
- Development of actinide radiochemistry methods in support of INL's expanding nuclear forensics R&D activities.

4.6 Space Nuclear Power and Isotope Technologies

4.6.1 Space Nuclear Power

Production of RPS has been an ongoing endeavor for DOE and its predecessor agencies for the past five decades. The overall mission of the RPS Program is to develop, demonstrate, and deliver compact, safe nuclear power systems and related technologies for use in remote, harsh environments (such as space), where it is impractical to provide the fuel and maintenance that more conventional electrical power sources require. This program was moved from the DOE Mound facility in Ohio to INL in 2002 due to security concerns after the 2001 terrorist events. Space nuclear power assets at MFC provide unique U.S. capability for assembly, testing, servicing, storage, transport, and ground support operations for RPS used in space and terrestrial missions. Space Nuclear Power and Isotope Technologies personnel provide turn-key services to support these capabilities, including establishment and management of temporary nuclear facilities at RPS launch or other user locations to meet DOE nuclear safety requirements. More details about RPS programs, facilities, and out-year plans for the next 5 years are described in Appendix B.

4.6.2 Isotope Technologies

The production and distribution of isotopes for medical and scientific benefit is the business of the Isotope Program Operations of the Office of Nuclear Physics in the DOE Office of Science. There is a single exception to this statement with Pu-238, which, by mutual agreement, is administered by the Space and Defense Power Systems Program and DOE-NE. Both of these groups work through the national laboratory systems and affiliate partners to provide for production, distribution, and use of these isotopes. INL currently is engaged with both providers of isotopes (DOE Office of Science and DOE-NE).

The recent efforts of DOE-NE to re-establish domestic production of Pu-238 for use in power systems for use by the National Aeronautics and Space Administration have been supported by INL in several ways. INL essentially houses all of the U.S. inventory of Np-237, which is the precursor target material required to make Pu-238. INL also houses the second of two reactors (i.e., ATR), which will be used along with the High Flux Isotope Reactor at ORNL to produce Pu-238 from the Np-237 target material. INL's role is to supply Np-237 to ORNL to fabricate targets for both reactors. INL will also provide irradiation services in ATR and ship irradiated targets to ORNL for processing into purified Pu-238. The ATR target should be qualified by the early 2020s; if additional funding is available, this process can be accelerated.

INL currently supports the production of Co-60 in ATR. This project is also performed in conjunction with ORNL. Co-60 is produced from neutron capture of Co-59. This isotope is used primarily for sterilization of medical equipment and blood. Improvement in efficiency and expansion of services provided by INL to the Co-60 pipeline will be explored with a 5-year (i.e., FY 2022) goal of doubling the business volume in this area.

The current DOE inventory of large quantities of Sr-90 in a purified form currently resides at Pacific Northwest National Laboratory. The Waste Encapsulation and Storage Facility at Pacific Northwest National Laboratory houses several hundreds of kilograms of Sr-90. This material is of interest for use in small (i.e., about 2 $W_{electric}$) commercial radioisotope thermoelectric generators. The use of RAL at INL would be required for material receipt and division into smaller quantities for encapsulation as heat sources. A 5-year goal (i.e., FY 2022) in this area is to develop a final design for the heat source radioisotope thermoelectric generators, have facility modifications underway at RAL, and have a completed National Environmental Policy Act action to facilitate movement of the isotope in a shipment-by-shipment fashion from Pacific Northwest National Laboratory to INL.

4.7 Additional Factors Necessary for Success

4.7.1 Data Management and Analysis

Focusing on increasing the quantity, fidelity, and types of data generated is a necessary, but not sufficient, condition to spur innovation. The objective must be to achieve a higher rate of knowledge generation through analysis of data. Knowledge used in context to answer a specific question provides the information that drives innovation. To accelerate innovation in the nuclear industry, the rate at which information is created must increase. Generating this information requires deployment and use of efficient experimental design and data management and analysis tools grown in parallel with reliable facilities, modern equipment and instrumentation, and efficient processes.

Current data streams range over ten orders of magnitude in length scale and include markedly different types of data (such as engineering drawings, images, linear dimensional information, tomographic data, time-resolved data on experiment operating conditions, and point data from chemical analysis). The shift to improved, three-dimensional characterization methods at both the engineering and microstructural scales will result in a further large increase in data. The capability to store, process, and analyze data must increase correspondingly. Further improvements in knowledge generation can be realized through concurrent visualization of test parameters, experimental results, and simulations. Requirements for a data management and analysis system that supports rapid generation of knowledge include the following:

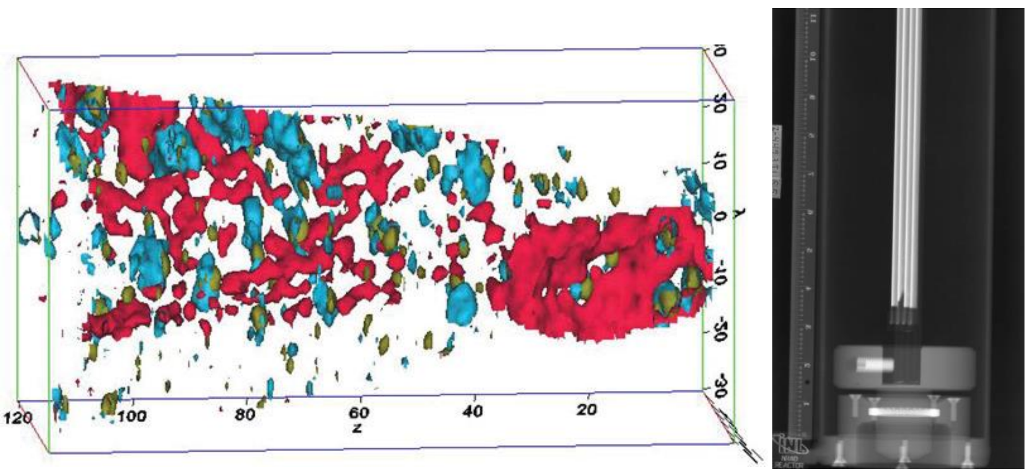


Figure 4-19. Example of three-dimensional data that ranges over 10 orders of magnitude in length scale. (Left) Atom probe tomography results from an alloy containing Fe-Cr-Mo and yttrium oxide. The scale is in nanometers; the map is built from the locations of individual atoms. (Left) Neutron tomography of a 1-m-long plate-type fuel element. Management and analysis of terabytes of data over this vast difference in length scales is a significant challenge.

- Data capture and storage in a commonly accessible location in usable formats.
- Data from experiments, experiment operating parameters, experiment design, and results from modeling and simulation meld seamlessly to allow the rapid validation of models and validation of hypotheses.
- Visualization of multiple data streams from examination (i.e., visual exam, dimensional measurement, microstructure, and atomic structure), fabrication (i.e., pre-irradiation microstructure, isotopics, and chemistry), irradiation history (i.e., temperature, flux, and fluence), and modeling and simulation results must be available simultaneously in three dimensions over ten orders of magnitude (engineering scale to the atomic scale) to allow rapid comprehension of system behavior.

