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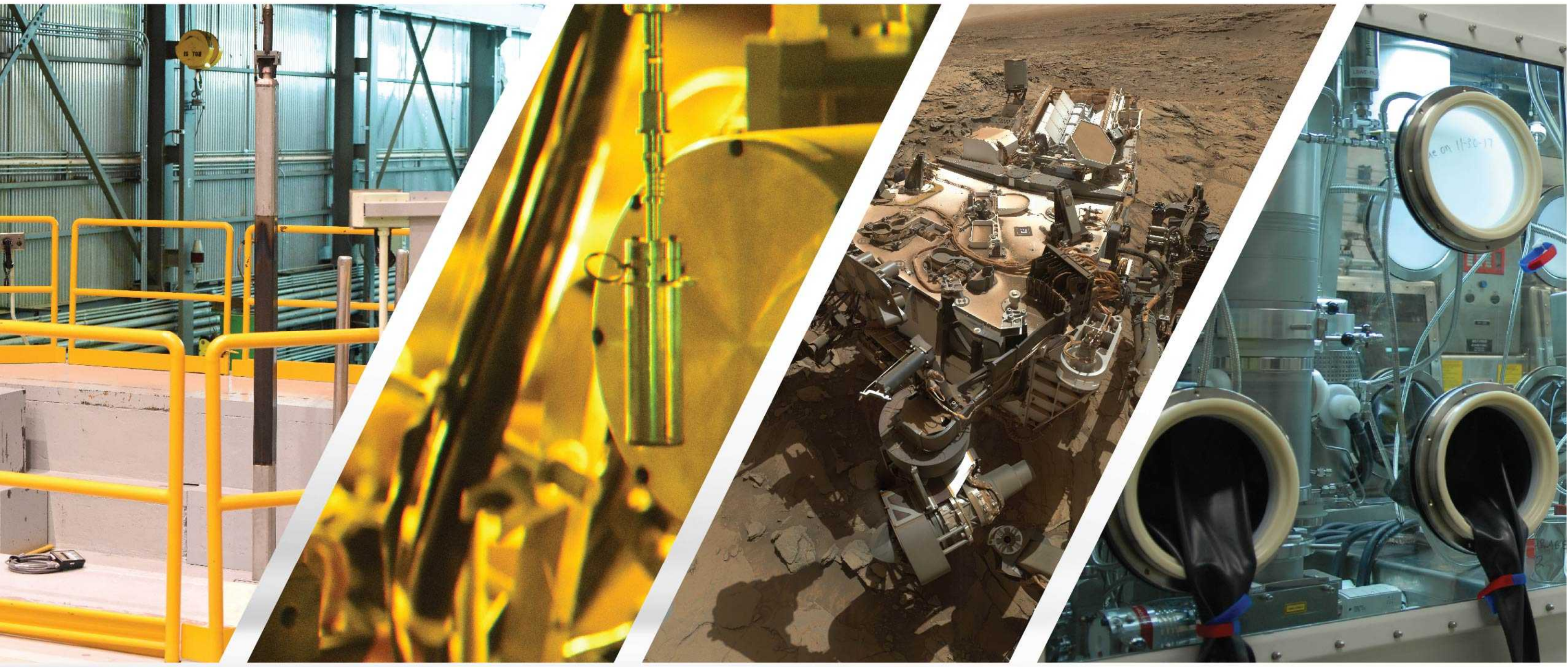

MATERIALS AND FUELS COMPLEX
Five-Year Mission Strategy

FY-19 – FY-23

April 2019

Idaho National Laboratory

DISCLAIMER

INL/EXT-19-52612

Materials and Fuels Complex
Five-Year Mission Strategy
FY-19 – FY-23

April 2019

Idaho National Laboratory
Idaho Falls, Idaho 83415

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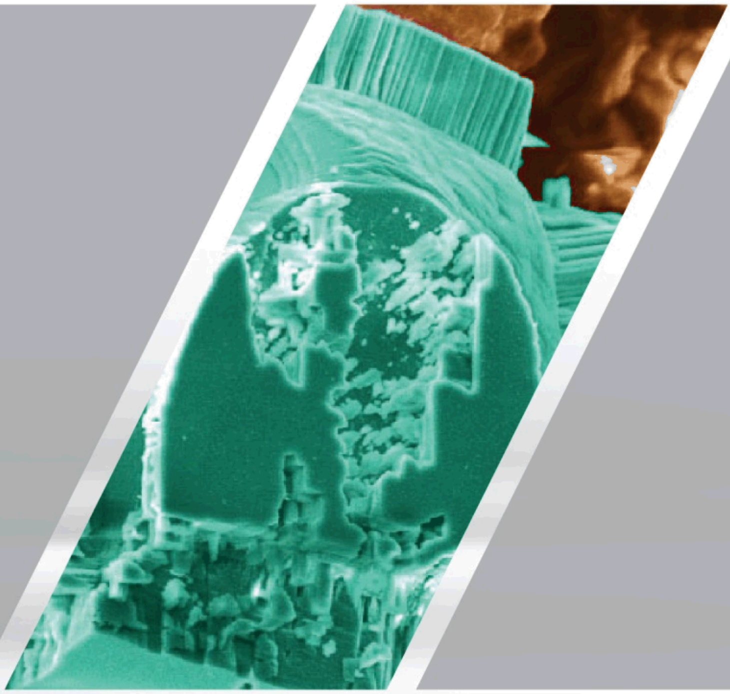


EXECUTIVE SUMMARY

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 (RD&D). 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, including the management and disposition of used nuclear fuel, and the regulatory risk associated with this investment in new nuclear technology. These barriers can be addressed, in good part, by development of new technology that is simpler and therefore simpler to license, and by establishing new technology development approaches that more quickly establish design and safety bases that provide risk-averse investors and regulators the confidence they need for new technology to enter the market. 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 seeks to sustain the current reactor fleet, to provide technology options for development of advanced nuclear energy systems, and to encourage the development of infrastructure to address the nuclear fuel cycle, including market provision of uranium enriched with U^{235} at 5 to 20% and management of used nuclear fuel. 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.

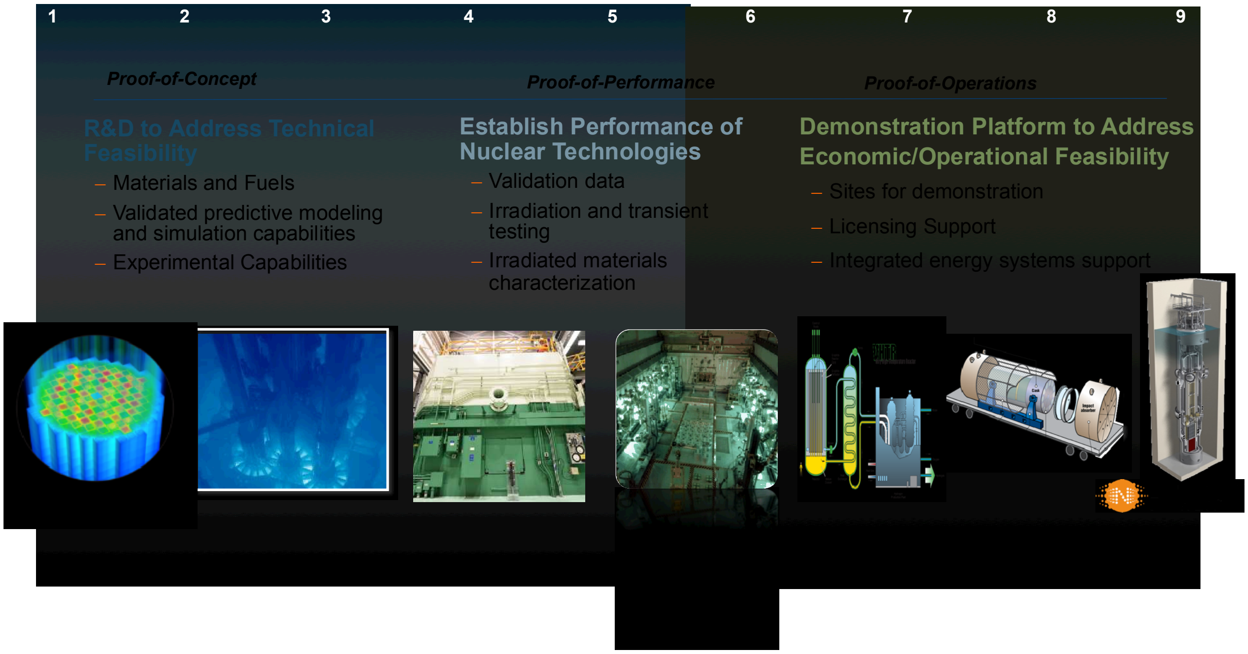
Development and deployment of new nuclear energy technology are discouraged by the investment and time duration needed to develop a technology through successive Technology Readiness Levels to deployment (Figure E-1). Specialized facilities designed for safe conduct of first-of-a-kind experiments, tests and demonstrations are prohibitively expensive for private industry in today's investment and regulatory environments; even long-established commercial developers and vendors have shut down nearly all of their facilities used for developing the light water reactors (LWRs) operating today. Furthermore, commercial developers and vendors are not able to maintain staff with specialized technical capabilities needed to develop details needed for design bases underlying new reactor technologies.

In order to more effectively support and encourage deployment of nuclear energy systems, the INL is establishing NRIC, building upon the original INL mission as the National Reactor Testing Station (NRTS), through which INL will identify and provide the capabilities most needed to accelerate commercial introduction of nuclear energy technologies. In this role, INL will partner with

DOE national laboratories and universities to engage the capabilities of the broader national test bed, with emphasis on the following initiatives:

- Replacing light water reactor irradiation testing capability lost with the pending shutdown of the Halden Reactor
- Demonstration of first-of-a-kind microreactors
- Location of a first-of-a-kind small modular reactor (SMR)
- Engineering-scale production of high-assay low-enriched uranium (HALEU) fuel for the first core of a demonstration reactor
- Engineering-scale production of HALEU fuel for lead test rods and/or assemblies to be loaded into LWRs
- Developing reactor fuel and fuel fabrication technology.

In addition, INL will continue to serve DOE-NE programs to develop new energy technology through more effective characterization of nuclear fuels and materials, and clearer understanding of the phenomena and behavior that limit performance of nuclear systems and components. 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.



Proof-of-Concept

R&D to Address Technical Feasibility

- Materials and Fuels
- Validated predictive modeling and simulation capabilities
- Experimental Capabilities

Proof-of-Performance

Establish Performance of Nuclear Technologies

- Validation data
- Irradiation and transient testing
- Irradiated materials characterization

Proof-of-Operations

Demonstration Platform to Address Economic/Operational Feasibility

- Sites for demonstration
- Licensing Support
- Integrated energy systems support

Figure E-1. INL and NRIC, in support of DOE-NE and GAIN, provide support for development of nuclear energy technology through all Technology Readiness Levels.

This plan outlines an MFC strategy that builds and sustains DOE-NE RD&D capability as part of the establishment of NRIC, increases access to MFC and broader DOE nuclear research capabilities, and prepares for 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 building on historical MFC capabilities that support demonstration-scale activities, such as microreactor demonstration, fuel fabrication and production (including high-assay low-enriched uranium, or HALEU, fuel), and capability to support operation of a fast-spectrum test reactor (specifically, the proposed Versatile Test Reactor, or VTR).

Implementing this 5-year strategy will position MFC and INL to support DOE-NE and NRIC in delivering deliver an effective nuclear RD&D capability that supports the current LWR fleet and advanced reactor developers and pushes forward solutions for the nuclear fuel cycle.

This mission strategy has an accompanying investment strategy titled, "The MFC 5-Year Investment Strategy," which details the investments (i.e., both detailed scope and estimated costs) necessary to implement this strategy.

CONTENTS

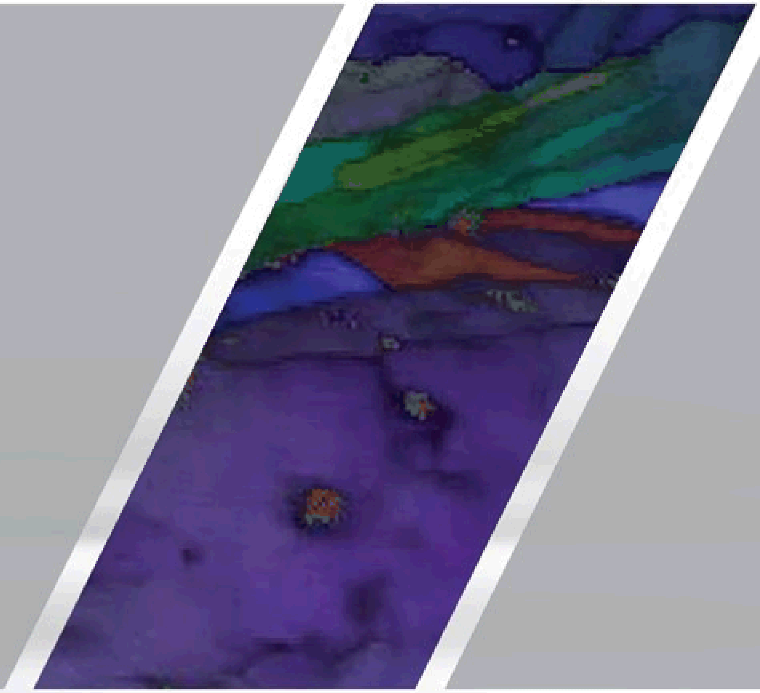
FIGURES

TABLES

ACRONYMS

AFF	Advanced Fuel Facility
AL	MFC Analytical Laboratories
DOD	Department of Defense
DOE	Department of Energy
EBR-II	Experimental Breeder Reactor-II
EFF	Experimental Fuels Facility
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DOE-SC	DOE Office of Science
FASB	Fuels 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 (location and directorate within INL)
NE	DOE Office of Nuclear Energy
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NNSA	National Nuclear Security Administration
NRIC	National Reactor Innovation Center
NS&T	Nuclear Science and Technology (directorate within INL)
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
VTR	Virtual Test Reactor
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 Idaho National Laboratory is a multi-program laboratory, with a main purpose of leading and conducting nuclear energy research, development, and demonstration (RD&D). The Laboratory also makes considerable contributions to national and homeland security-related technologies and technologies for non-nuclear energy generation. Given that, the INL serves the following mission and vision:

Vision–INL will change the world's energy future and secure our critical infrastructure.

Mission–Discover, demonstrate, and secure innovative nuclear energy solutions, clean energy options, and critical infrastructure

Beginning in FY 2019, INL will seek to serve its mission and fulfill its vision through a designation as the National Reactor Innovation Center (NRIC). The INL's Materials and Fuels Complex (MFC) is home to key facilities and expert personnel serving this mission. The MFC mission and vision are summarized as follows:

MFC Vision and Mission Statement: Engineering and experiments that drive the world's nuclear energy future

Context for the MFC Vision and Mission includes the INL Nuclear Science and Technology Strategy (NS&T), summarized as follows:

> Leverage the full resources of INL and partners to achieve maximum impact for nuclear energy with focus on critical and timely outcomes that support:

- Continued operation of current nuclear systems
- Replacement and future expansion of the U.S. fleet
- Management and disposition of spent nuclear fuel.

This MFC Five-Year Mission Strategy communicates actions that will position MFC capabilities for maximal impact to the Laboratory's mission. The context for the MFC mission is described further in this chapter, with emphasis on the nuclear energy mission and the national and homeland security mission, because those associated programs consistently use MFC. Subsequent chapters of this document briefly describe the core capabilities of MFC and the vision for MFC as a test bed and user facility, as part of the National Reactor Innovation Center (NRIC). MFC RD&D goals and priorities are then described, followed by a brief description of new capabilities targeted for the near future. Funding and investment strategy to fulfill this mission strategy are not included here, and can be found in the companion document "Materials and Fuels Complex FY-19–FY-23 Five-Year Investment Strategy," (INL/EXT-19-53607).

1.1 Nuclear Energy Mission

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.[a] DOE-NE is addressing the following three priorities (to which the aforementioned NS&T strategy aligns):

1. The existing light water reactor (LWR) fleet
2. The advanced reactor pipeline

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[a] "Nuclear Energy Research and Development Roadmap: Report to Congress," U.S. Department of Energy, Office of Nuclear Energy (April 2010). "Vision and Strategy for the Development and Deployment of Advanced Reactors," U.S. Department of Energy, Office of Nuclear Energy, DOE/NE-0147 (January 2017).

3. The long-term fuel cycle and associated infrastructure.

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. In all industrial and commercial sectors, innovative 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 of those materials and systems to in-service operating conditions or 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 ensure the system is sufficiently safe to protect itself, workers, and the public. 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 establish and maintain. Because of this, most are owned by the U.S. federal government (i.e., DOE) and operated by the national laboratory contractors. In 2018, the U.S. Congress passed legislation to establish NRIC, which INL proposes to implement as DOE's lead laboratory for nuclear energy.

Innovative ideas and concepts have been proposed, and many are being incorporated into new reactor technologies and designs. However, the RD&D needed to bring these ideas to commercial readiness is lengthy and expensive. DOE-NE's strategy for encouraging innovative ideas into the marketplace includes developing technology attractive to the private sector for commercialization, providing expertise to developers seeking to commercialize technology, and making technical expertise and crucial RD&D facilities available to private developers and vendors. To facilitate access to national laboratories and DOE assets for commercialization of nuclear energy technologies, DOE-NE established the Gateway for Accelerated Innovation in Nuclear (GAIN)[b] initiative. Idaho National Laboratory (INL) acts as integrator for the GAIN initiative and provides important nuclear RD&D capability.

Over the past decade, DOE-NE has been establishing 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 Experimental Breeder Reactor-II (EBR-II) and four other research reactors. The INL has maintained and repurposed these core capabilities for existing and future missions and demonstrations, making MFC a key part of NRIC. These core capability assets are available to, and are being used by, the nuclear industry and private-sector reactor developers at three levels of the technology maturation process: 1) to inform the selection of appropriate technologies for development; 2) to investigate design limits of and to improve these technologies; and 3) to establish sound technical bases for integrated demonstration at an appropriate scale. Effective use of this capability allows developers to reduce financial risks to investors and to establish strong technical cases for licensing of demonstration units.

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[b] gain.inl.gov

Figure 1-1. Materials and Fuels Complex.

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

- Accelerate and reduce the cost of nuclear RD&D through 1) private-public partnerships with key stakeholders; and 2) establishing the National Reactor Innovation Center, dramatically reducing the time needed to develop and qualify nuclear fuels, components, and materials, enabling demonstration of small modular reactors (SMRs) and advanced reactors, and establishing a new fast-spectrum test reactor.
- Safe, secure, and economic management of nuclear of nuclear fuel from conception (front-end) to final disposition (back-end) by 1) developing options for future fuel cycles, coupled with advanced reactors that improve energy competitiveness and minimize used nuclear fuel and secondary waste while improving proliferation risk; and 2) providing technical solutions that support the safe, secure, and economic management and disposition of current and future LWR-generated used nuclear fuel and high-level waste.

Additional strategic initiatives focus INL contributions toward integrated energy systems, national and homeland security, and application. These other initiatives will be supported by MFC.

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[c] Idaho National Laboratory Lab Agenda, 2019.

Capabilities and expertise located at MFC are a key part of the Laboratory's achievement of strategic-initiative goals. Increasingly, MFC will engage with INL's NS&T Directorate to develop approaches and techniques capable of accelerating introduction of new nuclear energy technologies into the market; in particular, methods to reduce the time needed to develop and qualify new nuclear reactor fuels, components, and materials will be sought.

1.2 National and Homeland Security Mission

The INL's National and Homeland Security (N&HS) Directorate serves a number of sponsors, meeting specialized needs. N&HS provides federal agencies, industry and academia partners with unmatched test range assets for conducting national security research, development, demonstrations and deployment focused on five challenging problems:[d]

- Critical infrastructure protection and resiliency
- Defense, intelligence, and public safety solutions
- Nuclear nonproliferation

Of those subjects, nuclear nonproliferation, in particular, is supported by capabilities at MFC, making use of facilities for fuel fabrication and characterization, for handling, characterizing, and analyzing radioactive materials and for accessing special nuclear material. Selected initiatives being pursued to attain the INL Strategic Objective to *develop critical national and homeland security capabilities* include the following:[c]

- Create multi-agency center to address critical control system challenges that require a national collaborative, inter-disciplinary environment within a modern research & education ecosystem
- Expand Next-Gen CITRC that is modernized for highly-instrumented, all-hazard experiments for multiple simultaneous customers on critical components, subsystems, and systems in lifeline infrastructures.

Within the N&HS Strategic Plan, the following goals and associated milestones are currently or potentially supported by MFC capabilities.[d]

Goal: Advance the nation's nuclear forensics and detection capabilities

Milestone: Establish advanced spectroscopy capability aligned with Department of Energy Office of Nuclear Energy (DOE-NE) programs

Milestone: Establish the Isotope Production Center for Verification Missions

Milestone: Lead NA-22 demonstrations at INL's pilot-scale nuclear and test range facilities

Goal: Support the development of next generation fuels and designs of advanced nuclear systems

Milestone: Engage NA-23 initiative on technology- enabled nonproliferation

Milestone: Establish Transient Research Test facility (TREAT) as a resource for nuclear security experiments

Goal: Conduct training and readiness exercises for emergency responders

Milestone: Establish the Full Spectrum Test Range and the Nuclear Security Training Center

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[d] *Idaho National Laboratory National & Homeland Security Strategic Plan 2108-2023*, July 2018.

N&HS personnel collaborate with MFC personnel and use MFC capabilities in their effort to achieve goals of those initiatives. Specific nonproliferation and security programs supported include development of high-density low-enrichment fuel for research reactors, characterization of irradiated fuels and radioactive materials for nuclear forensics, and training of first responders in the handling of special nuclear material.

1.3 The Need for NRIC: A Nuclear Energy RD&D Test Bed and Demonstration Platform

Development and deployment of new nuclear energy technology are discouraged by the investment and time duration needed to develop a technology through successive Technology Readiness Levels to deployment (Figure 1-2). Specialized facilities designed for safe conduct of first-of-a-kind experiments, tests and demonstrations are prohibitively expensive for private industry in today's investment and regulatory environments; even long-established commercial developers and vendors have shut down nearly all of their facilities used for developing the light water reactors (LWRs) operating today. Furthermore, commercial developers and vendors are not able to maintain staff with specialized technical capabilities needed to develop details needed for design bases underlying new reactor technologies.

INL has the capabilities to minimize the time required to enable construction and operation of privately funded experimental reactors: enabling physical validation of advanced nuclear reactor concepts; resolving technical uncertainty and increasing practical knowledge relevant to safety, resilience, security, and functionality of advanced nuclear reactor concepts; and providing general research and development to improve nascent technologies. For those reasons, INL is collaborating with commercial vendors, private developers, and government agencies (including NASA and DOD) requiring access to specialized facilities who seek support with:

- Demonstration of first-of-a-kind microreactors
- Location of a first-of-a-kind small modular reactor (SMR)
- Engineering-scale production of high-assay low-enriched uranium (HALEU) fuel for the first core of a demonstration reactor

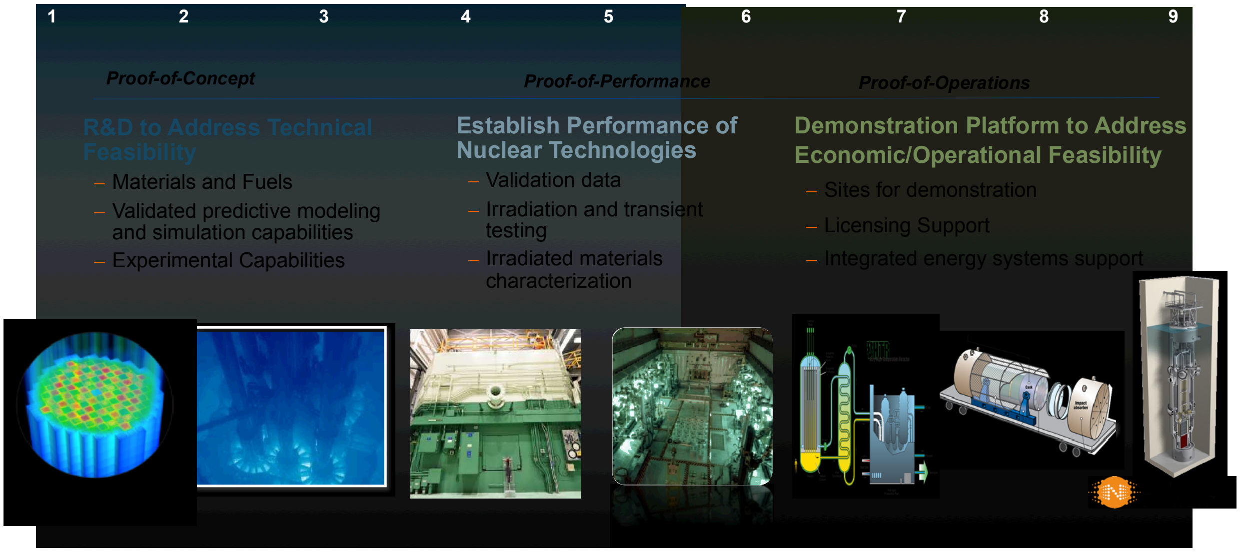


Figure 1-2. Illustration of typical development needed to bring a new nuclear technology through the Technical Readiness Level (TRL) scale to market. Barriers to successful development appear throughout the development progression, including significant cost and schedule barriers.

- Engineering-scale production of HALEU fuel for lead test rods and/or assemblies to be loaded into LWRs
- Developing reactor fuel and fuel fabrication technology.

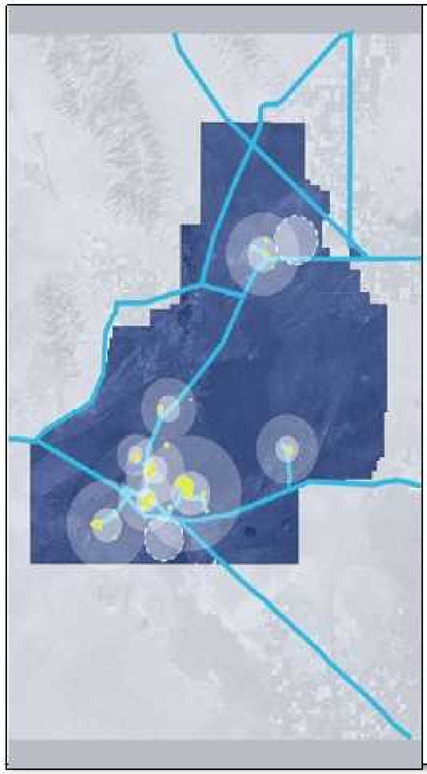
In order to more effectively support and encourage deployment of nuclear energy systems, the National Nuclear Energy Capabilities Act (NECA) of 2017 amended Subtitle E of title IX of the Energy Policy Act of 2005 by adding a new section "Nuclear Energy Innovation", which authorizes a new program — National Reactor Innovation Center (NRIC) — to enable the testing and demonstration of reactor concepts to be proposed and funded, in whole or in part, by the private sector. NRIC builds upon the original INL mission as the National Reactor Testing Station (NRTS), and through it INL will identify and provide the capabilities most needed to accelerate commercial introduction of nuclear energy technologies. In this role, INL will partner with DOE national laboratories and universities to engage the capabilities of the broader national test bed. The elements of NRIC extend beyond reactor testing and demonstration for performance assessment and licensing to also address the full spectrum of the fuel cycle, a regional supply chain, and the combination of nuclear with other energy forms and products (hybrid energy systems). Four avenues of engagement and support are envisioned:

- Demonstration of nuclear energy plants that are first of a kind, built in *greenfield sites* available at the INL under a General Use Permit (GUP), and licensed by the U.S. Nuclear Regulatory Commission (NRC);
- *Testing and demonstration of prototype reactors* and systems under an Authorization Agreement (AA) and operated in accordance with a DOE Safety Authorization Basis;
- *Research and Development using INL facilities and personnel* under any of several available collaboration mechanisms (Strategic Partnership Project, Cooperative Research and Development Agreement, DOE industry award or GAIN voucher, or as funded within a DOE R&D program, carried out in any of a number of facilities and test reactors at INL and other DOE national laboratories;
- Technical *support of an off-site demonstration or deployment project*, under terms of an appropriate contracting or authorization mechanism.

The foundation for supporting external users has been set through operation of the Nuclear Science User Facility (NSUF) over the previous decade, and through the emerging user facility model being established at INL’s MFC facility. As envisioned, developers can engage INL selectively to varying degrees in any part of, or throughout, the technology maturation process (“jump-on, jump-off engagement”).

The NRIC is based upon the facilities and capabilities already in place at INL (Figure 1-3), with a view toward new capabilities to be added, such as the Sample Preparation Laboratory (SPL) or the Virtual Test Reactor (VTR). As a next step in preparing INL to serve as NRIC, DOE-NE reacquired responsibility for the EBR-II Reactor Building (i.e., the containment dome, or “Dome”) from DOE Office of Environmental Management (DOE-EM), preventing the Dome’s demolition scheduled for FY-19. Retention of the Dome is crucial at a time when INL leadership is challenged with identifying building spaces suitable for the following:

- Demonstrating first-of-a-kind micro-reactor designs
- High-assay low-enriched uranium (HALEU) fuel fabrication for reactor demonstration projects
- Fabrication of lead-use assemblies (LUAs) of new LWR fuel designs
- An accelerator laboratory for producing isotopes in support of national security missions.



NRIC BY THE NUMBERS

Area: 890 square miles (largest research park in the U.S.)

Number of companies: 35 (20 of which are in nuclear energy R&D)

Average worker pay: $78,000

Top employers in nuclear energy research:

- Idaho National Laboratory
- NUSCALE Power
- Terra Power

NEPA permitted

Spending on nuclear energy research facilities since 2019: $270 million (resulting in 500,000 sq ft of new facilities)

Total Sq Ft of nuclear energy research facilities: 1.17 Million

Utilities: connectivity ready

Figure 1-3. NRIC Overview.

Figure 1-4. Illustration of NRIC implementation at INL.

1.4 A Mission 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 and demonstration platform. The strategy described in this document will guide the efforts to build, expand, and sustain 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 and security 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 fabrication and characterization
- Transient irradiation testing
- 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.

Over the next five years, MFC will continue to build and improve 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:

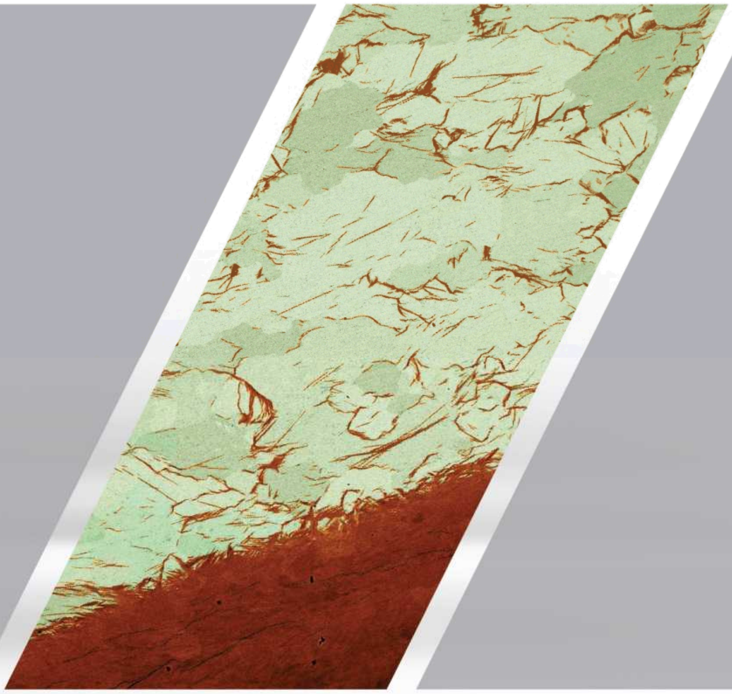
- Focusing research and capability development in areas where MFC has a core strength.
- Delivering on programs and projects for private-sector nuclear reactor developers and vendors.
- Establishment of the National Reactor Innovation Center at the INL
    - Reviving and improving historical MFC capabilities that support demonstration-scale activities of nuclear systems
    - Implementing MFC capability to support an INL-based LWR Irradiation Testing Platform (i.e., post-Halden testing mission)
- Prioritizing and pursuing funding for construction of needed capabilities where none exist and for maintaining, improving, and constructing support infrastructure to ensure the safe operation of MFC.
- Developing relationships and furthering partnerships with DOE-NE's extended research network, including Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (ANL), 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.
- Managing in accordance with the MFC Management Model, which promotes collaboration across the multiple MFC organizations, vest ownership for MFC with MFC leaders, and holds leaders 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.

- Continuously improving operations to increase the efficiency, reliability, and safety of MFC operations.
- Continuously improving MFC RD&D performance, to increase impact and benefit to sponsors
- 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.
- Deploying advanced experiment vehicles for transient testing under extreme environments including liquid metal and water reactor conditions.
- Establishing the capability to remanufacture and re-instrument pre-irradiated reactor fuels for irradiation testing in TREAT and ATR.

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:

- Application and demonstration of advanced manufacturing techniques to 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, methods, and data handling that dramatically increase post-irradiation examination (PIE) throughput and efficacy, provide higher quality data, and/or expand our capabilities to support nuclear energy RD&D.
- Application of the EBR-II spent fuel treatment product to first-of-a-kind demonstration of reactor and fuel technologies requiring high-assay low-enriched uranium (HALEU).
- Earn and deliver on opportunities to develop fabrication processes for new fuel designs under development in the private sector and to demonstrate first-of-a-kind production of those designs at engineering scale.

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

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.[e] 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-spectrum irradiation testing	Advanced Test Reactor (ATR)			
Transient Irradiation testing	Transient Reactor Test Facility (TREAT)			
Refabrication and re-instrumentation of pre-irradiated fuel		HFEF, TREAT		
Fast-spectrum irradiation testing		Versatile Test Reactor (VTR)	X	EBR-II
Microreactor demonstration		EBR-II Dome		
In-pile instrumentation for selected phenomena	Multiple, including ATR and TREAT	X	X	
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		
Lab-scale and bench-scale fuel fabrication, including advanced manufacturing methods	Experimental Fuels Facility (EFF), Fuels and Applied Science Building (FASB), Fuel Manufacturing Facility (FMF)	Advanced Fabrication Facility (AFF) for adv. mfg. of reactor fuel		
Engineering-scale fuel fabrication			LEU fuel fab; Pu fuel fab for VTR	EBR-II fuel fab in FMF and FASB
Reconfigurable thermal-hydraulic loops of different scale and heaters	University and industry capabilities National laboratory partners (ORNL, ANL)		X	

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[e] 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
Advanced flowing loop experiment transient irradiation vehicles		TREAT		
Component fabrication and testing (e.g., machine and instrumentation and controls shops and Engineering Development Laboratory)	Multiple			
Remote process development and testing	Fuel Cycle Facility (FCF), HFEF			
Reactor physics testing	ATR-C, TREAT			Zero Power Physics Reactor (ZPPR)
Centralized modeling and simulation knowledge and validation function			X	
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		Collaborative Computing Center (C3)	

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 Complex

With EBR-II, MFC successfully supported demonstration of on-site remote fuel recycling and operation of a sodium-cooled fast reactor and power plant. With TREAT, MFC successfully identified and demonstrated fast reactor fuel failure thresholds and behavior and performed many other transient irradiations for a diverse set of R&D programs. MFC operated those reactor facilities and associated research and testing programs over a period of nearly 35 years. Those missions required a diverse set of facilities at the MFC site that could address every aspect of R&D with the nuclear fuel cycle. 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 N&HS 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 for the following:

- 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.