- Built-in quality assurance functionality, including data review, acceptance, and archival.

Development of effective data management, processing, and visualization tools that function seamlessly with MOOSE-based applications will dramatically increase the rate of comprehension of complex systems and validation of fuel and material performance models and codes (Figure 4-19). Effective implementation of such a system, along with implementation of improved analysis methods, provides the ability to revolutionize the current regulatory paradigm by ensuring that validated, high quality data are readily available.

4.7.2 Material Sharing with the Nuclear Research Community

DOE-NE's extended research capability is world-class and will soon become world-leading. This capability is maximally effective when transfers of material and information across DOE-NE's network are seamless. This combined and connected capability, centered at MFC, supports DOE-NE's transition to a science-based approach to R&D that relies on coupling modeling and simulation with detailed experimentation to improve the ability to predict performance.

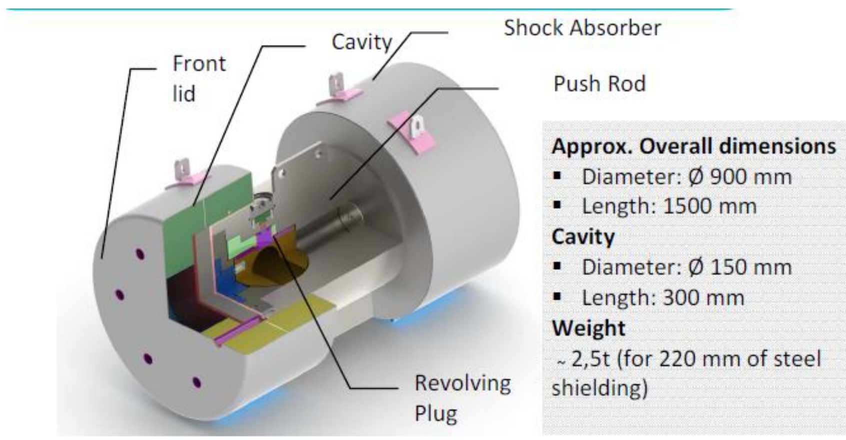


Figure 4-20. International air transportable cask being developed on behalf of the International Hot Labs working group by TransNucleaire International.

This world-class research capability will also be in high demand by international partners, some of which possess unique capabilities that can provide important data that DOE-NE does not wish to invest in. Likewise, it may be desirable to transport material from the United States to international partners when unique capabilities exist in other nations. One of the primary difficulties associated with research within this network is the availability of shipping packages that allow rapid transport of material from ones site to another. This issue can be resolved nationally and internationally by adopting the recommendations of the international Hot Labs Working Group to develop and license an international 'Flying Pig'[t] shipping cask (Figure 4-20) that allows rapid air or vehicle transport of small quantities of materials between research sites.

4.7.3 Support for Classified Programs

Research on classified fuels and materials benefits from the MFC capabilities, especially as other segments of the national nuclear research infrastructure that support National and Homeland Security, NNSA, and Naval Nuclear Propulsion programs age and lose functionality. Work that MFC performs in these areas aligns with MFC research focus areas and takes advantage of capabilities at MFC, including HFEF, AL, IMCL, and Electron Microscopy Laboratory. Increased work scope is anticipated in these facilities. This research typically requires facilities to switch modes of operation from an open and collaborative user facility environment to an access-controlled environment, where access to material and data are carefully controlled. A program-funded secure conference room will be added to the MFC site in FY 2016 to support some aspects of this research by allowing classified videoconferencing and data exchange.

[t] http://hotlab.sckcen.be/~/media/Files/Hotlab/Plaquette%20FP.PDF?la=en.

4.7.4 Laboratory Investment in the Nuclear Test Bed

4.7.4.1 Expansion of Laboratory-Directed Research and Development. Investing in advanced technology and development of the MFC scientific workforce is critical for driving expansion of capabilities that support a nuclear test bed. Developing advanced instrumentation and measurement methods and aligning this capability with university and industry needs will expand research and demonstration competencies needed to achieve GAIN objectives. Laboratory-directed R&D funding plays a vital role in this area. Optimizing the use of existing instrumentation by developing new, innovative techniques fully leverages current capabilities and ensures that additional capability needs are well understood and future investment in those capabilities is based on sound decision-making. Stable and strategic laboratory investment establishes a sound basis for planning and executing capability expansion.

4.7.4.2 Program Development. Program development is another strategic investment source that can be leveraged to support the test bed by enabling rapid response to inquiries from potential collaborators about new analysis methods, capability, or conceptual experiment or demonstration designs in MFC facilities. Requests for proposals, cost estimates, and conceptual experiment or demonstration designs are examples of areas where program development can support the test bed.

Program development funding can also be used to support needs assessments, workshops, and proposals. Program development may also be able to support outreach to industry and universities. Coordinating with NSUF is key to ensuring that the limited funding available is optimized across the laboratory and DOE-NE programs.

PROPOSED FUTURE CAPABILITIES (2023 THROUGH 2027)

Picture on the front depicts: After obtaining tiny, intact nuclear fuel samples, INL researchers take slices to analyze using a transmission electron microscope, which can magnify up to 500,000 times and reveal features a few nanometers (1-millionth of a millimeter) across. After collecting images of about 200 slices, researchers reassemble the images to make a 3-D picture of the sample's fine features.

5. PROPOSED FUTURE CAPABILITIES (2023 THROUGH 2027)

5.1 Radioanalytical Chemistry

Because of the shortage of nuclear facility research space at MFC, several capabilities unrelated to AL's primary quantitative analysis and radiochemistry mission have been installed in AL's approximate 10,000-ft^2 laboratory research space. Examples include the casting laboratory (used for fabrication of TRU-bearing fuel specimens), waste form testing glovebox, and the recently installed thermal property measurement gloveboxes and radiological mass separator. Although these capabilities are necessary to the function of MFC, they detract somewhat from AL's primary analysis mission and also indicate the need for additional general purpose nuclear facility laboratory space at MFC.

As was the case for development of EBR-II and the Integral Fast Reactor, pilot-scale development of advanced reactor technology as part of the nuclear test bed will require comprehensive and flexible analytical chemistry capability. The need for a comprehensive radioanalytical capability that supports the nuclear test bed concept and a general need for nuclear research space at MFC indicate the necessity for a new or expanded AL facility. Because of the continuing need for nuclear research space, current refurbishment activities should continue. Beginning in FY 2018, options for a sustainable radioanalytical capability will be developed with DOE-NE, with a proposed path forward by the end of FY 2019 for implementation within the next 10 years.