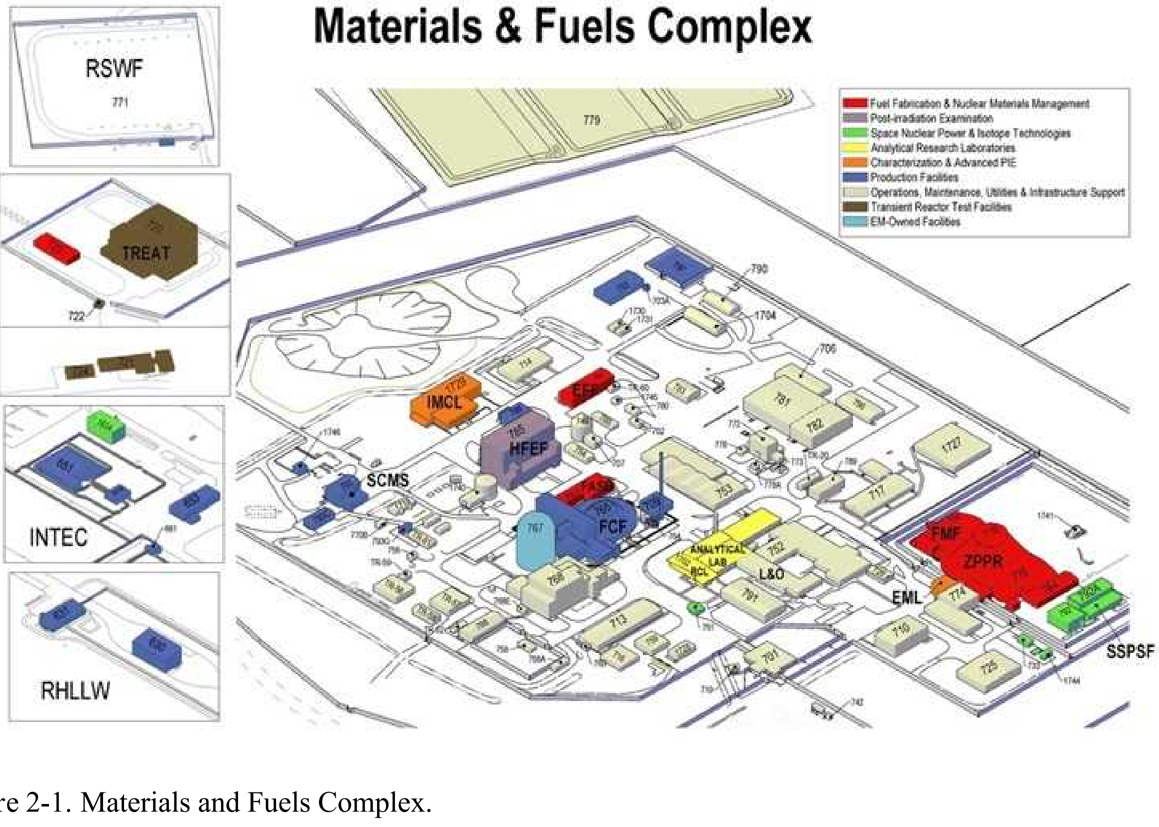

Figure 2-1. Materials and Fuels Complex.

  - 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.
  - Advanced Fuels Facility (AFF) – Our newest facility being repurposed into a radiological laboratory to house our expanding capabilities in advanced manufacturing. Some of the initial capabilities include Spark Plasma Sintering, Laser additive printing and dry bag isostatic pressing.
- 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 (Irradiated Materials Characterization Laboratory) – State-of-the-art user facility for characterization of the microstructure, thermal properties, and micromechanical properties of irradiated fuels and materials on the millimeter to atomic scales. Tightly coupled with HFEF and SPL. Handles Hazard Category 2 quantities and high dose rate materials. Shielded FIB (Focused Ion Beam) instruments (2), EPMA (Electron Probe MicroAnalysis), and sample preparation cells (SSPA – Shielded Sample Preparation Area) are fully operational for use with highly active materials. High resolution TEM (Transmission Electron Microscope) is operational, but currently being upgraded. Thermal property shielded cell instrument installation will be completed in FY 2019. Installation and commissioning of additional instruments is funded and will also be completed in FY 2019, including a Zeiss x-ray microscope, JEOL-7600 SEM (Scanning Electron Microscope), and Quantum Design PPMS (Physical Property Measurement System).
  - EML (Electron Microscopy Laboratory) – Radiological laboratory focusing on microstructural analysis of unirradiated fuels and materials and small quantities of irradiated fuels and materials. Mission will shift to focus on characterization of classified materials in FY 2019, although unclassified work may still be conducted in the facility. Legacy shielding from the AFSR (Argonne Fast Neutron Source) reactor will be removed to more fully utilize space in the facility. The obsolete JEOL 2010 TEM will be replaced with a new FEI Talos TEM, currently temporarily installed in IMCL in FY 2020. The aging SEM and FIB will be replaced as funding is available.
  - SPL – (Sample Preparation Laboratory) – Focused on sample preparation, characterization, and testing of high activity irradiated structural and cladding materials, SPL closes an identified nuclear energy research capability gap by greatly increasing sample throughput and closely linking performance and properties to underlying nanoscale structure. SPL provides the capability for high throughput research and development, shortening the nuclear material development cycle. SPL will generate the experimental data required to develop and validate higher fidelity material performance models. 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 funding identified in the FY 2019 budget, with ground breaking planned for summer 2019.

- 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 Power Systems Learning Building (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 has been partially addressed through resumption of operations at TREAT and will be resolved with re-establishment of supporting scientific infrastructure. The TREAT reactor is collocated at MFC and uses various 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). The easily accessible core also provides unique nuclear instrument testing capabilities under reactor transient conditions. The current capabilities include fuel testing in capsules and separate-effects testing for specific physics phenomena.

Figure 2-2. Transient Test Reactor at MFC.

- Microreactor demonstration:
    - EBR-II Dome (MFC Building 767) – One of three existing INL buildings available for microreactor demonstration (along with buildings PBF-612 and PBF-613), the original EBR-II Reactor Building (the "EBR-II Dome") in its current remediated condition offers a large internal volume with a working space of 78-ft internal diameter and 40-ft floor-to-crane height. The Dome has been transferred back to DOE-NE as landlord and plans for its demolition are deferred indefinitely. The Dome is being restored to original structural capacity, with potential to be restored to original 24-psi containment capacity, if needed.
    - HALEU supply – Most microreactor designs currently being proposed call for use of high-assay low-enriched uranium fuel (HALEU) with ^{235}U enrichment ranging from 5% to 20% and which is not currently available in the commercial uranium market. INL manages storage and disposition of uranium of various enrichments in several spent fuel forms. Included in that inventory is the uranium being removed from EBR-II sodium-bonded spent fuel and downblended in FCF to less than 20% enrichment. Recent studies have determined the uranium product can be better decontaminated to allow its fabrication into new fuel using glovebox confinement systems, without need for hot cell shielding. Upon DOE direction, this material can be made available to fuel first cores of demonstration microreactors, with application to fast-spectrum systems being most likely (because of their ability to accommodate diverse heavy metal isotopes and other contaminants that can complicate thermal-spectrum reactor application).
    - Engineering-scale fuel fabrication – Production of fuel needed for first cores of demonstration microreactors is key capability needed to support such demonstration. Although INL does not currently operate an engineering-scale capability (so, designated to distinguish scale from lab-scale and commercial production scale), several options exist to establish such a capability, as addressed in Section 5.2 of this document.

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 one to two orders of magnitude the rate of knowledge generation that directly supports nuclear energy innovation. 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 contraction of development timelines, reduced investment risk, shorter time to market, and deployment of new technology by the commercial nuclear sector.

In addition to the described R&D facilities, MFC has developed both internal and external waste treatment capacity to address legacy waste streams and provide avenues for the responsible management and disposal of newly generated research-related waste/materials real-time. This ensures research facilities are available to support the important RD&D mission. Available treatment and disposal options include reactive material treatment, macroencapsulation, direct disposal, thermal oxidation, and vitrification. Waste disposal pathways for transuranic waste have been developed utilizing the EM contractor capabilities and certified TRU disposal program.

2.1.2 Materials and Fuels Complex Research and Development Core Competencies

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 core competencies provide the intellectual 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 – MFC currently has the capability to produce nearly any fuel type at lab scale. MFC has previously operated engineering-scale fuel production capabilities (i.e., FMF) in support of EBR-II. 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, increased residence and coping time, and proliferation resistance; advanced reactors cannot function without advanced fuels. Many fuel development needs associated with advanced reactors include adaptation of fast reactor fuel technology to new reactor concepts.

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 preparation of measurement standards that support verification measurements to detect nuclear detection for the Comprehensive Test Ban Treaty Organization, performing research that addresses the detection of nuclear 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 can be extended to develop and demonstrate safeguards technology appropriate for inclusion in new facility design.
6. Space nuclear power and isotope technologies – Production of radioisotope power sources (RPSs) 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. MFC facilities are an important link in the RPS supply chain, which also includes Oak Ridge National Laboratory and Los Alamos National Laboratory.

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

Although MFC has a broad spectrum of nuclear RD&D capabilities that are available to experimenters outside the INL, MFC does not have all the capacity or capabilities needed to accommodate a nuclear energy RD&D community that has grown over the past decade. To accommodate these needs, INL coordinates for DOE-NE the National Science User Facilities (NSUF), which is a set of facilities located at facility partner institutions (universities and national laboratories) that are made available to external users. NSUF research supports Department of Energy-Office of Nuclear Energy missions. Most of the research looks at either understanding the mechanisms of radiation on materials and fuels to address the challenges of the current fleet of reactors or looks at materials and fuels for the next generation. The NSUF and its partner facilities (see Figure 2-3) create a nationwide infrastructure that greatly expands the types of research available. This model utilizes a distributed partnership with each facility bringing exceptional capabilities to the relationship, including: reactors, beamlines, instruments, hot cells, and most importantly, expert mentors. The specific capabilities offered by each of these NSUF partner facilities can be accessed through the NSUF website.[f] As of 2017, NSUF participation included 42 Principal Investigator and User institutions and 21 Partner Facilities.

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 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.

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[f] www.atrnsuf.inl.gov

Figure 2-3. NSUF Partner Facilities and user institutions.

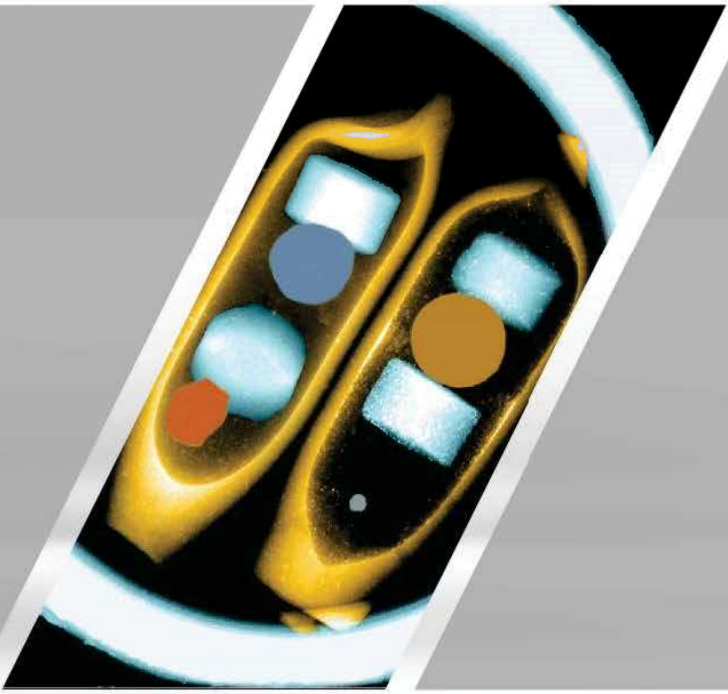
2.3 Materials and Fuels Complex Contribution to the NRIC

The types of capabilities and accommodations needed to support technology demonstration (advancing to higher Technical Readiness Levels) are different than those needed to establish proof of concept (advancing through the lower end of the Technical Readiness Level scale). In general, many requirements for *demonstrating* and deploying first-of-a-kind nuclear systems can be found at DOE sites, including the following:

- A well-characterized 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.

However, the INL concentration of co-located capabilities, including RD&D facilities and equipment, make it uniquely well suited for its mission comprising the NRIC, and much of that capability is located at the MFC site.

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, over 50 reactors have been 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 and TREAT 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 the NRIC AT THE MATERIALS AND FUELS COMPLEX

Nuclear research facilities are high-hazard facilities that are heavily regulated and 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. Reestablishing MFC as a national nuclear test bed and demonstration platform 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 RD&D needs using both MFC and DOE-NE's broader research network. 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.

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. For the present purposes, it is helpful think of research capabilities in terms of research facilities, instrumentation, and expert personnel.

MFC facilities supporting the nuclear R&D mission are briefly described in Section 2.1.1, and additional facilities proposed for MFC are addressed in Chapter 5 of this document.

The type, quality and performance of the instrumentation available to researchers is critical to ensuring the right data or high quality 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.

A dedicated cadre of expert personnel (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.

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. MFC can improve ability to deliver quality R&D results on time and on budget with focused efforts improving operational effectiveness. Such improvement will earn the trust and confidence of DOE, industry, and university collaborators, which further enables the development and deployment of advanced nuclear technology

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; however, 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 3.3 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.

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.[g] 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.

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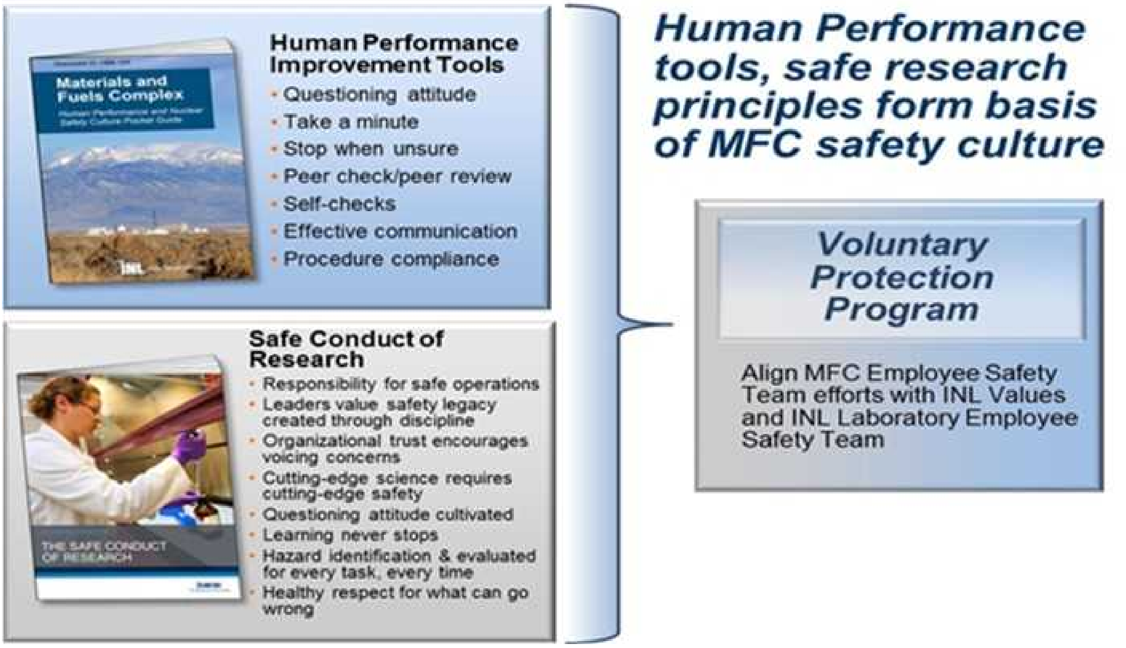
g. DOE-HDBK-1028-2009, "Human Performance Improvement Handbook," June 2009.

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.



Human Performance Improvement Tools
- Questioning attitude
- Take a minute
- Stop when unsure
- Peer check/peer review
- Self-checks
- Effective communication
- Procedure compliance

Safe Conduct of Research
- Responsibility for safe operations
- Leaders value safety legacy created through discipline
- Organizational trust encourages voicing concerns
- Cutting-edge science requires cutting-edge safety
- Questioning attitude cultivated
- Learning never stops
- Hazard identification & evaluated for every task, every time
- Healthy respect for what can go wrong

Human Performance tools, safe research principles form basis of MFC safety culture

Voluntary Protection Program

Align MFC Employee Safety Team efforts with INL Values and INL Laboratory Employee Safety Team

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 was achieved through 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. Proactive management of issues through development and execution of a structured improvement agenda is an important means for improving performance.

Integrated work planning is being implemented at MFC in FY 2017, as a means to improve cost and schedule performance. 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

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 identify staffing and procedural needs). Understanding exactly which instrument is needed in a facility and at what time allows MFC to optimize facility and instrument use.

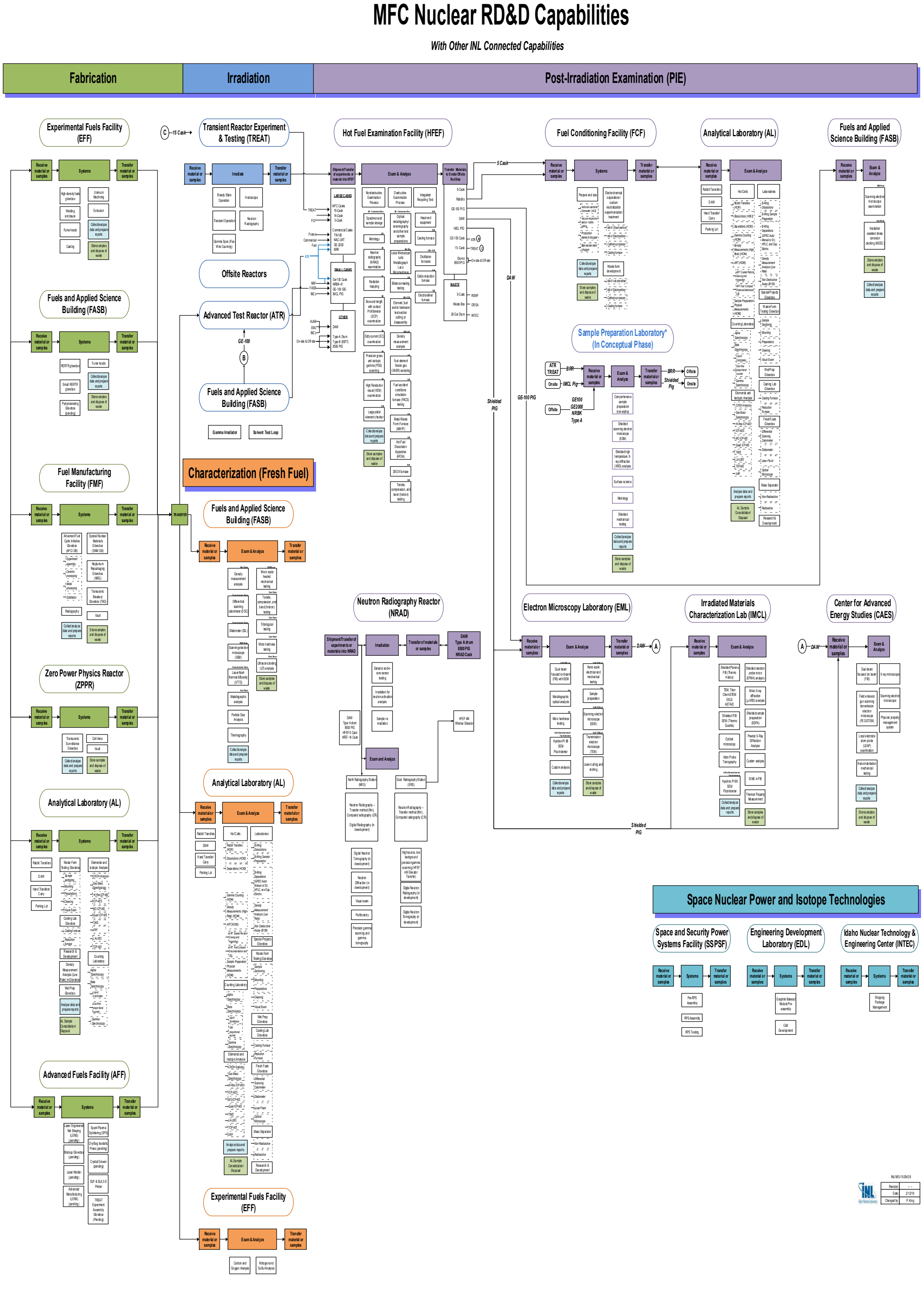


Figure 3-2. Example of experiment process flow.

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 to compliment this mission strategy and can be found in the companion document “Materials and Fuels Complex FY-19–FY-23 Five-Year Investment Strategy,” (INL/EXT-19-53607). This plant health strategy identifies near-term (i.e., FY 2019 through FY 2023) and longer-term (i.e., FY 2024 to FY 2028) opportunities to increase the R&D output from MFC. In general, as current facility reliability issues are addressed, the focus of life-cycle funding will shift to R&D capability needed to drive development of advanced nuclear technology.

3.3 Improving RD&D Performance

Fulfilling MFC’s role in INL and NRIC requires continuous improvement not only in operating effectiveness but also in research performance. RD&D performance can be measured in different ways, but most important for MFC are on-time delivery and RD&D impact. On-time delivery metrics reflect a number of performance characteristics including 1) schedule planning and execution, 2) operational efficiency, 3) equipment and instrument operability and reliability, and 4) technical skill in operating instruments and performing difficult operations. These are best indicated by successful completion of milestone activities and completion of tasks to be handed off. RD&D impact is indicated by publication of journal papers authored and co-authored by MFC personnel, by the impact factor of the journals in which MFC authors publish, and by the numbers of citations of MFC-authors’ work. These indicators reflect the degree to which MFC work is accepted by peers as technically sound and original and the degree to which MFC work advances the state and utilization of knowledge. These metrics are assessed at the end of each fiscal year for year-over-year performance and monitored formally and informally during the year for year-to-date performance.

Improvement in MFC RD&D performance is sought through measures that will improve MFC RD&D culture. Because culture is best considered as a set of shared values and behaviors, RD&D culture is not as easily indexed or measured as, say, RD&D output. However, in an effort to encourage R&D staff to value RD&D principles embodied in technical integrity, inquisitiveness, professional growth, and collaboration, the following measures were implemented in FY 2018 (many of which were underway less formally in FY 2017):

- Journal publications authored by MFC staff are encouraged and/or incentivized through staff performance measures and bonus awards for top performers
- MFC staff participation in technical and professional societies is encouraged and/or incentivized through staff performance measures
- Numbers of MFC seminars presented by internal and external speakers are tracked, and participation is encouraged by division and department leaders
- Hosting and mentoring of graduate fellows, post-doctoral appointees, and GEM fellows (through the National GEM Consortium) are tracked and encouraged by MFC and division leaders
- MFC leadership purposefully develops staff to qualify and compete for external awards, and nominates those best suited.

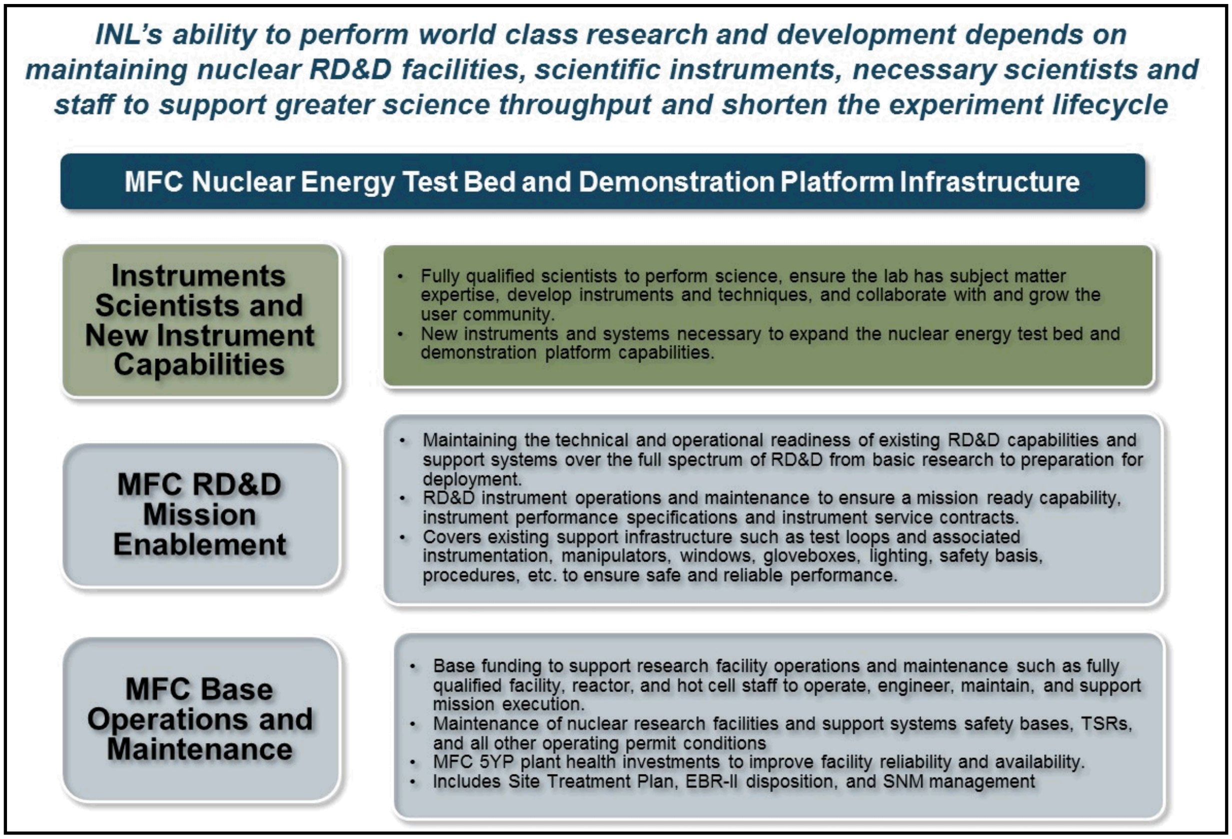
3.4 Proposed Nuclear Research and Development Test Bed Funding Model

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 to meet GAIN and Laboratory objectives for support of private-sector initiatives. A modified funding model is proposed to build and maintain the DOE-NE RD&D capability required for the test bed concept, which will enable MFC's role in NRIC. The current funding model is not sufficient for proactive management of infrastructure, research capability, and scientific and support staff needed for a nuclear test bed. The proposed user-facility 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 RD&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. (Note that the proposed model is not directly applicable to the demonstration platform function at MFC, which would entail funding arrangements with private commercial organizations and DOE.)

The proposed user-facility 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 model accounts for three key lines of asset funding: (1) MFC Facility Base Operations and Facility Mission Enablement, (2) MFC RD&D 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 RD&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 companion document "Materials and Fuels Complex FY-19–FY-23 Five-Year Investment Strategy," (INL/EXT-19-53607). That document accompanies this mission strategy to provide scope recommendations and funding levels necessary for supporting revitalization of the nuclear energy test bed at MFC.



INL's ability to perform world class research and development depends on maintaining nuclear RD&D facilities, scientific instruments, necessary scientists and staff to support greater science throughput and shorten the experiment lifecycle

MFC Nuclear Energy Test Bed and Demonstration Platform Infrastructure

Instruments Scientists and New Instrument Capabilities

- Fully qualified scientists to perform science, ensure the lab has subject matter expertise, develop instruments and techniques, and collaborate with and grow the user community.
- New instruments and systems necessary to expand the nuclear energy test bed and demonstration platform capabilities.

MFC RD&D Mission Enablement

- Maintaining the technical and operational readiness of existing RD&D capabilities and support systems over the 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.
- Covers existing support infrastructure such as test loops and associated instrumentation, manipulators, windows, gloveboxes, lighting, safety basis, procedures, etc. to ensure safe and reliable performance.

MFC Base Operations and Maintenance

- Base funding to support research facility operations and maintenance such as fully qualified facility, reactor, and hot cell staff to operate, engineer, maintain, and support mission execution.
- Maintenance of nuclear research facilities and support systems safety bases, TSRs, and all other operating permit conditions
- MFC 5YP plant health investments to improve facility reliability and availability.
- Includes Site Treatment Plan, EBR-II disposition, and SNM management

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 model ensures that facilities, instruments, and personnel are maintained and ready 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 DEMONSTRATION PRIORITIES

MFC was developed as a self-contained site supporting nuclear energy research and demonstration projects (primarily R&D programs to develop the fast reactor and associated fuel cycle), which employed EBR-II, FCF, HFEF, TREAT, the Analytical Laboratory, and ZPPR. The capabilities established by those earlier programs have since been repurposed and updated to now enable a wide range of research, development, and pilot-scale demonstration. Current R&D programs 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.

The establishment of NRIC capitalizes highlights INL’s opportunity to apply expertise help sustain the current reactor fleet and overcome the barriers that limit deployment of advanced nuclear technology. These opportunities address 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. INL’s contribution can include 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.

Success will 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.

Recent developments abroad have led to the planned shutdown of the Halden Reactor in Norway, where the Halden Reactor Project served the international LWR industry with irradiation testing services and valuable expertise in devising and interpreting irradiation tests. INL personnel have evaluated the void created by loss of the Halden capability and determined how DOE and INL can best contribute to meeting the new needs.[h] The conclusion of the evaluation recommended that INL establish the following capabilities to ensure the LWR community continues to have the RD&D platform needed to support continued development of new fuel designs and to address regulatory issues around fuel behavior under increasingly challenging operating conditions:

- Establish in-pile pressurized water irradiation loops in ATR and TREAT
- Establish advanced refabrication and reinstrumentation facilities needed for testing materials irradiated in commercial NPPs
- Develop and implement reliable instrumentation for key fuel performance measurements and materials testing.

The MFC role in establishing these LWR irradiation testing capabilities is elaborated in different ways throughout this Chapter. Research on 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 and determining off-normal behavior using transient irradiation tests and out-of-pile safety testing.

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[h] C. Jensen, et al., *Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations*, INL/EXT-18-46101, Rev. 1, December 2018.

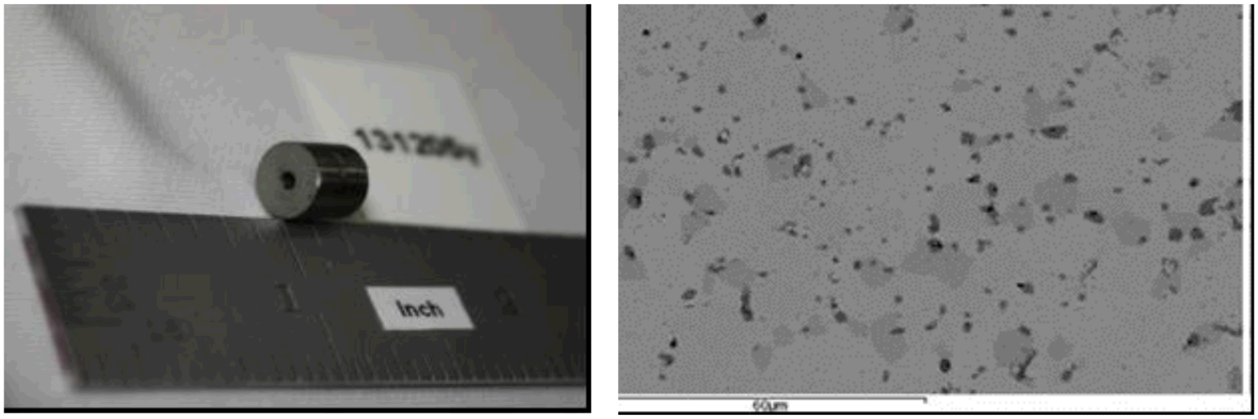

Figure 4-1. Sintered high-density U_3Si_2 pellets (left) and U_3Si_2 microstructure (right).[i]

4.1.1.2 Driver Fuel for a Versatile Test Reactor. In FY 2017, DOE-NE began funding a program to scope and specify a new fast test reactor facility, currently known as the Versatile Test Reactor (VTR), which would address the U.S. need for fast-spectrum irradiation testing and is proposed to be located at or near the MFC site at INL. Key features targeted for the facility are a peak fast flux of ~4×10^{15} n/cm^2/sec, sufficient versatility to accommodate testing in closed loops containing lead or lead-bismuth, sodium, and helium, and selection of tried and mature fast reactor technology to minimize cost and operational uncertainty. Current planning calls for the reactor to be fueled with metallic U-20Pu-10Zr fuel, based on prior U.S. experience with metallic fuel in EBR-II and FFTF. Use of Pu in the fuel alloy is highly preferred to achieve desired irradiation characteristics in a core of modest size (for VTR, a peak fast flux of $4 \times 1\text{-}^{15}$ n/cm^2/sec with core power of 300 MW has been selected as a design objective). Current efforts are assessing potential sources of Pu feedstock for the VTR driver fuel. Because the U.S. does not have an operating Pu fuel fabrication facility available, VTR planning necessarily includes establishing such a facility, possibly at the MFC site. The VTR program, then, includes preparation of a conceptual design and cost estimate for the Pu fuel fabrication facility, which entails laying out and specifying a fabrication process line. The envisioned process calls for known metal fuel fabrication technology but will incorporate proven improvements that have been developed since metal fuel was last produced for EBR-II in the early 1990s.

U-Pu-Zr fuel injection casting and fuel rod fabrication scale-up from EBR-II fuel dimensions and production rates to VTR fuel dimensions and production rates must be demonstrated to reduce VTR planning and cost estimating uncertainties. This will entail re-establishing successful U-Pu-Zr casting parameters on equipment prototypic of production size and demonstrating reliable fabrication rates, thereby completing the scale-up of U-Pu-Zr production from lab-scale to the engineering-scale production previously established for EBR-II U-Zr driver fuel.

4.1.1.3 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. Until a new test facility, such as

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[i] 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*.

the VTR proposed by DOE-NE, is built, 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 simulation can be used to show the feasibility of candidate transmutation fuel/cladding systems. Eventually, fast-spectrum irradiation testing will be 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.