5.2 Fuel Fabrication Laboratory

Enabling fuel development functionality that supports a nuclear test bed requires the following:

- Analysis of the likely range of fuel test and development products that will be required to support DOE-NE Program research planning and nuclear industry collaboration for the next several decades
- Consideration of modern fabrication processes (e.g., additive manufacturing, laser welding, and electron-beam lithography) that may be applicable and developing concepts for deployment of current and advanced manufacturing technologies in a flexible and reconfigurable fuel fabrication facility that supports DOE-NE needs for the next four decades.

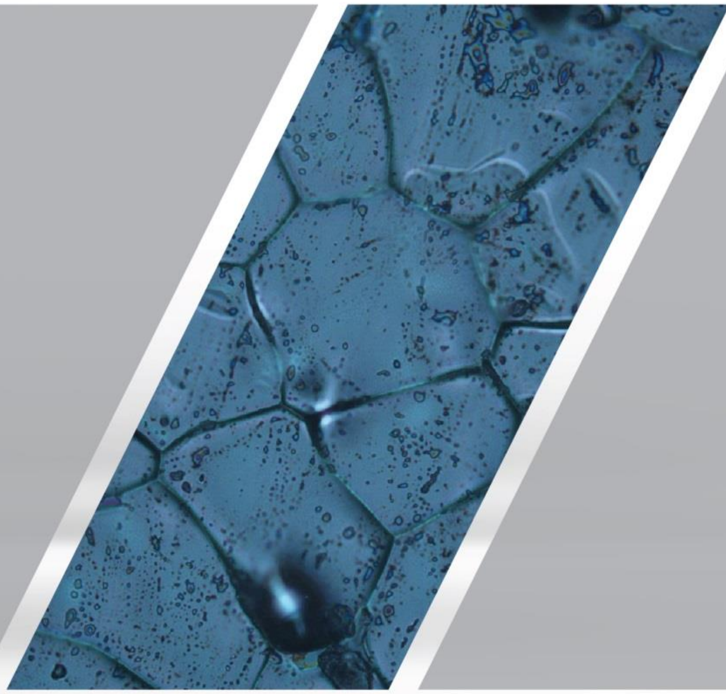
From 2016 to 2020, emphasis will be placed on experimental testing of advanced fuel manufacturing processes and developing concepts for an advanced fuel fabrication R&D laboratory to demonstrate and deploy these technologies. A flexible, reconfigurable fuel fabrication laboratory will be key to meeting GAIN objectives for transitioning technology from laboratory to commercial use. This need can be partially met by the proposed Reactor Fuels and Structural Materials Support Facility (Section 8.3), but will likely require additional capability in a current or new facility for TRU materials.

5.3 Nuclear Nonproliferation and Nuclear Forensics Laboratory

For nuclear power to continue to be a viable energy option in any country, including the United States, nuclear security, material protection control and accountancy, and safeguards must be maintained at a high level. New challenges are evolving in the area of nuclear nonproliferation and nuclear forensics research due to the continued spread of nuclear technology throughout the world, the international expansion of nuclear energy, changes in the nature of physical threats against nuclear facilities and materials, and the constantly changing nature of cyber threats. Because of MFC's past activities related to nuclear energy RD&D and its current hands-on experimental activities related to handling nuclear and radiological materials, MFC plays a key role in support of important U.S. nuclear nonproliferation and National Technical Nuclear Forensics programmatic activities.

Increasing scope in this area will require additional nuclear laboratory space to support new activities and relieve pressure on HFEF and AL. This space will be highly complementary with other MFC investments in capability. A new facility at MFC that supports the nuclear nonproliferation and nuclear forensics mission, while leveraging and supporting development of advanced reactors and fuel cycles, is highly desirable. The intent of this facility would be to provide dedicated nuclear facility R&D space for classified and unclassified nuclear nonproliferation and forensics programs. Proximity to HFEF, AL, and ZPPR is desired to maintain connectivity to the laboratory mission and leverage the wealth of materials handled and available at MFC that are a national asset to National and Homeland Security missions.

Pre-conceptual design of this facility will be explored in conjunction with parallel activities related to the MFC AL, Reactor Fuels and Structural Materials Support Facility, and Fuel Fabrication Laboratory in conjunction with NNSA and DOE-NE.



MATERIALS AND FUELS COMPLEX FACILITY DATA SHEETS

Picture on the front depicts: Advanced nuclear fuels can be developed from a better understanding of how fuel in the nation's current reactors conducts heat during operation. For insight, researchers need to understand how gas bubbles or other characteristics impact heat transfer. These characteristics are particularly important at the boundaries between individual crystals of material, such as those seen here in a fabricated bit of nuclear fuel surrogate.

6. MATERIAL AND FUELS COMPLEX FACILITY DATA SHEETS

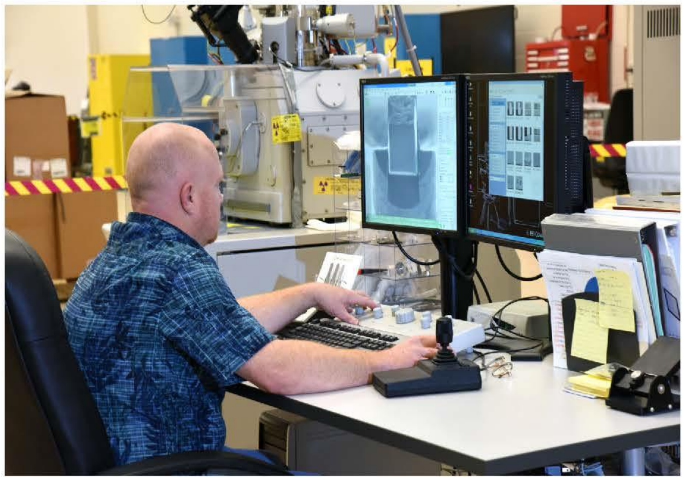
FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

IRRADIATED MATERIALS CHARACTERIZATION LABORATORY

POST IRRADIATION EXAMINATION

BASIC DESCRIPTION:

The Irradiated Materials Characterization Laboratory (IMCL) is a Hazard Category 2 nuclear facility that focuses on microstructural, thermal, and mechanical characterization of irradiated nuclear fuels and materials. IMCL's unique design incorporates advanced characterization instruments that are sensitive to vibration, temperature, and electromagnetic interference into modular radiological shielding and confinement systems. The shielded instruments allow characterization of highly radioactive fuels and materials at the micro, nano, and atomic levels, the scale at which irradiation damage processes occur. Enabled by its modular design, IMCL will continue to evolve and improve capability throughout its 40-year design life to meet the national and international user demand for high-end characterization instruments.