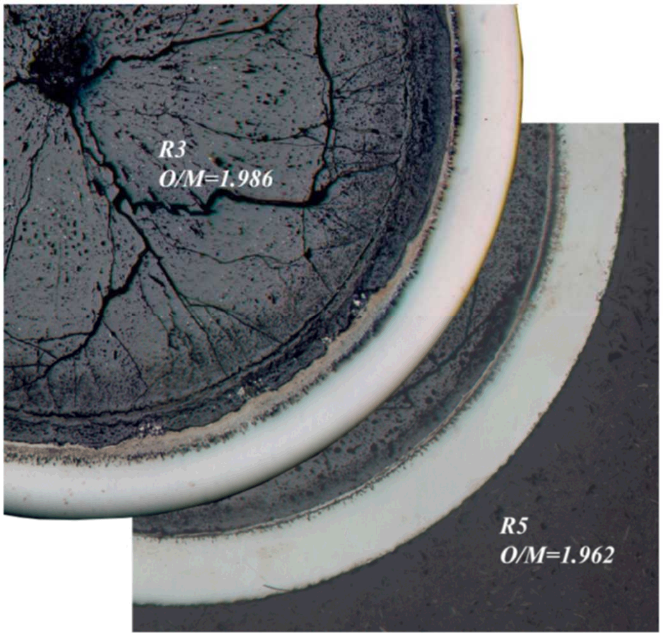

Figure 4-2. Comparison of the effect of the oxygen-to-metal ratio (i.e., O/M) in minor actinide mixed oxide fuel. A lower oxygen-to-metal ratio results in reduced fuel-cladding chemical interaction.

4.1.1.4 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.

4.1.1.5 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 and to fuel product quality 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 with 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.

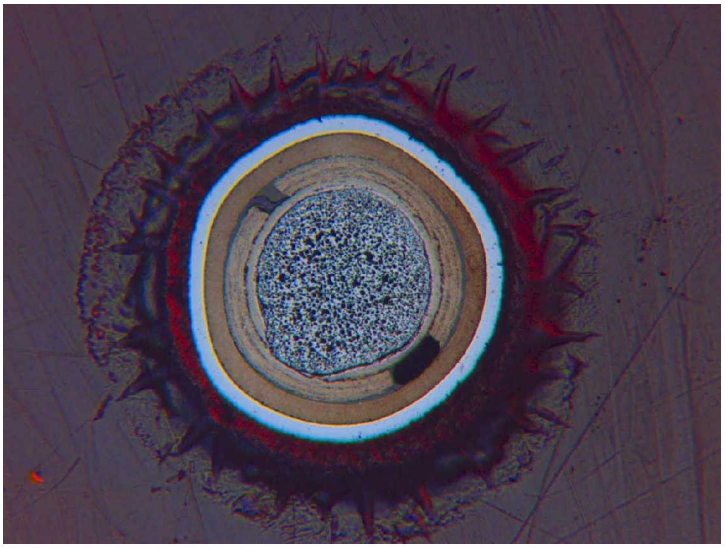

Figure 4-3. Next-generation nuclear reactor fuels are designed to be more efficient and resistant to accident conditions. TRISO fuel contains a layer of silicon carbide that serves as the primary containment for radioactive material (center). Researchers have subjected TRISO fuel to extreme temperatures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

4.1.1.6 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.

4.1.1.7 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.

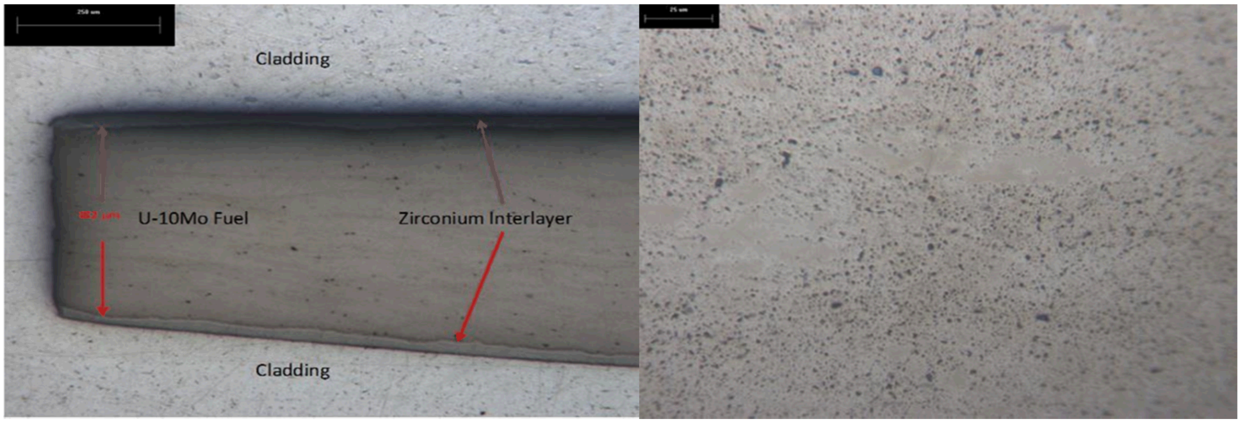

Figure 4-4. An optical micrograph of an irradiated low-enriched uranium monolithic fuel plate showing laminated fuel structure (top) and fuel microstructure (bottom) after irradiation to a fission density in excess of 4.1×10^{21} fissions/cm^3, showing fission-gas bubbles within recrystallized regions, 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 and FY 2020, examination of the MP-1 irradiation test will require a significant fraction of HFEF and IMCL 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 has explored the possibility of production of these fuels to meet the needs of the nuclear community, and although there does not currently appear to be an INL role in TRIGA fuel production, MFC personnel will periodically revisit this matter.

4.1.1.8 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. In fact, application of advanced manufacturing techniques may allow use of fuel design features previously not practical (or even possible) with conventional fuel fabrication methods. Assessing new designs may also require new or modified PIE instruments and techniques.

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, complicates the understanding of microstructural evolution and the interaction between radiation damage processes, and challenges the formulation general models that accurately predict the evolution of microstructure and associated physical properties. These limitations confound efforts 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.
- Integrate 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 establishing 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, EFF, and AFF 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.

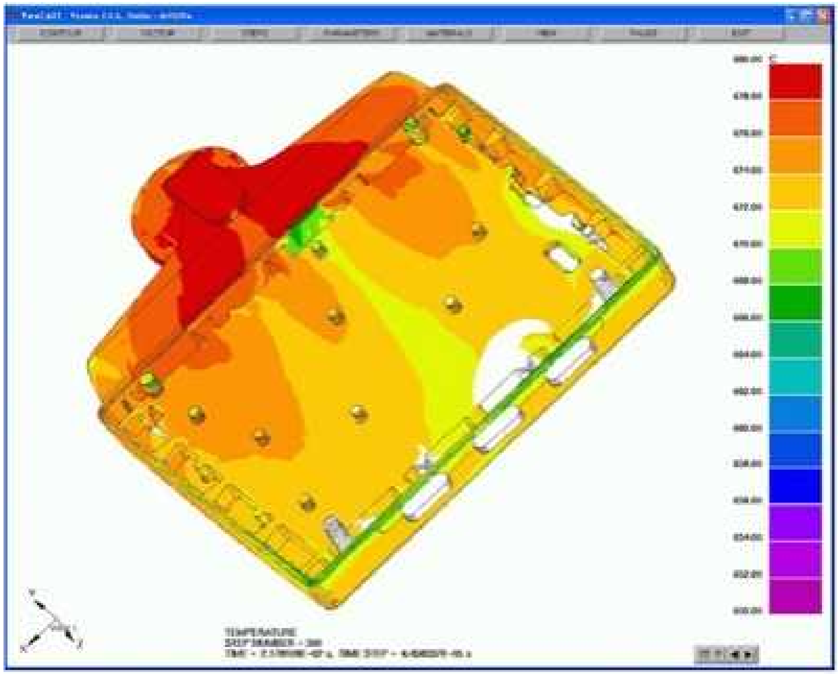

Figure 4-5. Fabrication process modeling can be used to determine optimum casting mold geometry and thermal conditions, reducing time for development of advanced fuel fabrication technology.

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 RD&D needs as they evolve.

Additional configurable fabrication space will be made available for testing and optimization of the new processes required for new fuels as RD&D needs evolve. In particular, private-sector interest continues for MFC fuel fabrication capability for fabrication process development, lead-assembly fuel fabrication and even first cores for first-of-a-kind demonstration reactors. If those program opportunities emerge with funding, then additional MFC fuel fabrication space will be essential. Space will be made available over the next 5 years through strategic reconfiguration of current fuel fabrication facilities (e.g., FMF, FASB, EFF, the Radioactive Liquid Waste Treatment Facility, and AL) to remove unused equipment and gloveboxes and transfer characterization equipment to new facilities (i.e., IMCL and SPL).

4.1.2.1.3 Advanced Manufacturing Techniques Applied to Nuclear Fuel—Advanced fuel systems enabled by advanced manufacturing will potentially lead to revolutionary advances in the nuclear industry. Creating the capability to fabricate and deploy new fuel systems, expand reactor market opportunities, improve economic and safety performance, reduce supply chain challenges and help to re-establish the United States as a global leader in nuclear energy technology development. Recently-developed advanced manufacturing techniques have not been fully applied to the fabrication of nuclear fuel systems. Beyond the potential to produce existing fuels in a less expensive manner, advanced manufacturing technologies have the potential to significantly expand the design options for fuel systems. The ability to fabricate non-homogeneous distributions of fuel constituents opens the door to possibilities not available with traditional fabrication methods. Advanced fabrication techniques also open the possibility of shapes and microstructures not possible with traditional methods. Because fuel and cladding performance is the basis for a reactor's safety performance and its economic competitiveness, deployment of new fuel designs and production techniques made possible by advanced manufacturing methods could have significant impact on the operating economics of the current LWR fleet and could enable operating regimes otherwise not possible in advanced reactors.

Additive manufacturing technology[j] is currently being developed in other major technology sectors (Figure 4-6).[k] 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[l,m] and fuels.[n] NNSA is also exploring the use of this technology for fabrication of low-enriched conversion fuel for the TREAT reactor.

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,

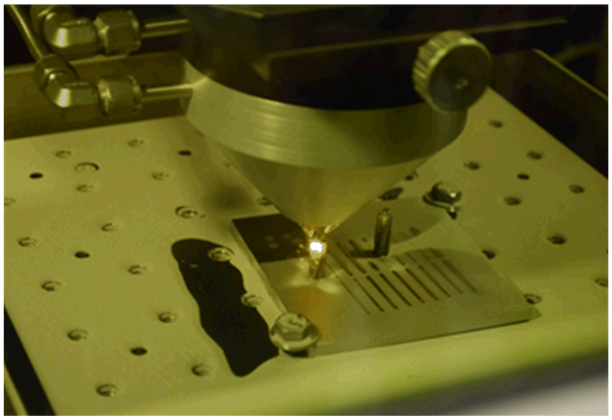

Figure 4-6. Laser additive manufacturing is being developed and applied for use in the manufacturing of advanced materials, for example, turbine engine components. The method will be applied to the development of advanced nuclear fuels at MFC.

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[j] Ian Gibson, David Rosen, and Brent Stucker, 2015, "Add and Direct Digital Manufacturing," second edition, Sprin

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

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

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

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

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.

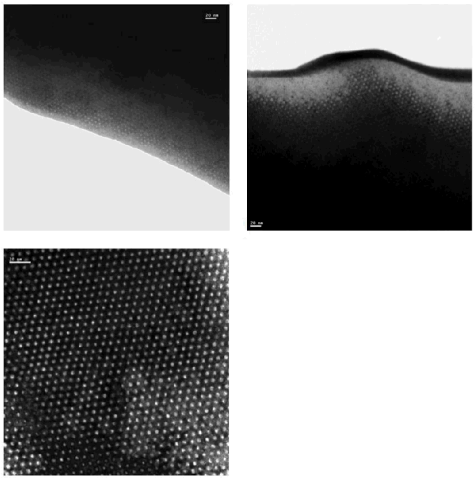

Figure 4-7. Transmission electron microscopy images of an ordered array of fission gas bubbles in U-Mo fuel at high burnup. The ordered array of high-pressure gas bubbles provides a stable and efficient mechanism for storing fission gas (INL/EXT-10-20466).

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[o] 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.

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

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[o] 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.

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. Other mechanisms for fission gas management and means to mitigate FCCI (fuel-cladding-chemical- interaction) are also of high interest.

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; key among these are understanding of fracture and irradiation creep behavior.

With the advent of modern laser-based methods for measurement of thermal and mechanical properties and the advent of in-situ micromechanical testing methods, 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.

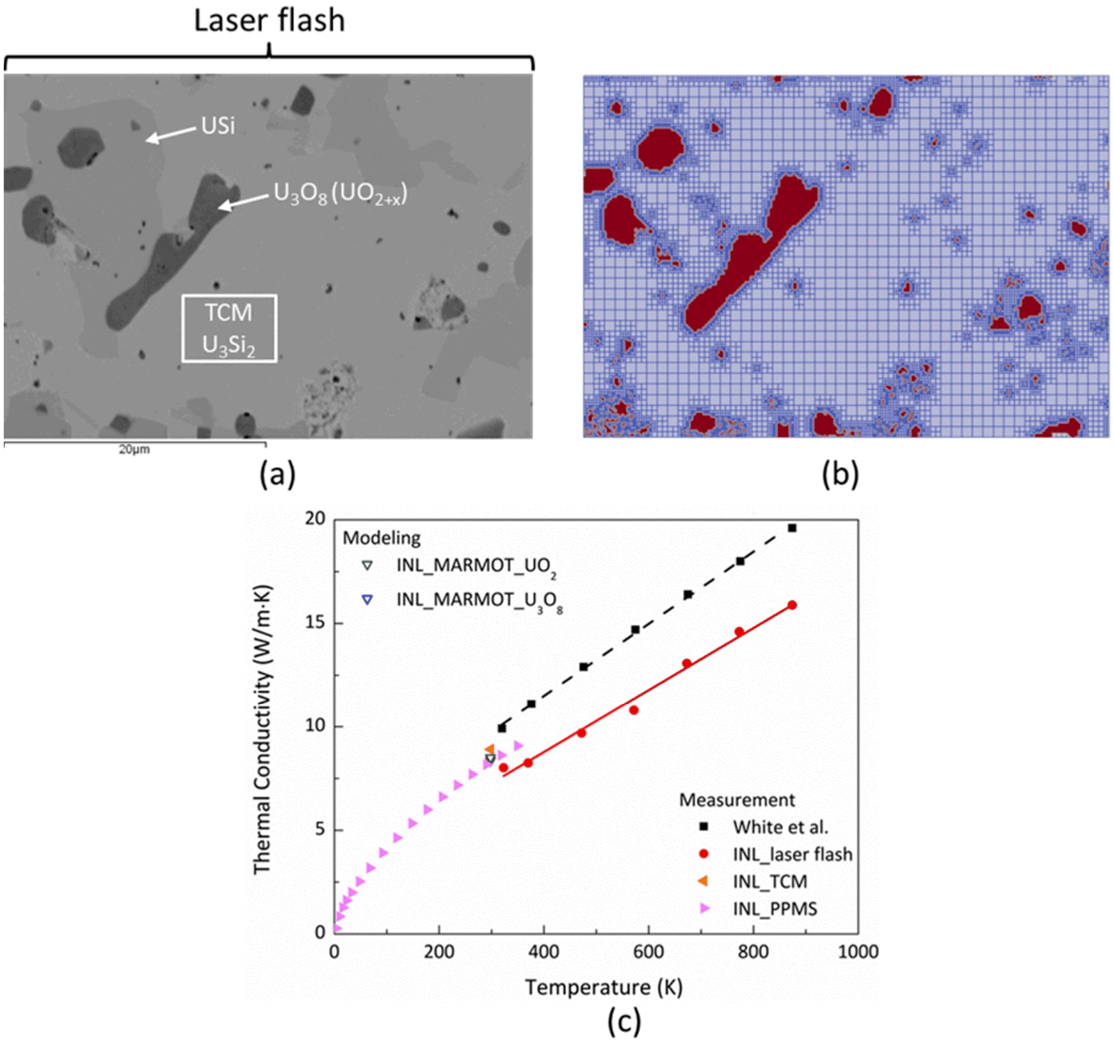


Figure 4-8. Thermal conductivity measurements of U_3Si_2 using several methods comparing different length scales and a wide range of temperatures. (a) Scanning electron microscopy image of an U_3Si_2 sample, (b) reconstructed microstructure and mesh in MOOSE for MARMOT calculations, and (c) thermal conductivity 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.

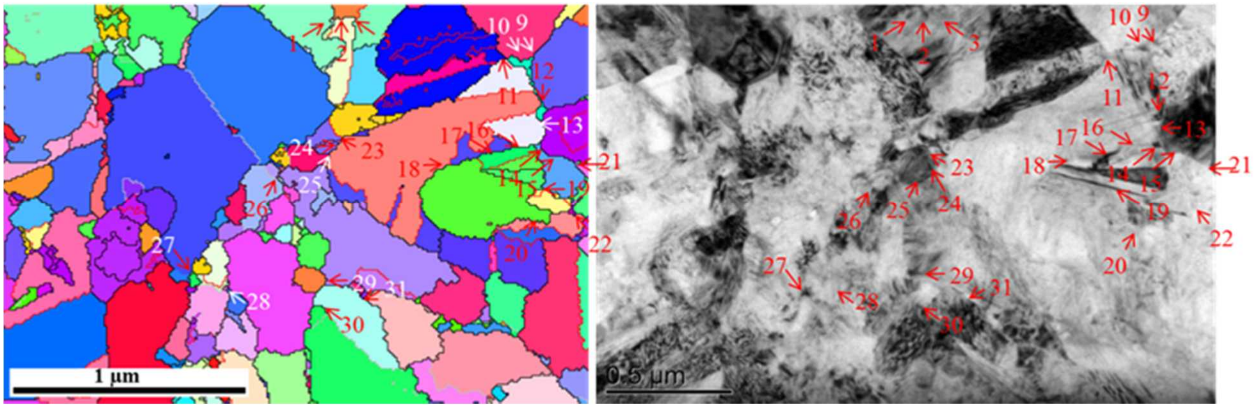
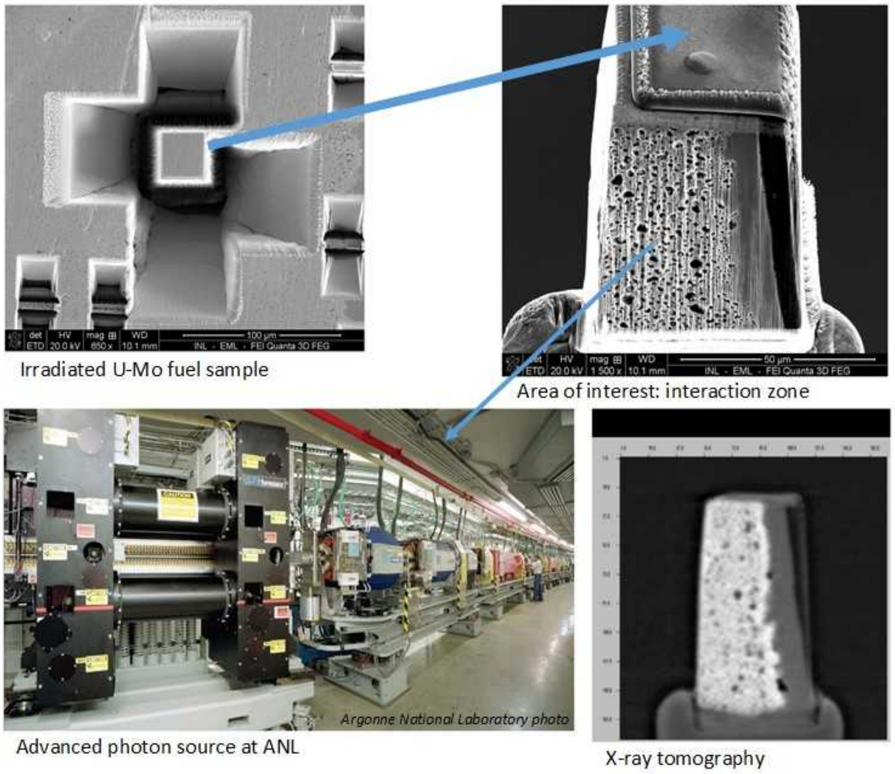


Figure 4-9. Silver transport through the silicon carbide layer in TRISO fuel has been a known issue for more than four decades, but has not been understood. Analysis using advanced PIE in HFEF, AL, and ORNL, coupled with high-resolution transmission electron microscopy is now helping to identify transport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



Irradiated U-Mo fuel sample

Area of interest: interaction zone

Advanced photon source at ANL

Argonne National Laboratory photo

X-ray tomography

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.

A three-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. Instrument scientists at the National Synchrotron Light Source-II[p] have proposed and developed a design concept for a beamline (MRE, Materials in Radiation Environment) focused on the receipt and characterization of radioactive materials. The proposed beamline would be separate from the NSLS-II main facility. The Advanced Photon Source[q] has also 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.

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

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

- Development of neutron scattering based on the Neutron Radiography reactor (NRAD) as the neutron source. Ongoing evaluation of neutron diffraction options is being conducted in consultation with experts from ORNL and MIT. This capability will be most suitable for providing basic, but very important, information on crystal structure and phases present in larger samples of highly active materials, such as intact fuel rods. Collocating the MEITNER PIE station with neutron diffraction and neutron imaging in the NRAD North Radiography station (NRS) provides an opportunity for correlated, multimodal nondestructive characterization, for example linking macrostructural information from gamma emission tomography to data on crystal structures from specific microstructural locations.
- Development of concepts for a high brightness, laboratory-scale x-ray and neutron scattering capability at MFC as a supplement or backup to a dedicated beamline at a synchrotron facility. Leading concepts are based on inverse Compton scattering using laser light sources of varying frequency coupled with LINAC or cyclotron electron sources, which could be housed in SPL. These light sources offer even greater ease of access, but at a significant penalty in x-ray brightness. Cost of an installed capability is estimated to be in the range of $15 M.

4.1.2.4 Transient Testing. TREAT provides 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) helping advance the state of nuclear energy science and technology. TREAT capability for testing LWR fuel is even more important with the pending shutdown of the Halden Reactor. 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:

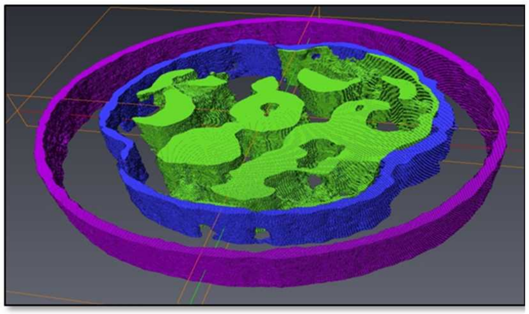

Figure 4-11. Tomographic reconstruction of archived neutron radiography reactor images taken from TREAT experiments provides an efficient and comprehensive method for assessment of fuel performance. The reconstruction can also be used with a three-dimensional printer to make a physical model of the disrupted 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. The results of this testing feeds into advanced modeling and simulation development at INL and in the industry.
- 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, propulsion and terrestrial space power systems, nuclear vendors, the Electric Power Research Institute, domestic and foreign regulators, and nuclear power generating companies.

4.1.2.4.1 Advanced Flowing Vehicle Loops—Design and development of advanced flowing loop transient test experiment vehicles is underway to provide the extreme environment needed to simulate actual reactor transient conditions. The loops will be capable of providing flowing liquid metal reactor conditions, Boiling Water Reactor (BWR) conditions, and Pressurized Water Reactor (PWR) conditions. These vehicles will provide the conditions needed for fuel qualification testing.

4.1.2.4.2 TREAT Reactor Parameter Measurement Capability—Development of measurement capability at TREAT is needed to understand and tune the transient parameters needed for successful transient testing. The developed method will provide fast turnaround of data including fission rate, Power Coupling Factor (PCF), and neutron spectrum enabling better customer response. The capability will also allow the measurement of more parameters to feed advanced modeling and simulation of the TREAT reactor enabling better and faster design of transient experiments.

4.1.2.4.3 Narrow Pulse Width for Prototypic LWR Transients—Pulse widths, defined as the full width at half maximum (FWHM), of Reactivity Insertion Accidents (RIAs) for pressurized water reactors (PWR) are in the range of 25-65 ms. The pulse width for boiling water reactors is on the order of 45-75 ms. TREAT’s minimum pulse width demonstrated in FY-18 is 89 ms. For TREAT to more accurately simulate Light Water Reactor (LWR) RIAs pulse width narrowing capability is needed for TREAT. The development of poison assemblies for strategic placement in TREAT to change the effective sized of the core and shorten the neutron lifetime. The effect of results in a pulse width around 70 ms. This gets the TREAT pulse width into the BWR RIA pulse width range. Designing and incorporating a He-3 injection system will shorten the pulse width even more making it possible to simulate PWR RIAs.

4.1.2.4.4 Advanced In-Pile and In-Experiment Instrumentation—Instrumentation is under development and being tested to provide real time transient parameter measurements. The instrumentation, including Linear Variable Differential Transformers (LVDT), Micro-Pocket Fission Detectors (MPFD), Infrared (IR) pyrometers, boiling water detectors, Self Powered Neutron Detectors (SPND), Self Powered Gamma Detectors (SPGD), and advanced thermocouples, is designed with the form factor to be able to be included in the very limited space of the transient test vehicles as well as the cooling channels of TREAT. The real time data will not only provide experiment and reactor conditions for experimenters, but will also feed into improving the advanced modeling and simulation efforts to model 3D kinetics of reactors.

4.1.2.4.5 Fuel Motion Monitoring System—A key nondestructive examination system at TREAT is the Fuel Motion Monitoring System, also called the Hodoscope. The Hodoscope is a fast-neutron imaging system mounted at the reactor's north beam port that provides real-time information about the location, deformation, and relocation of experimental fuels held within test devices during high-power transient events. The system currently incorporates about a hundred channels of the possible 360 channels of data operated in parallel and is capable of recording movement at sub-millisecond timescales over a large field of view. The additional detectors needed to fill the full 360 channel capacity are currently being designed and tested and will be deployed in the near term. It is capable of simultaneously imaging an entire advanced-reactor fuel assembly. However, individual image pixels within the hodoscope are coarse and are not optimized for studies of small-scale effects in single fuel pins, such as the quantification of minor axial fuel swelling or fuel-clad bowing. New investments are needed to design and develop a new FMMS optimized for the measurement and analysis of smaller-scale phenomena in single pins, with higher image-plane spatial resolution, higher signal rates, and better signal-to-noise performance than the current hodoscope.

4.1.2.4.6 Neutron Radiography—Neutron radiography capability is collocated at TREAT providing in-process irradiation examination capability for experiment campaigns of multiple planned transients including multiple specimen irradiations. The in-process radiography can provide data for tuning the subsequent transients in the irradiation campaign without waiting for detailed Post Irradiation Examination (PIE). The current neutron radiography capability is able to identify initial test configuration pre-irradiation and test configuration and fuel disruption post- irradiation. The resolution is adequate to potentially see major fuel cladding deformation. The development of a new collimator is under way to increase the resolution of the system to better inform experiment campaigns though will not approach the capabilities of NRAD. NRAD will still be used for high-resolution neutron radiography.

4.1.2.4.7 Re-fabrication and Re-instrumentation—Collocated at the TREAT facility is a need for a shielded experiment handling cell for the assembly and disassembly of lower activity experiments. This shielded experiment handling cell would include the capability of remanufacturing and instrumenting smaller quantities of pre-irradiated fuel into transient testing experiments. The re-fabrication and re-instrumentation effort will start at the HFEF facility with the process completing at the collocated facility at TREAT. The cell will also have some non-destructive PIE measurement capabilities for rapid post irradiation data collection before shipment to a facility such as HFEF for more detailed PIE.

4.1.2.4.8 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 an INL engineering document.[r]

4.2 Radiation Damage in Cladding and In-Core Structural Materials

The limiting factors in both fuel and reactor operating lifetime are cladding[s] and structural materials. Research for developing the scientific basis for understanding and predicting the response of materials to 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 a capability for rapid development of materials, including fabrication, performance testing in a realistic environment, and characterization. Also key are the availability of materials for study by the nuclear energy research community, the ability to fabricate standard test samples from irradiated materials mined from current reactors, and the ability to transport materials to and from NSUF partner facilities as appropriate.

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

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[r] K. Davies, *“Evaluation of HFEF capability to Support TREAT Restart.”* TEV-3093*,* November 7, 2017.

[s] 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.

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). At INL, SPL will serve as a user facility and as a material supply hub in national and international efforts to develop these materials.

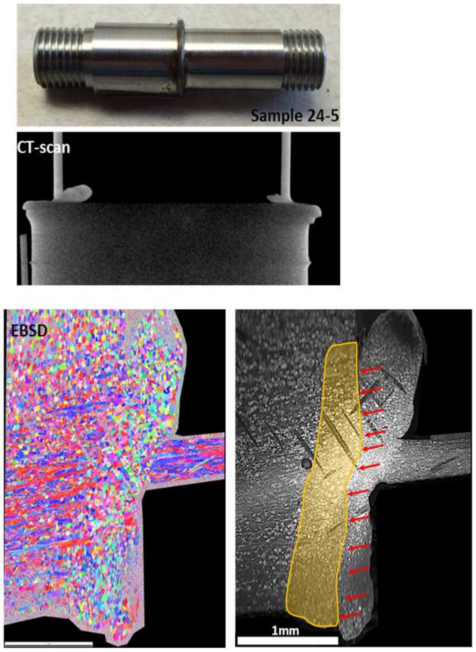

Figure 4-12. Thin-walled tubing is being developed as an alternative to zircaloy cladding for use in LWRs.

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

4.2.2.1 Zirconium-based Light Water Reactor Fuel Cladding. Significant reduction in LWR operating costs may be achieved by a reduction in outage costs. This entails extending fuel burnup and increasing the number of maintenance activities conducted while the reactor is on line. Both of these strategies require improvements in current fuel cladding performance and testing to validate the thermomechanical response of cladding materials to RIA (Reactivity Insertion Accidents) and LOCA (Loss of Coolant Accident) events. The required improvements in cladding performance may be realized through development of and effective coating technology. This development involves a combination of steady-state irradiation testing, transient irradiation testing, out-of-pile thermal testing, and standard and specialized mechanical testing to determine cladding embrittlement thresholds.

4.2.2.2 Accident-Tolerant Cladding Materials. Developing accident-tolerant fuel concepts revolves around improving oxidation behavior of current zircaloy cladding materials through surface modification, or developing oxidation-resistant steel or ceramic materials. These cladding materials are currently being irradiated in ATR and in commercial light water reactors as part of the Accident-Tolerant Fuel Experiment series of experiments and tests. 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.

The Sample Preparation Laboratory mission for development and testing of materials will include the testing of light water reactor cladding materials, with the risk of alpha cross contamination mitigated through defueling of cladding and use of local confinement barriers, such as gloveboxes, where necessary.

4.2.2.3 Radiation-Tolerant Cladding Materials for Fast Reactors. Development of cladding for fast-spectrum reactor systems seeks to improve on the excellent swelling resistance of ferritic/martensitic steels, such as 12Cr-1Mo-based alloys (e.g., HT9) and 9Cr-1Mo-based alloys (T91) with improvements in high-temperature strength and irradiation creep resistance. 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 nanoscopic 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. A promising alloy developed at ORNL is a nano-structured ferritic alloy (NFA), which uses a very high density of Y-Ti-O nano-features to impart resistance to dislocation climb and glide and to enhance point defect recombination.[t] MFC's role in development of new cladding 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. The SPL will play a central role in this effort.

A new class of high entropy alloys has shown promising radiation-resistant behavior during early testing. This class of alloys occupies a large compositional parameter space, and will require considerable initial development, out-of-pile testing, irradiation exposure, and testing of irradiated material. Because of the large parameter space and extensive testing required, development of this alloy class is a candidate test case for the application of high-throughput and combinatorial material science methods to nuclear materials.

Many of these materials are difficult to join; alternatives to traditional fusion welding are being developed. As an example, 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 4-12 (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.

The SPL will be central to the research and development of improved fast reactor cladding alloys through conventional testing and through the development and application of high throughput and combinatorial material science methods to nuclear materials.

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[t] G. R. Odette and D. T. Hoezler, "Irradiation-tolerant Nanostructured Ferritic Alloys: Transforming Helium from a Liability to an Asset," JOM, September 2010, 84-92.

Figure 4-13. IASCC test rigs for high-activity materials.

4.2.2.4 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 4-13) is used to make these measurements on materials with gamma dose rates up to 40,000 R/hr.

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.

4.2.2.5 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. Alloy X-750 is a material used today in many commercial reactor applications, but its performance is not as favorable as expected (Figure 4-14). 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, based on what is learned from currently used materials, into design of new reactors that further increase the operating lifetime would provide substantial benefit to the nuclear industry.

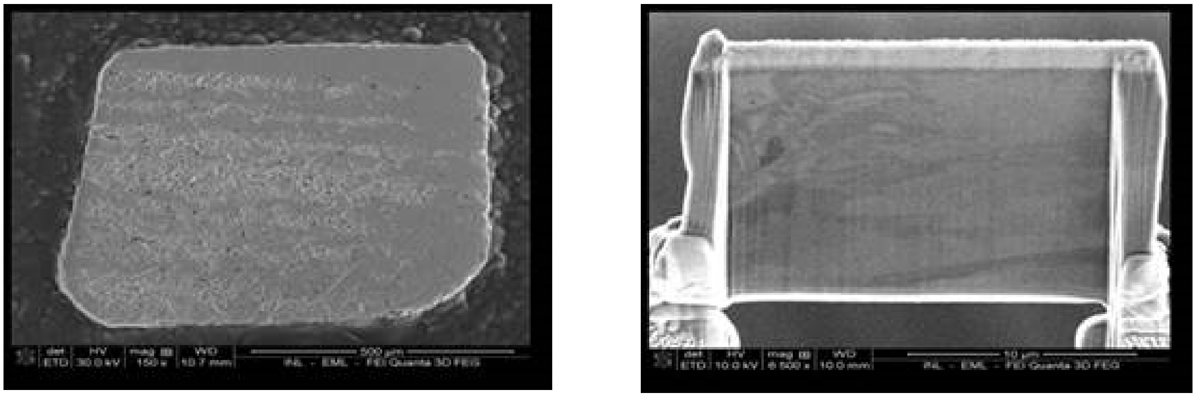

Figure 4-14. Irradiated X-750 nickel alloy specimens (left) were prepared by focused ion beam (right) for Atomic Energy Canada Limited. This joint work helps to address the root cause of a material performance issue in CANDU reactors and define improved material specifications.

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 recycling 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 is used as the feed for kilogram-scale pyroprocessing equipment installed in the HFEF argon-atmosphere hot cell. Through electrochemical oxide reduction and electrorefining, the oxide fuel is reduced to a metal, and TRU accumulates in the molten electrorefiner salt. When a sufficient quantity of TRU has accumulated, these metals can be recovered from the salt through application of a liquid cadmium cathode. The resulting uranium/TRU alloy has been used to make fuel samples for irradiation testing in ATR and subsequent PIE analyses in HFEF. Although alternative irradiated material has been used as feedstock for this demonstration, pushing this research forward to conclusion calls for the receipt and use 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 4-15).