BASIC CAPABILITIES:

- Preparation of high-activity samples
- Optical microscopy
- Electron probe microanalysis (EPMA)
- Dual-beam focused ion beam (FIB)
- Transmission electron microscopy (TEM)
- Scanning electron microscopy (SEM)
- Thermal-property characterization

KEY INSTRUMENTS:

- Shielded Sample Preparation Area (SSPA hot cell)
- Shielded Cameca SX100R EPMA
- Shielded FEI QUANTA 3G field emission gun (FEG) dual beam (FIB)
- FEI Titan ChemiSTEM FEG-STEM
- Shielded FEI Helios dual beam SEM/plasma FIB
- Shielded optical microscopy
- Space for future user-defined capability
- Shielded thermal property measurement cell
  - Laser-flash thermal diffusivity
  - Differential scanning calorimetry
  - Thermal conductivity microscope

Idaho National Laboratory

16-GA50206-01-R2

FACILITY CAPABILITIES – ADVANCED TEST REACTOR COMPLEX

ADVANCED TEST REACTOR

IRRADIATION

BASIC DESCRIPTION:
The Advanced Test Reactor (ATR) supports nuclear science and engineering missions for the U.S. Department of Energy's Office of Nuclear Energy research and development programs, Naval Reactors, and a variety of other government and privately-sponsored commercial and international research. It is the only U.S. research reactor capable of providing large-volume, high-flux neutron irradiation in a prototypical (e.g., pressure, temperature, and chemistry) environment. The ATR makes it possible to study the effects of intense neutron and gamma radiation on reactor materials and fuels in a much shorter time frame, permitting accelerated research efforts.

BASIC CAPABILITIES AND FEATURES:
- Critical national and international irradiation testing capability
- High power (250 MW) test reactor operating at low pressure and temperature, but with six individual experiment locations with conditions adjustable to >500°C and >1000 psig
- Reactor cooled by light water with a beryllium reflector for high neutron efficiency
- Unique serpentine core allows reactor's corner lobes to be operated at different power levels, making it possible to conduct multiple simultaneous experiments under different testing conditions

KEY INSTRUMENTS:
- Large test volumes – up to 48 inches long and from 0.5 to 5 inches in diameter
- 77 testing positions
- High neutron flux (up to ~10^{15} n/cm²/sec) available
- Fast/thermal flux ratios ranging from 0.1 – 1.0
- Constant axial power profile
- Individual experiment pressure and temperature control possible
- Frequent experiment changes possible each outage
- Programmatic operational commitment to at least 2050
- Accelerated testing for fuel and materials development
- A key capability within the Nuclear Science User Facilities (NSUF) and the Gateway for Accelerated Innovation in Nuclear (GAIN) programs
- The reactor is capable of isotope production (e.g., cobalt-60) for medical, commercial, and other research applications

16-GA50206-02-R2

Idaho National Laboratory

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

TRANSIENT REACTOR TEST FACILITY

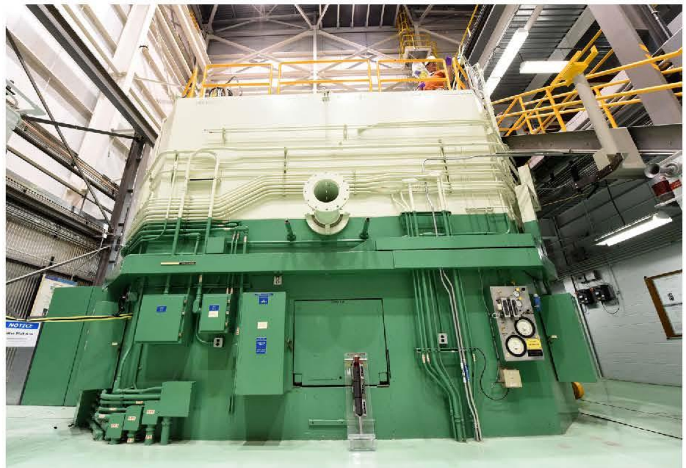
IRRADIATION

BASIC DESCRIPTION:

The Transient Reactor Test Facility (TREAT) provides transient testing of nuclear fuels and materials. The facility is used to study fuel melting behavior, interactions between fuel and coolant, and the potential for propagation of failure to adjacent fuel pins under conditions ranging from mild upsets to severe accidents.

TREAT is an air-cooled, thermal-spectrum test facility specifically designed to evaluate the response of reactor fuels and structural materials to accident conditions. The reactor was originally constructed to test fast-reactor fuels, but its flexible design has also enabled its use for testing of light-water-reactor fuels as well as other exotic special-purpose fuels, such as space reactors. TREAT has an open-core design that allows for ease of experiment instrumentation and real-time imaging of fuel motion during irradiation, which also makes TREAT an ideal platform for understanding the irradiation response of materials and fuels on a fundamental level.

TREAT will provide a valuable capability to support efforts to develop accident-tolerant fuels light-water reactors as well as the advanced reactor fuels, both of which will allow nuclear energy to remain the primary source of emission-free baseload energy in the future.



BASIC CAPABILITIES:

- High-intensity (20 GW), short-duration (80 ms) neutron pulses for severe accident testing
- Shaped transients at intermediate powers and times (flexible power shapes with up to 60 seconds duration)
- 120 kW steady state operation
- Testing capability for static capsules, sodium loops, and water loops
- Neutron-radiography facility

KEY INSTRUMENTS:

- Nondestructive examination of assemblies up to 15 feet long in steady state operating mode by neutron radiography
- Neutron 'hodoscope,' providing real-time imaging of fuel motion during testing
- Open core design helpful to instrument experiments during testing

Idaho National Laboratory

16-GA50206-03-R3

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

SPACE AND SECURITY POWER SYSTEMS FACILITY

FUELING, TESTING, AND DELIVERY OF RADIOISOTOPE POWER SYSTEMS

BASIC DESCRIPTION:

Most of the Radioisotope Power Systems (RPS) Program assembly and testing operations take place in the 792A annex, which comprises most of the Space and Security Power Systems Facility (SSPSF). Building 792, adjacent to the 792A annex, is used for administration and operations support functions, including equipment storage. Building 792 is a non-nuclear, nonradiological facility while the 792A annex is a Hazard Category 2 nonreactor nuclear facility. Building 792 was originally constructed in 1971 and used for storage of various mock-up components. It is approximately 50 ft. x 60 ft. x 25 ft. tall. In 2004, the 792A annex was added.