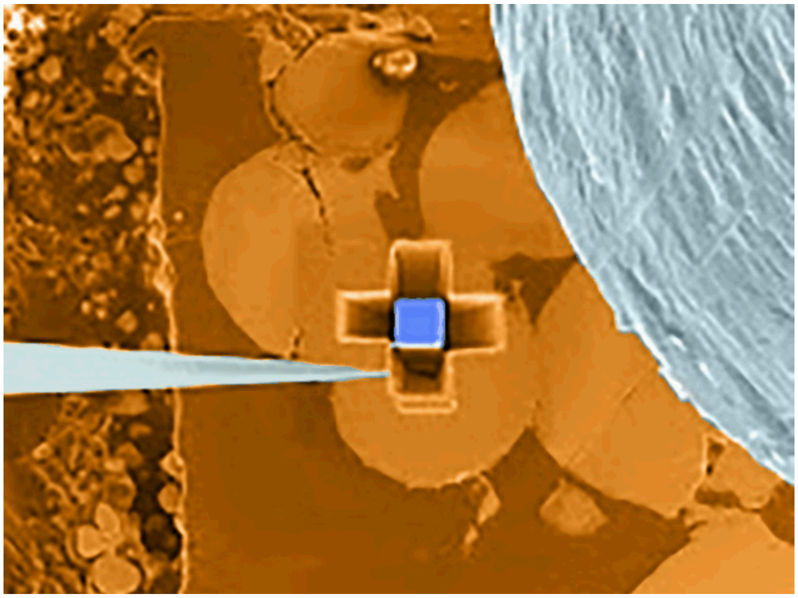

Figure 4-15. INL researchers have demonstrated a new sample preparation technique that makes it easier to examine irradiated fuel at the nanoscale. The new technique uses an ion beam to mill material sections that are just tens of nanometers thick. A platinum layer (i.e., the blue square) protects the surface and an Omniprobe needle (i.e., gray) is used to lift the tiny sample. After preparation, the sample has low radiological activity and can 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*,[u] 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[v] 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
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.

In 2017, the DOE's Office of Basic Energy Sciences directly addressed nuclear research needs through a Basic Research Needs workshop on Future Nuclear Energy—Inspiring Science at the Extremes of Chemistry and Materials.[w]

> *[Advanced Nuclear Reactors] demand the discovery and design of revolutionary new materials and fuels, coupled with innovative approaches to materials synthesis and processing and optimization of the performance and certification of the new components. Combining modeling and simulation with in situ characterization methods will reveal and predict processes that dictate performance and degradation*

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[u] "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).

[v] "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).

[w] "Basic Research Needs for Future Nuclear Energy," Report from the Basic Research Needs for Future Nuclear Energy Workshop, U.S. Department of Energy, Office of Science (2017).

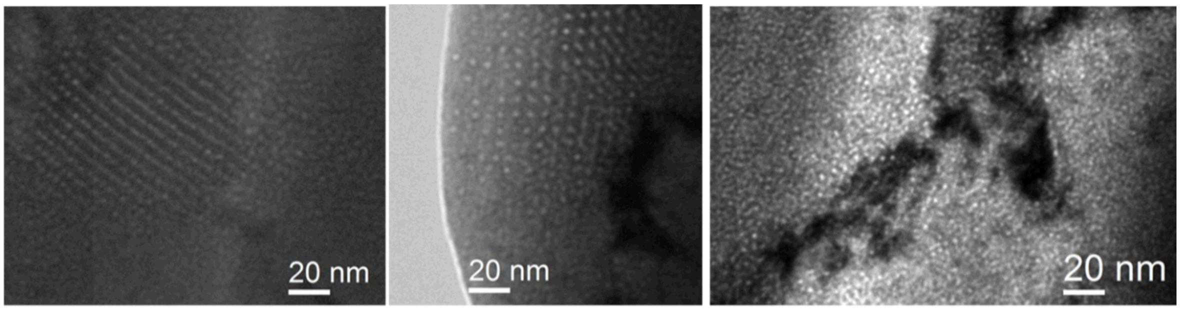
> *under extreme operational conditions… New computational tools and data analytics will expedite the identification of chemical compositions and structures of materials with tailored properties required to withstand the harshest reactor environments, followed by innovative synthesis and processing capabilities for materials production.*

This workshop identified five priority research needs directly applicable to nuclear energy:

1. Enable design of revolutionary molten salt coolants and liquid fuels
2. Master the hierarchy of materials design and synthesis for complex, reactor environments
3. Tailor interfaces to control the impact of nuclear environments
4. Reveal multiscale evolution of spatial and temporal processes for coupled extreme environments
5. Identify and control unexpected behaviors from rare events and cascading processes.

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.

Figure 4-16 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.



Residual bubble superlattice Residual bubble superlattice High concentration small bubbles

Figure 4-16. 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.

MFC's significant inventory of actinide materials and capability to handle and process significant quantities of these 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 fundamental properties and underlying physics of 5f electron materials.

4.4.2 Focused Basic Research Goals

Basic research that supports longer-term goals for improved nuclear fuel is focused on understanding nuclear fuel degradation processes physical properties of actinide-bearing materials. This understanding enables the ability to design fuel materials with improved burnup potential.

4.4.2.1 Fundamental Behavior of Nuclear Fuel Under Irradiation. The in-service behavior of nuclear fuels is complex and unlike any other material system. Massive electronic energy deposition from fission fragments into the fuel matrix leads to material changes including initial in-pile densification followed by volumetric swelling; grain refinement and growth; composition (actinide) redistribution across the pellet diameter; restructuring into nanoscale grains at the fuel pellet periphery; and large compositional changes due to fission reactions that lead to dissolved metallic fission products, metallic and oxide fission products in the form of nanoscale precipitates, and bubbles of insoluble gas.

The damage mechanisms and microstructural evolution in fuels is very different and much more complex than for the neutron interactions with non-fissile materials. Although nuclear fuels have been in use for more than six decades, this complex behavior is not well understood, making the rational design of improved nuclear fuels nearly impossible. Achieving major increases in performance requires a more complete understanding fission-induced phenomena from the initial energy deposition and defect production, long-term microstructural evolution, and fission gas behavior.

Achieving a mechanistic understanding of fission fragment energy deposition in fuel matrices is an important fundamental research field. One of the main unsolved questions is the spread of the deposited energy as a function of space and time and its conversion into atomic motion in the target material. An important research area is the understanding of the thresholds for persistent damage (fission tracks), a direct indicator of the radiation response of fuel materials. Fission fragment ‘damage’, in some cases, can be used to shape fuel response in a positive manner through changes in crystal structure and re-solution of second phase precipitates and fission gas bubbles. This research area requires careful irradiation in reactor or through the use of swift heavy ion sources to low fission densities. Characterization of the discrete fission tracks produced is used along with multiscale methods developed to simulate individual fission events provides the information required to understand irradiation response. The TREAT reactor provides an ideal vehicle for this testing.

The link between specific microstructure changes and the nature of fission-induced damage is complex and constantly evolving during irradiation. In some cases, rapid degradation of properties and behavior occurs; in others annealing of preexisting damage or formation of new structures leads to improved properties. These effects are dependent on numerous material-specific factors, including free electron density, electron-phonon coupling, and the starting microstructural state. Early experiments show that material response can be controlled using tailored electronic states, solid state chemistry, precipitate structure, crystal structure, and physical properties, allowing stabilization of non-equilibrium crystal structures, control of grain size and crystallinity, and development of fine precipitate structures that act as fission gas nucleation sites. Control of these microstructural features determines resilience to radiation damage. Effective research in this area requires the use of higher flux reactors such as ATR to expose a matrix of materials designed for radiation tolerance to the fission environment, followed by determination of macroscopic response and microstructural analysis; again, linked to modeling of microstructural evolution that includes the damage source term.

The behavior of the noble fission gases xenon and krypton in nuclear fuel is of critical importance, and ultimately limits the usable life of nuclear fuel. The diffusion, nucleation, growth, mobility, and re-solution of noble gas bubbles influence both the amount of material swelling and the quantity of fission gas released. These behaviors are closely linked to microstructural evolution, but these relationships are not well defined. Fission gas evolution processes have a strong spatial dependence and occur across a range of time scales from the sub-picosecond fission fragment energy deposition process to the $>10^8$ s fuel operating lifetime. Progress in this area requires in-pile experiments specifically targeted at understanding noble gas behavior and coupling this experimentally derived knowledge to multiscale simulations.

4.4.2.2 Fundamental Properties of Actinide Materials. 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[x] 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 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 specialized research tools installed in nuclear research facilities. Measurements performed at cryogenic and moderate ($\leq$ 800K) temperatures under extreme conditions such as pressure and magnetic fields provide the richest fundamental information on actinide material behavior because of larger variations in properties with small changes in temperature, less uncertainty, and larger differences in properties for different materials. Characterization of property variations measured with high fidelity allow development of the best predictive modelling capability 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.

Because actinides are difficult to handle in normal laboratory environments, a Physical Property Measurement System (PPMS, Figure 4-17) designed to make the measurements described above will be installed in IMCL. 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. The integration of this technology with microscopic samples produced by FIB will be a key enabling factor for the 5f physics and chemistry research communities. Efforts required to produce high purity actinide materials for research are also under way. The results obtained from research conducted using this capability will provide fundamental understanding of nuclear material properties tied to performance, and fill in missing parameters for advanced modeling and simulations crucial for model validation and development.

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[x] 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.

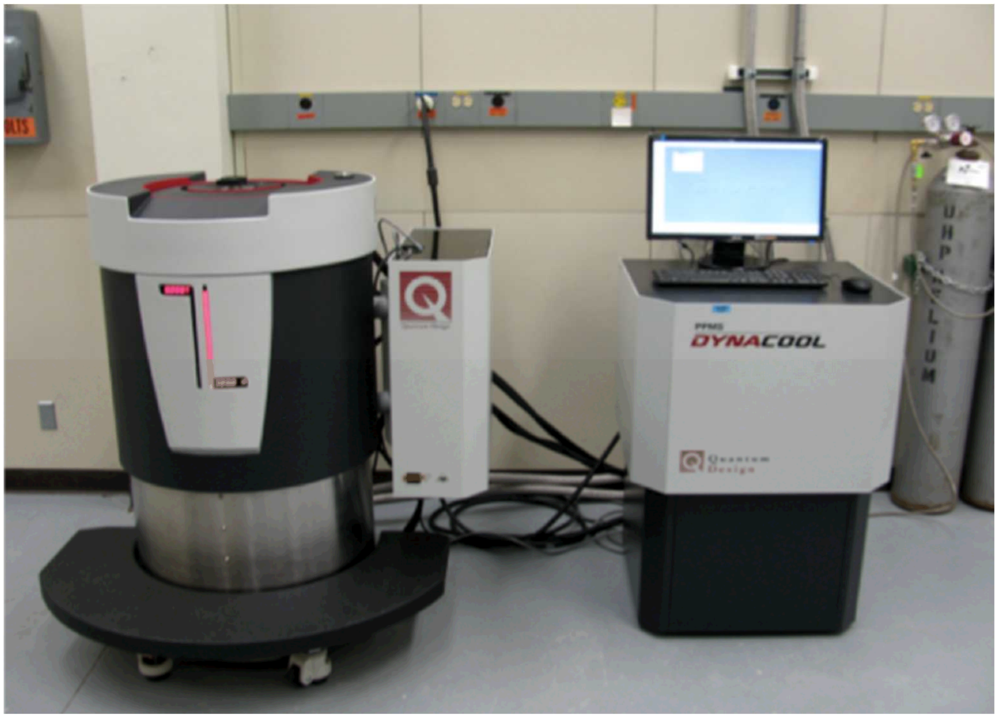

Figure 4-17. Physical Property Measurement System (DynaCool-9, currently installed at the INL Idaho Research Center). Availability of this capability in IMCL will result in unique capability for understanding the fundamental properties of the actinides and actinide-bearing ceramics and alloys.

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. The programmatic mission is supporting the development of test and measurement standards and materials for the nuclear forensics community. 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 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 use in medical, industrial, and scientific endeavors, along with research and development to support this, is the primary focus for the Isotope Program of the Office of Nuclear Physics in the DOE Office of Science (DOE-SC). One exception is for the isotope Pu-238 which by mutual agreement is administered by the DOE-NE Nuclear Facilities Infrastructure Program. Both of these DOE programs work through the national laboratory systems and affiliate partners to provide these isotope services. The Idaho National Laboratory (INL) currently is engaged with both DOE providers of isotopes (DOE-SC and DOE-NE).

4.6.2.1 Pu-238. 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 (NASA) have been supported by the INL in several ways. The INL houses essentially all of the United States store of neptunium-237 (Np-237), which is the precursor target material required to make Pu-238. The INL also operates the Advanced Test Reactor (ATR), which will be used along with the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) to produce Pu-238 from the Np-237 target material. The role of the INL is to supply Np-237 to ORNL to fabricate targets for both reactors. The INL will also provide irradiation services in ATR and ship irradiated targets to ORNL for processing into purified Pu-238.

To better serve this mission, INL staff are currently investigating approaches to accelerate and increase Pu-238 production from ATR irradiations. DOE-NE and NASA managers have recently indicated a need for accelerates production to reduce risk to continued space exploration missions, which relies on the availability of this isotope. Initial, short-term efforts include scoping and trade studies to assess production potential from each of the types of ATR irradiation positions, considering neutronic, thermal and structural factors that impact production rates. In the longer term, slight variations in the ATR target pellet or capsule design could be considered for additional production improvements and to reduce the thermal limitations; such changes could include smaller diameter pellets, target length (longer or shorter), addition of spacer pellets, increasing neptunium oxide loading, etc.

4.6.2.2 Co-60. Current DOE-SC isotope production activities at INL entail irradiation of Co-59 targets in ATR to produce Co-60. This program is also performed in conjunction with ORNL. ORNL led the target design effort and fabricated the latest target type in 2014-2015, of which 67 targets are currently being irradiated in ATR. These are planned for discharge beginning in summer 2019 through approximately 2022. There are currently no subsequent contracts for additional cobalt targets (beyond the 67) to be irradiated. However, some new end-user customers for various specific activities of Co-60 have recently been identified and negotiations have begun with the Isotope Business Office, operated by DOE-OS.

4.6.2.3 Other Isotopes. Growth of DOE-SC-sponsored work at INL is possible. Examples include production of Ir-192 through irradiation of Ir-191 targets. ORNL has been working on a couple of different designs for the Ir-191 targets that could be irradiated in HFIR and ATR.

Other isotopes of interest to DOE-SC could also be produced in ATR. In approximately 2010, a hydraulic shuttle system was installed in ATR's B7 irradiation position, in which target materials could be shuttled in and out of the reactor core for partial cycle irradiations. Neutronics analyses were completed and reported comparing production rates in the B7 position for several isotopes.[y] This system had to be removed in 2017 because of concern that vibrations from the system was causing some unexpected cracks in the Be reflector region near the shuttle position. Some design changes for the shuttle system are being considered that could eliminate this issue so it could be reinstalled during the upcoming ATR core internals changeout in 2021. However, without a strong motivation for future use of the shuttle

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[y] Idaho National Laboratory, "*Isotope Generation Analysis for Elements in the ATR B-7 Position Using Origen 2.2*," ECAR-2325, Rev. 0, August 11, 2016.

system, design efforts and reinstallation may be dropped. INL personnel propose to engage senior ORNL isotope program managers to develop a roadmap for use of ATR to enhance production of selected, high-value isotopes.

4.7 Additional Factors Necessary for Success

4.7.1 Data Management and Analysis

Innovation in science requires three major elements:[z]

1. Intellectual capital: our research staff with their knowledge and ideas
2. Necessary supplies: equipment, available data of appropriate quality, materials and supplies (including special nuclear materials needed for investigation of nuclear energy technology)
3. Investment and its financing: resources for RD&D and for technology introduction.

When resources and investments are available, innovation is limited only by the rate at which intellectual capital can be generated. To accelerate innovation within the nuclear industry the rate at which needed information is created and used must increase

Current data streams span over ten orders of magnitude in length and include markedly different types of data (examples include, but are not limited to, engineering drawings, images, linear dimensional information, time-resolved experimental and operating conditions, thermal properties, chemical composition, and atomic positions). Refinement of these streams into the usable and useful form required for nuclear innovation can be quite cumbersome and slow due to the pure size and diverse nature of data. In addition, with the increasing use of 3-D characterization at the engineering and microscale, accelerated innovation will not occur without a paradigm shift in the methods used to manage data streams and the tools that evolve for their analysis.

The ability to efficiently store (and recall), process, and analyze data is paramount. Furthermore, effective data management will enable novel means for interpreting data through concurrent visualization of test parameters, experimental results, and simulations. Requirements for a data management and analysis system that supports rapid generation of intellectual capital must include the following:

- Automated digital data capture and storage in a commonly accessible location in usable formats (to make data more broadly available).
  - Inclusion of metadata will be critical for recognizing the data source, recording instrument condition and parameters, as well as correlating analyzed material across multiple length scales.
  - Storage must be designed to grow in size (Petabytes worth of information acquired at a continually increasing rate) and nature over time.
- Seamless integration of experimental data, operating parameters, and design into an amenable form for modeling and simulation and vice versa.
  - Seamless integration will allow rapid validation of hypotheses and model assumptions.
- Development and implementation of a visualization framework capable of simultaneously examining multiple data streams in three or more dimensions allowing rapid comprehension of system behavior and structure-property and design relationships.
  - Data streams should include characterization (i.e., visual exam, dimensional measurement, microstructure, and atomic structure), fabrication (i.e., pre-irradiation microstructure, isotopic composition, and chemical composition), irradiation history (i.e., temperature, flux, and fluence), and modeling and simulation results.