BASIC CAPABILITIES:

- Pre-RPS assembly operations, involving placement of fueled clads into graphite components to form the general-purpose heat source modules
- RPS assembly operations, involving placement of heat sources into converters
- RPS acceptance testing
- RPS servicing and storage

KEY INSTRUMENTS:

- Gloveboxes for assembly or repackaging
  - Module assembly glovebox
  - Inert-atmosphere assembly chamber
  - Multipurpose fueling glovebox
  - Repackaging glovebox (aka, submarine glovebox)
- Systems for RPS testing, storage, transport
  - Vibration
  - Mass properties
  - Magnetics
- Thermal vacuum testing chambers (2)
- Module reduction and monitoring manifold
- Truck lock with crane

Idaho National Laboratory

16-GA50206-04-R1

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

SAMPLE PREPARATION LABORATORY

POST IRRADIATION EXAMINATION

BASIC DESCRIPTION:
The Sample Preparation Laboratory (SPL) will, beginning in 2020, provide for the needs of a growing nuclear energy research community.

BASIC CAPABILITIES:
SPL will provide instrumentation and capability not currently available for analysis of irradiated materials, including many for understanding material-aging issues, improving materials for use in advanced nuclear-energy systems.

- Load frame and charpy testing machines, each with an environmental chamber to simulate a wide range of environments from cryogenic to high-temperature
- Micro- and nanohardness testers to determine material properties such as modulus of elasticity, hardness, yield strength and fracture toughness in a very small area of sample

- Scanning electron microscopy for fracture surface analysis, a critical component of materials research
- Surface science instruments such as secondary ion mass spectrometry and X-ray photoelectron spectroscopy for chemical characterization of oxide films and fracture surfaces
- X-ray diffraction for determination of crystal structure of phases and the phase array in a material, residual stress measurement, and texture measurement to evaluate the evolution of these traits during irradiation

Idaho National Laboratory

16-GA50206-05-R1

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

ZERO POWER PHYSICS REACTOR

FUEL FABRICATION, NUCLEAR MATERIAL MANAGEMENT, NONPROLIFERATION ACTIVITIES

BASIC DESCRIPTION:

Zero Power Physics Reactor (ZPPR) is a Hazard Category 2 nuclear facility that consists of a workroom, cell area, and material-storage vault. The workroom houses the equipment utilized for material inspection and repackaging. The cell area is used for experiment and detection training for various customers, including National and Homeland Security. The vault contains and supplies materials used for programs in multiple facilities at MFC and other INL locations.

The ZPPR Materials Control Building (784) is a Hazard Category 3 facility primarily used to store and stage non-fissile nuclear materials.

BASIC CAPABILITIES:

- Transuranic and enriched-uranium materials storage
- Transuranic and enriched-uranium material inspection/repackaging
- Transuranic and enriched-uranium material handling for experiments/training
- Vault storage
- Cell area that can be reconfigured as necessary for experiment/training activities

KEY INSTRUMENTS:

- Transuranic surveillance glovebox line

Idaho National Laboratory

16-GA50206-06-R1

FACILITY CAPABILITIES – IDAHO NUCLEAR TECHNOLOGY & ENGINEERING CENTER

IDAHO NUCLEAR TECHNOLOGY & ENGINEERING CENTER

WASTE FORMS AND SEPARATIONS

BASIC DESCRIPTION:

The Idaho Nuclear Technology and Engineering Center (INTEC) was established in the 1950's as the Idaho Chemical Processing Plant (ICPP) to recover usable uranium in spent nuclear fuel used in government reactors. ICPP recovered more than $1 billion worth of highly enriched uranium, which was returned to the government fuel cycle. In 1998, the plant was renamed INTEC. Expanded capabilities will be determined by DOE funding and repurposes of existing facilities.

BASIC CAPABILITIES:

- Safe transfer of spent nuclear fuel from wet to dry storage and preparation for final disposal at an off-site repository or until the material is used for other purposes
- Radioactive material storage and repackaging capabilities
- Support Homeland Security in developing decontamination techniques
- Develop fuel cycle research capabilities

KEY INSTRUMENTS:

- Material Security and Consolidation Facility (MSCF) - CPP-651
  - MSCF provides secure storage for the Spent Fuel Treatment Program (SFTP) and unirradiated uranium in compliance with DOE safety, safeguards, and security requirements. The primary mission of MSCF is to provide a storage location for SFTP until permanent storage is available or until the material is used for other purposes. MSCF also provides a storage location for unirradiated uranium (metals and oxides) awaiting program identification and readiness for subsequent shipment or transfer to the designated site or facility.
- CPP-609
  - Office space for researchers and operations personnel
- CPP-653 - Fuel Cycle Research and Development - Material Recovery Project
  - The Material Recovery Project aims to design a material recovery fluidized bed system for scoping tests of the ZIRCEX process. The ZIRCEX process utilizes hydrochlorination (or chlorination) of nuclear fuel zirconium cladding in a fluidized bed with gaseous hydrochloric acid (HCL) or chlorine gas (Cl_2) at 350–450°C, which vaporizes Zr as $ZrCl_4$(g) and other constituents of zircaloy from the remainder of the fuel. The uranium does not form volatile compounds and is left in the chlorination vessel. The remaining fuel material would then be oxidized and, in the actual process, sent to dissolution and solvent extraction. This system would conduct the chlorination and oxidation steps on zircaloy samples and nonirradiated fuel samples.
  - Support Homeland Security in developing decontamination techniques
  - Hood
  - Inductively coupled plasma-mass spectroscopy (ICP-MS)
  - Decontamination tent
- CPP-661 - Guard gate for security
- CPP-1674 - Central Alarm System (CAS) and office space
- CPP-1634 - Engineering Development Laboratory

Idaho National Laboratory

16-GA50206-08-R1

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

EXPERIMENTAL FUELS FACILITY

FUEL FABRICATION, PROCESS DEVELOPMENT

BASIC DESCRIPTION:
The Experimental Fuels Facility (EFF) houses a wide range of fuel fabrication capabilities, supporting customers in DOE's Office of Nuclear Energy and private industry partners through INL's cooperative research & development program.

BASIC CAPABILITIES:
- Uranium and uranium-alloy casting
- Uranium and uranium-alloy extrusion
- Uranium-machining equipment capable of processing unalloyed and alloyed uranium metal and ceramics at all enrichments
- Inert-atmosphere uranium-processing glovebox line for fabrication and handling of alloys and powders
- Multiple furnaces with temperature capability up to 2000°C in vacuum, argon, air, hydrogen, and nitrogen atmospheres
- Non-radiological machine shop to support advanced fuel development

KEY INSTRUMENTS:
- Radiological fume hoods (4)
- Inert-atmosphere, radiological gloveboxes (3)
- Powder metallurgy process equipment
- Fuel experiment assembly equipment
  - Annealing quench furnace
  - Sodium glovebox
  - Sodium-settling furnace
  - Orbital capsule and cladding welding
- Uranium forming and machining
  - CNC lathe
  - Electrical discharge machine
  - Centerless grinder
  - Rolling mill
  - Shears and punches
  - 150-ton extrusion press
  - Hydraulic straightener/draw bench
  - Gun drill
- High-temperature applications
  - Arc-melting furnace
  - Molten-salt bath
  - Billet-casting furnace
  - High-temperature annealing furnace

Idaho National Laboratory

16-GA50206-09-R0

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

HOT FUEL EXAMINATION FACILITY

POST-IRRADIATION EXAMINATION

BASIC DESCRIPTION:

The Hot Fuel Examination Facility (HFEF) is a multiprogram hot cell facility. HFEF provides shielding and containment for remote examination, processing, and handling of highly radioactive and TRU-bearing materials in its argon-atmosphere hot cells, and maintains unshielded labs, support areas, and special equipment for handling, examining, and testing of highly radioactive materials. It also houses a shielded metallography box, an unshielded hot repair area, and a waste characterization area.

The main hot cell (70′ L x 30′ W x 25′ H) is stainless-steel lined with a purified argon atmosphere, 15 workstations, four-foot-thick walls and windows, and two rapid insertion ports. The decontamination hot cell (20′ L x 30′ W) is air atmosphere with a water wash spray chamber for decontaminating equipment.

BASIC CAPABILITIES:

- Non-destructive and destructive post-irradiation examination of irradiated samples
  - Imaging – visual and neutron
  - Dimensional analysis
  - Spectrometry
  - Machining and disassembly of fuel and material experiments
  - Sample preparation for optical microscopy, chemical and isotopic analysis, and electron microscopy
  - Mechanical testing of irradiated fuels and materials
- Bench-scale electrochemical separations research
- Handling and loading facilities capable of receiving large shipping casks and fuel pins up to 13 feet long
- Furnaces for simulating accident conditions at temperatures up to 2,000° C for extended periods of time

KEY INSTRUMENTS:

Non-destructive instruments include:

- 300 kW TRIGA Neutron Radiography Reactor (NRAD)
- Eddy Current (EC) probe for measurement of oxide thickness
- Precision gross and isotopic gamma spectrometer (PGS)
- Element contact profilometer (ECP)
- Visual examination machine (VEM)
- Large plate/element dimensional measurement bench

Destructive instruments include:

- Laser puncture gas collection and analysis system
- Fuel Accident Condition Simulator (FACS) furnace
- Metal waste form furnace
- Blister annealing, DEOX, and oxide reduction furnaces
- Optical microscopes, including microhardness tester

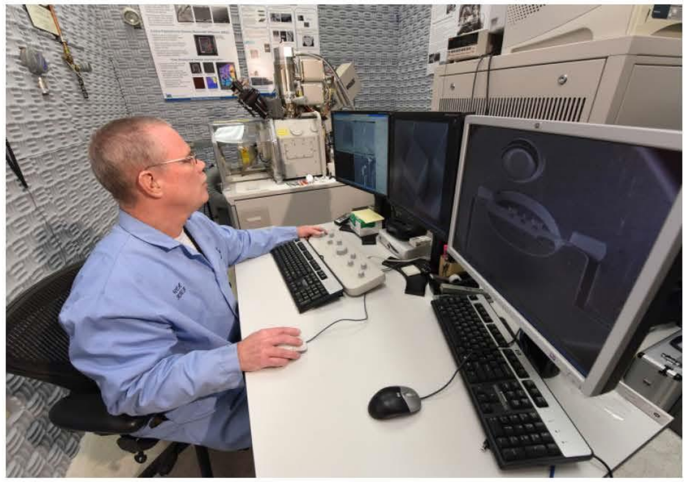
Idaho National Laboratory

16-GA50206-10-R3

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

ELECTRON MICROSCOPY LABORATORY

POST IRRIDIATION EXAMINATION



BASIC DESCRIPTION:

The electron microscopy lab (EML) is a user facility dedicated to materials characterization, using primarily electron and optical microscopy tools. Sample-preparation capabilities for radioactive materials ensure that high-quality samples are available for characterization.

BASIC CAPABILITIES:

- Scanning electron microscopy (SEM) with microchemical analysis and grain-orientation imaging
- Dual-beam focused ion beam (FIB) with microchemical analysis and orientation imaging
- Transmission electron microscopy (TEM) with microchemical analysis
- Optical microscopy
- Microhardness testing
- Precision ion polishing and coating systems
- Sample preparation of irradiated metals, ceramics, and small quantities of irradiated fuel for examination in gloveboxes and chemical hoods

KEY INSTRUMENTS:

- FEI QUANTA 3G field emission gun (FEG) dual-beam focused ion beam with energy dispersive spectroscopy (EDS), wavelength dispersive spectroscopy (WDS) and electron backscatter diffraction (EBSD) detectors and omniprobe micromanipulator
- JEOL JSM-7000f SEM with EDS, WDS and EBSD detectors
- JEOL JEM 2010 scanning transmission electron microscope with LaB6 electron gun and EDS
- Gatan precision ion polishing systems (PIPS-2)
- Gatan precision etching and coating system (PECS)

Idaho National Laboratory

16-GA50206-11-R1

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

FUELS & APPLIED SCIENCE BUILDING

FUEL FABRICATION, IRRADIATION, CHARACTERIZATION, POST IRRADIATION EXAMINATION, PROCESS DEVELOPMENT

BASIC DESCRIPTION:

The Fuels and Applied Science Building (FASB) is a radiological facility that has broad capability in fuel fabrication and characterization in support of nuclear-energy research and development.

The most recent addition to FASB is the irradiation assisted stress corrosion cracking (IASCC) hot cell. This addition supports several program customers through the Department of Energy's Nuclear Science User Facilities (NSUF) program to perform crack-growth-rate measurements on irradiated structural materials to support light water reactor life extension.

BASIC CAPABILITIES:

- Uranium-fuel development at all enrichments
- Materials characterization
- IASCC testing of irradiated materials
- Multiple uranium gloveboxes to support fuel development
- Cobalt-60 gamma irradiator with a radiolysis/hydrolysis test loop

KEY INSTRUMENTS:

- Inert, radiological gloveboxes (4)
- Radiological fume hoods (4)
- Cobalt-60 gamma irradiator
  - Solvent test loop
- Laboratory-scale molten salt electrorefiner
- Fabrication equipment
  - Arc-melting furnace
  - Induction furnace
  - Hot isostatic press
  - Hot rolling mill
- Powder metallurgy
  - Atomizer
  - Hydriding/nitriding apparatus
  - Sieving
  - Powder milling
  - Particle-size analysis
  - Pressing/sintering
- Characterization equipment
  - Density measurement (He pycnometer)
  - Differential scanning calorimeter
  - Dilatometer
  - Laser-flash thermal diffusivity
  - Scanning electron microscopy
  - Optical microscopy
  - Metallographic sample preparation
  - Microhardness testing
  - Positron-annihilation spectroscopy
  - Tensile, compression, and bend testing
  - Ultrasonic testing
  - Tribological testing
  - High-temperature corrosion testing

Idaho National Laboratory

16-GA50206-12-R2

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

FUEL MANUFACTURING FACILITY

FUEL FABRICATION, NUCLEAR MATERIAL MANAGEMENT

BASIC DESCRIPTION:
The Fuel Manufacturing Facility (FMF) is a Hazard Category 2 nuclear facility that consists of multiple workrooms and a material storage vault. The workrooms house the equipment utilized to support multiscale fuel development. The vault contains and supplies the feedstock materials used for numerous programs in multiple facilities at MFC.

BASIC CAPABILITIES:

- Transuranic metallic and ceramic fuels development
- Transuranic and enriched-uranium materials storage
- Transuranic and enriched-uranium feedstock production, purification and breakouts

KEY INSTRUMENTS:

- Gloveboxes:
  - Advanced Fuel Cycle Initiative glovebox (AFCI)
    - › Experiment assembly
    - › Ceramic processing
    - › Metal processing
    - › Feedstock distillation/ purification
  - Special nuclear materials (SNM) glovebox
    - › Sodium separation (feedstock production)
  - Neptunium repackaging glovebox (NRG)
    - › Recertification of neptunium packages
  - Transuranic breakout glovebox (TBG)
- Radiography
- Vault storage
- Active-well neutron center
- Arc-melting furnace
- Distillation furnace
- Sintering furnace

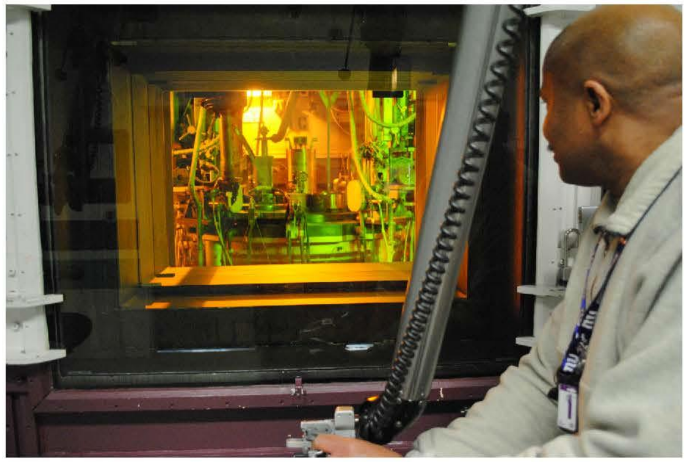
Idaho National Laboratory

16-GA50206-13-R1

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

FUEL CONDITIONING FACILITY

WASTE FORMS AND SEPARATIONS



BASIC DESCRIPTION:

The Fuel Conditioning Facility (FCF) supports nuclear energy research and development for the U.S. Department of Energy and other customers. Its unique capabilities make FCF an ideal facility for its primary mission to support treatment of DOE-owned sodium-bonded metal fuel.

In a secondary role, FCF also supports work to demonstrate the technical feasibility of pyroprocessing technology for treating used nuclear fuel for DOE's Fuel Cycle Research and Development Program. Pyroprocessing is a family of technologies involving high-temperature chemical and electrochemical methods for separation, purification, and recovery of fissile elements from used nuclear fuel. FCF has an air-atmosphere cell where fuel assemblies are disassembled into individual fuel elements, an argon-atmosphere cell where the spent fuel elements are prepared and treated, and a hot repair area located in the basement where contaminated equipment can be washed and repaired.

BASIC CAPABILITIES:

- Engineering-scale equipment for treatment of sodium-bonded metallic fuel to deactivate the reactive sodium metal, recover fissionable uranium, and separate fission and activation products for incorporation into solid waste forms suitable for geologic disposal
- Systems to support handling of heavily shielded shipping casks for fuel receipt and waste disposal
- Hot repair area equipped with remotely operated decontamination equipment, a specialized manipulator repair facility, and other maintenance and waste-handling equipment

KEY INSTRUMENTS:

- Electrochemical separations/ sodium neutralization experimentation/treatment
- Pneumatic rabbit transfer system
- Canister-cutting machine
- Remote uranium casting furnace
- Manipulator repair glovebox
- Vertical assembler/dismantler (VAD), vacuum inspection station/ bottle cutting, production element chopper, blanket element chopper
- Hot cells
- Suited Entry Repair Area
- Mock-up area

Idaho National Laboratory

16-GA50206-14-R1

FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

ANALYTICAL LABORATORY

CHARACTERIZATION, POST-IRRADIATION EXAMINATION, FUEL FABRICATION

BASIC DESCRIPTION:

The current mission of the Analytical Laboratory (AL) is to (a) perform chemical, radiochemical, and physical measurements; (b) provide non-destructive analysis measurements; and (c) conduct applied research and engineering development activities in support of advanced nuclear fuel design, waste management, environmental, and other programs conducted at MFC and INL. The mission is accomplished through a broad range of analytical- chemistry capabilities. As a result of this mission, a wide variety of samples is received into AL from across INL as well as from other outside entities. Sample types include liquids, solids, and irradiated/unirradiated fuel related to activities such as R&D, material accountability, radiation monitoring, process monitoring, and environmental monitoring. Engineering development activities, such as the preparation of samples for irradiation testing, are also supported by the AL.

BASIC CAPABILITIES:

- Analysis and characterization of as-built and post-irradiated nuclear fuels and reactor components
- Analysis of hazardous, mixed, or highly radioactive waste, other waste form, and samples
- Analytical chemistry support for nuclear forensics
- Determinations of inorganic isotopic constituents and radionuclides
- Radioisotope separation
- Characterization of engineered materials
- Expertise in characterization of engineered materials and the nuclear fuel life cycle

KEY INSTRUMENTS:

- Hot cells (6 - interconnected)
- Gloveboxes
  - Special form (SPG)
  - Radiochemistry (RG)
  - Waste form testing
  - Casting lab (CL)
  - Wet prep (WPG)
  - Fresh fuels (FFG)
  - Carbon nitrogen oxygen hydrogen (CNOH)
  - Inductively coupled plasma – atomic emission (ICP-AES)
- Fume hoods
- Counting laboratory
  - Gamma
  - Alpha spec
  - Gas proportional counter
  - Scintillation
- Gas mass spectrometer (GMS)
- Mass spectrometers
  - Inductively coupled plasma-mass (ICP-MS)
  - ICP-AES
  - Multi-collector – inductively coupled plasma –mass (MC-ICP-MS)
  - Thermal ionization mass (TIMS)
- Furnaces
- X-ray diffractometers
- Glovebox advanced casting system (GACS) furnace
- Chemistry laboratory
- Bridge crane (5-ton, overhead, loading dock)

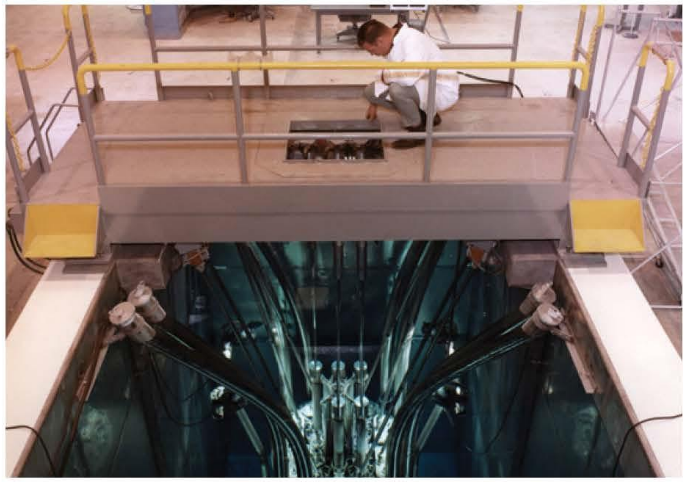
Idaho National Laboratory

16-GA50206-15-R1

FACILITY CAPABILITIES – ADVANCED TEST REACTOR COMPLEX

ADVANCED TEST REACTOR CRITICAL FACILITY

IRRADIATION



BASIC DESCRIPTION:
The Advanced Test Reactor Critical (ATRC) Facility is located at the Advanced Test Reactor (ATR) Complex. Before an experiment can be placed in the ATR its effect on core reactivity must be known with accuracy and precision. It is often necessary to determine the calculated reactivity through experimental testing in the ATRC. The ATRC has also been used by the Nuclear Scientific User Facilities to perform experiment irradiations directly without using the ATR.

The ATRC is a low-power, full-size nuclear replica of the ATR, designed to evaluate experiments before irradiation of the experiments in the ATR. The ATRC provides valuable reactor physics data that contribute to evaluating (a) control-element worths and calibrations, (b) excess reactivities and charge lifetimes, (c) thermal-and fast-neutron distributions, (d) gamma-heat-generation rates, (e) fuel-loading requirements, (f) effects of inserting and removing experiments and experiment-void reactivities, and (g) temperature and void reactivity coefficients.

The ATRC is a pool-type reactor located in an extension of the ATR canal. Normal power level is 600W or less; maximum power is 5kW. When ATRC testing is necessary, experimenters are required to furnish prototypes of capsule experiments. It is not unusual to test these designs in the ATRC prior to each ATR cycle to ensure the reactivity effects are known.

Idaho National Laboratory

16-GA50206-16-R2

FACILITY CAPABILITIES – CENTER FOR ADVANCED ENERGY STUDIES

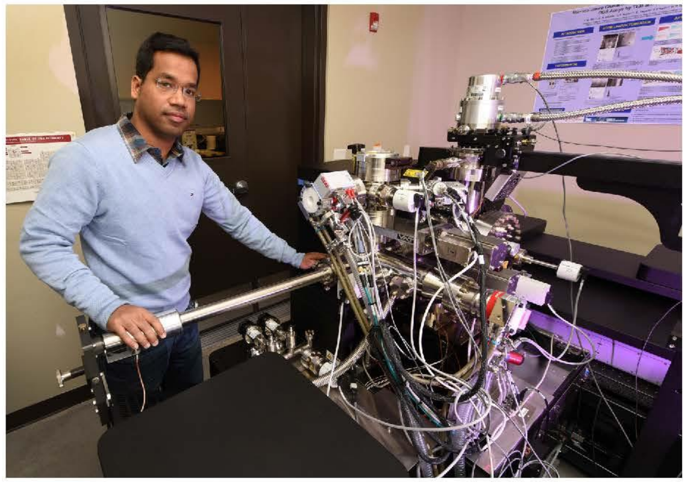
CENTER FOR ADVANCED ENERGY STUDIES

CHARACTERIZATION, POST-IRRADIATION EXAMINATION

BASIC DESCRIPTION:

The Center for Advanced Energy Studies (CAES) is a research and education consortium that includes Boise State University, Idaho National Laboratory, Idaho State University, University of Idaho, and the University of Wyoming. The CAES industry-affiliate program allows industry access to collective CAES R&D capabilities (people, partners, facilities) that can strengthen regional and national industry competitiveness. Industrial partners gain a window into advanced energy studies research programs and core capabilities.

CAES research is focused on nuclear science and engineering; materials science and engineering; energy systems design, analysis and testing; fossil carbon conversion; geological systems and applications; policy; and environmental and resources sustainability. Several CAES laboratories operate as user facilities for low-level radiological research, providing a cost-effective, innovative, and productive environment for exploring fundamental science questions and executing basic research complementary to research at INL Site facilities. The Microscopy and Characterization Suite (MaCS) provides high-end microstructural characterization capabilities that are heavily used by outside and INL researchers.



BASIC CAPABILITIES:

- MaCS
- Advanced Materials Laboratory
- Fluids Laboratory
- Radiochemistry Laboratory
- Analytical Chemistry Laboratory
- Analytical Instrumentation laboratory
- Applied Visualization Laboratory

KEY INSTRUMENTS:

- Dual beam focused ion beam (FIB)
- Field emission gun scanning transmission electron microscope (FEG-STEM)
- Local electrode atom probe (LEAP)
- X-ray diffraction (XRD)
- Scanning electron microscope (SEM)
- Nanoindenter and atomic-force microscope (AFM)
- Transmission electron microscope (TEM)
- Two temporal analysis of products reactor systems

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FACILITY CAPABILITIES – MATERIALS AND FUELS COMPLEX

ENGINEERING DEVELOPMENT LABORATORY

FABRICATION, ASSEMBLY, AND TESTING OF RESEARCH AND DEVELOPMENT AND PRODUCTION EQUIPMENT

BASIC DESCRIPTION:

The Engineering Development Laboratory is used to fabricate, assemble, mock up, and test various R&D and production equipment. The majority of work conducted in EDL is for the Space Nuclear Power & Isotope Technologies Division. The EDL is a non-nuclear facility, managed as a laboratory space in accordance with INL work control requirements.

The EDL occupies most of Building 772 at the Materials and Fuels Complex (MFC). Two rooms within the building are used by the MFC Quality Assurance organization for non-destructive examinations, e.g., radiography and film processing. Two mezzanines, which constitute the second floor, can be moved to accommodate tall equipment (30-ft. floor-to-crane hook). The facility includes equipment and gloveboxes for welding, including an electron-beam welder; furnaces for bake-out of graphite components; forming equipment for heat source hardware; and various machine tools.

BASIC CAPABILITIES:

- Fabrication
- Assembly
- Mock-up
- Testing

KEY INSTRUMENTS:

- Inert-atmosphere gloveboxes
- High-temperature bake-out furnaces
- Welding systems
- Forming equipment
- Pre-assembly operations for radioisotope power systems

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