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[z] Tom Nicholas, "What Drives Innovation?" *Antitrust Law Journal* 77, no. 3 (September 2011).

- Built-in quantitative assessment functionality of the quality and pedigree of data with the ability to incorporate data review, acceptance, and archival.

Development of effective and efficient data management, processing, and visualization tools that function seamlessly with modeling and simulation tools (e.g., MOOSE-based applications in use at INL) will dramatically increase our comprehension of the complex, interconnected, fuels and materials systems of interest to nuclear science. A better grasp of the underlying mechanisms and phenomena that govern nuclear materials and fuel behaviors (such as those indicated in Figure 4-18) in turn lead to better models and more rapid validation of codes. Ultimately, this will spark rapid innovation in the nuclear industry as it will provide a revolutionary approach to regulators based on the availability of validated and high-quality data.

Achieving a vision to implement data analytics approaches using MFC-generated data requires pointed effort to make large amounts of MFC data available to collaborators and users inside and outside INL. In general, the following measures can be implemented to position MFC to better support this development:

- Connect all data-gathering MFC instruments to the Private Facility Control Network (PFCN) to increase data rates, allowing transfer of large amounts of data
- Upgrade hardware used to store and process data, to improve management of large amounts of data
- Identify and implement cybersecurity measures needed to ensure users can access data in a manner that ensures data integrity and protects INL data systems

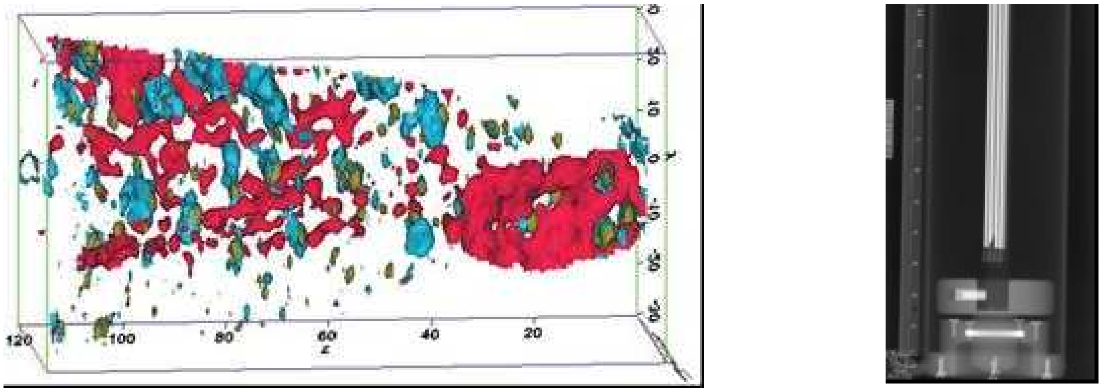


Figure 4-18. Example of three-dimensional data that ranges over 10 orders of magnitude in length scale. (Left) Atom probe tomography results from an alloy containing Fe-Cr-Mo and yttrium oxide. The scale is in nanometers; the map is built from the locations of individual atoms. (Left) Neutron tomography 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.

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.

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 one 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'[aa] shipping cask (Figure 4-19) 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 emphases and takes advantage of capabilities at MFC, including HFEF, AL, IMCL, SPL, and the Electron Microscopy Laboratory (EML). Additional work scope of this type 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 to be added to the MFC site in FY 2020 is expected to support this research by allowing classified videoconferencing and data exchange. In addition, removal of the Argonne Fast Source Reactor shield block from EML is scheduled for FY 2019, which will installation of additional equipment and instruments needed to support classified programs in EML.

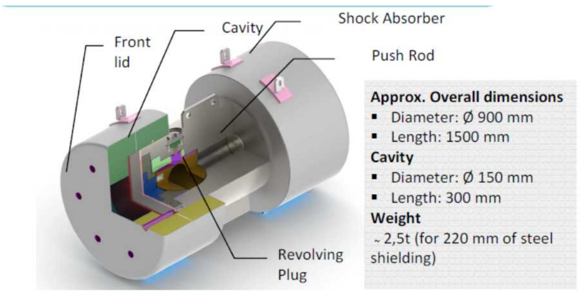


Figure 4-19. International air transportable cask being developed on behalf of the International Hot Labs working group by TransNucleaire International.

[aa] 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 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 for accelerating nuclear energy technology deployment. Laboratory-directed R&D funding is vital toward this end. 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 program development activities that can support the test bed.

Program development funding can also be used to support needs assessments, workshops, and proposals and 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 (2024 THROUGH 2028)

As nuclear energy and national and homeland security RD&D needs evolve or grow, new and updated capabilities at MFC will necessary. Although the envisioned capabilities are more than notional, the details and requirements are preliminary and subject to change. This chapter summarizes current thinking on some of those capabilities.

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 (and for nearly every other RD&D program activity at the MFC site), 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 will 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. In addition, FY 2018 studies to determine how best to accommodate a VTR fuel fabrication mission at MFC will include assessment of options for analytical chemistry support of fuel production. The envisioned high-throughput analyses of Pu-bearing fuel for VTR will drive consideration of lab space meeting requirements for security, hazard classification, and equipment layout.

5.2 Engineering-Scale Fuel Fabrication

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.
- The capability to install and operate fuel fabrication equipment needed for campaign-style fuel production at engineering-scale (i.e., production at greater than benchscale), as might be needed to support lead-assembly fabrication of a new LWR fuel technology or first-core fuel production for a first-of-a-kind reactor demonstration.

Progress in FY 2018 on INL's initiative for Advanced Design and Manufacturing gave additional impetus to establishing INL advanced manufacturing capabilities for nuclear fuel. Planned installations and improvements to the Advanced Fuel Facility (AFF) continued in FY 2018, with preparations for relocation of the LENS 3D printing machine and the stereo lithography machine into AFF gloveboxes. A ventilation upgrade is also planned.

A particular need emerging from commercial reactor and fuel developers is engineering-scale production of high-assay low-enriched uranium fuel (HALEU), U-235 enrichments ranging from 5% to 20%. Commercial facilities are currently limited to processing of uranium fuels with 5% or less U-235 enrichment, and those vendors are reluctant to invest in equipment, safety analyses, and licensing for higher enrichments until a sufficient market emerges to ensure return on investment. However, commercial technology developers are not able to demonstrate new fuel fabrication processes or to fuel new demonstration reactors without a supply of HALEU. Therefore, the DOE is seeking to establish HALEU supply and fuel fabrication capability as part of the demonstration platform at INL. Toward this end, INL is evaluating facility options for engineering-scale HALEU fuel fabrication to meet the near-term need, including the repurposing of existing facilities or a new Hazard Category 2 nuclear facility building. Evaluation emphasis is placed on 1) process validation of fuel manufacturing processes at engineering-scale and 2) HALEU fuel production at rates needed to support the aggressive demonstration schedules of microreactor developers seeking expedited reactor demonstration at INL. Existing spaces considered thus far are the FCF Mockup Shop location (MFC-765), Building MFC-798 (Radioactive Liquid Waste Treatment Facility, or RLWTF), The ZPPR Vault/Workroom and Reactor Cell (MFC-775 and MFC-776, respectively), FMF (MFC-704), the EBR-II Dome (MFC-767), and INTEC Building CPP-1634. More-detailed evaluation has determined that the FCF Mockup Shop location, MFC-798, and CPP-1634 can accommodate either a pellet-type fuel line or a metal fuel line (each laid out somewhat generically, to be indicative) scaled for 2 MT HALEU fuel per year. More than one building space is being considered, because near-term needs motivate prompt establishment of at least one fabrication line, with other needs expected to emerge soon thereafter. However, the need appears sufficient to motivate the construction and startup of a new, Hazard Category 2 fuel fabrication building, capable of housing operation of two or more HALEU fabrication lines for campaign-style production efforts supporting reactor demonstration. Regardless of the building configuration chosen, a flexible, reconfigurable engineering-scale fuel fabrication laboratory, in one more buildings, will be key to meeting GAIN objectives for transitioning technology from laboratory to commercial use.

5.3 Reactor Demonstration Building

As part of the INL role as a nuclear technology demonstration platform, the INL is evaluating existing buildings and possible new construction (simple confinement buildings) for housing reactor demonstration projects. As envisioned, such projects could be government projects (e.g., military reactors) or private-public projects to demonstrate a new reactor technology to facilitate licensing and market introduction. The DOE and INL can help reduce the barrier to market introduction by providing green-field locations on the INL site where reactor demonstration projects can be placed to benefit from INL site characterization, the INL controlled emergency-planning zone, and close proximity to INL support infrastructure and personnel. Other projects might need more than a green-field site, benefitting from an empty and available reactor building with connected utility infrastructure and base safety analysis. Some of those reactor projects might even require a qualified containment building, even if only to demonstrate reactor performance to justify to regulators a design and safety basis that does not need a containment. For this purpose, DOE recently cancelled plans for the FY 2019 destruction of the EBR-II, following a feasibility and programmatic evaluation that favored repurposing of the EBR-II Dome (MFC-767) to house reactor demonstration projects (or other uses). Because the Dome was partially (but not irreversibly) prepared for final destruction, selected repairs are needed to restore the Dome's original structural and pressure-containment capabilities and to restore utilities and others functional components (e.g., cathodic protection, internal AC power, an HVAC system, personnel and equipment doors, penetration seals). These repairs, and other actions to improve the Dome's general appearance, are being initiated in FY 2019 and completed to the degree necessary to serve emerging and anticipated missions. Additional improvements will be made as needed, depending on the specific requirements of the next mission.

5.4 Versatile Test Reactor Fuel Fabrication and Disposition

If the Versatile Test Reactor (VTR) is funded for construction and operation, then capabilities for fabricating fresh U-Pu-Zr driver fuel and treatment of used VTR fuel must be built and made operational 3 to 4 years prior to scheduled VTR startup (by 2022, in accordance with the current VTR schedule). The facilities will need to be capable of producing 25 to 40 U-20Pu-10Zr fueled assemblies per year (up to 1.7 MTHM of U-20Pu-10Zr fuel per year) and also treating a similar number of used VTR driver fuel assemblies for final disposition. Selection of a location for the VTR and its associated fuel production and disposition will be evaluated and determined through the VTR NEPA process, and location at INL will be one of the alternatives considered. In support of the concurrent NEPA process for VTR fuel production, current evaluation indicates that FMF and the ZPPR Reactor Cell have sufficient floor space to support VTR fuel production at the necessary, provided that Pu feedstock or U-Pu-Zr ingots can be supplied to INL ready for casting (i.e., no pre-processing of Pu feedstock is necessary). Detailed investigation of used fuel treatment options has not been completed, but a leading option to be considered is electrometallurgical treatment using the same process in FCF currently being applied to treatment of EBR-II spent fuel. Scale-up of the FCF process to accommodate the VTR throughput rate and Pu content will require installation of additional in-cell processing equipment, at a minimum, and possibly a new hot cell located in FCF for disassembly of VTR fuel assemblies prior to fuel introduction into the FCF air cell. Variant processes or other treatment options will be considered for reduced cost and to minimize facility impact.

As described in Section 4.1.1.2, scale-up and demonstration of U-Pu-Zr fuel fabrication at VTR fuel dimensions and production rate remains to be completed. The most expedient means to accomplish that scale-up on a schedule to support VTR operations planning and cost estimation is to design, procure, and install into FMF a developmental injection casting furnace and fuel rod fabrication capability.

5.5 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. 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. This space will be highly complementary with other MFC investments in capability, providing 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 is being explored in FY 2018 in conjunction with other MFC facility modifications and additions to meet needs for NNSA and DOE-NE.

5.6 INL Accelerator Complex

5.6.1 Vision

A multi-purpose experimental facility is envisioned for accelerator-based activities that support isotope production, neutron and photonuclear cross section measurements, radiolysis experiments, and materials characterization. Initially, the complex can be designed to support two high energy pulsed Bremsstrahlung linear accelerators: one for isotope production and one for radiolysis experiments that support fuel cycle chemistries, the Laboratory-owned Pelletron proton accelerator, neutron irradiation and beam-line time of flight (measurement of neutron cross-sections for minor actinides that support the fast neutron test reactor and reactor-based transmutation of higher actinides) and imaging (radiographic and tomographic imaging) capabilities. As envisioned, the complex will house basic radiochemical analysis instrumentation, supporting actinide and transuranic target manufacturing and chemistry purification capabilities. The MFC is a suitable location for the Complex, with close proximity to the Transient Test Reactor (TREAT), the 250-kW NRAD research reactor, a stable and a radioactive electromagnetic isotope separator, and hot-cell chemistry and radiochemical analysis facilities. Concepts for the facility, including potential locations at the MFC site have been informally presented and discussed among NHS and MFC personnel, and the vision appears to be feasible and appropriate for the MFC site, though many details remain to be determined.

5.6.2 Potential Sponsors

Agencies to be approached for support to establish the facility include the Department of Homeland Security (DHS) and the Department of Defense (DOD). The DHS has supported the development and operations of two electromagnetic isotope separators located at MFC. The separator has produced 99.1% enriched ^{134}Ba for certification at NIST. DHS currently supports the isotope separation programs at a funding level of approximately $1M per year. A multi-year isotope separation campaign to produce ^{236}Np is scheduled over the next several years.

The Defense Threat Reduction Agency funds INL to evaluate isotope production methods using high energy bremsstrahlung irradiations at ISU. Expanded isotope production capabilities are needed to meet the demands of the nuclear forensics community. High-energy bremsstrahlung-induced photonuclear reactions were shown to efficiently generate ^{236g}Np, ^{237}U, ^{115}Cd, ^{111}Ag, ^{179}Ta, ^{185}W and a variety of Au and Pt isotopes, all of which are important to the nuclear forensics community. Photo-fission, (γ,xn) and (γ,p) reactions and INL's electromagnetic separation capabilities provide multiple methods to produce carrier free isotopes. INL is currently negotiating with several agencies (Office of Science, and USAF) to establish a production capability to support the long-term nuclear forensics exercise and measurement program.

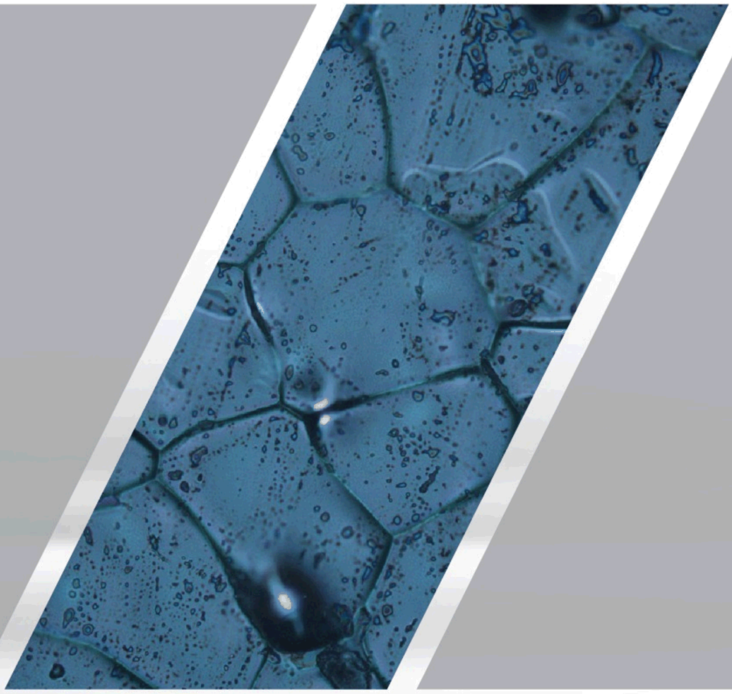
The US Air Force is investing in research and development efforts to improve the production and purity of its radioactive noble gas Xe, Kr and Ar isotopes that support measurement standards for treaty verification measurements by Comprehensive Test Ban Treaty Organization monitoring stations and laboratories. This research will lead to long-term isotope production for rare gas standards.

5.7 ARES - Advanced Radiography Examination Station

An important experimental resource needed to support advanced transient testing research and development at TREAT is an instrument station for performing gamma-ray spectrometry, single-photon emission computed tomography (SPECT) imaging, and high-energy x-ray radiography and tomography imaging of fuel held within transient test devices. Gamma-ray spectrometry scanning will provide valuable 1-dimensional (1-D) information concerning the spatially-dependent power coupling factor (PCF) within test devices. SPECT imaging, based on passive gamma-ray spectrometry, will provide 2-D spatially-dependent PCF information within test devices and important information concerning volatile fission product diffusion and condensation. High-energy x-ray radiography, enabled using bremsstrahlung from a multi-MeV electron accelerator, will enable critical pre-transient inspections to verify test device integrity upon receipt from MFC and equally important post-transient inspections to quantify fuel deformation (e.g., elongation, swelling, fragmentation) and fuel relocation. The high-energy x-ray radiography capability will also support generation of 3-D tomographic images, providing quantitative, high-resolution, spatially-resolved images of intact fuel, failed fuel, failed cladding, and other structural materials in singe-element and multi-element fuel assemblies.

5.8 Pyrochemistry R&D Glovebox Facility

Nuclear materials pyrochemistry R&D of requires use of gloveboxes providing inert atmosphere and containment of radioactive materials. Older and degraded gloveboxes in the Fuels and Applied Science Building (FASB) used for uranium-only pyrochemistry RD&D are being removed in FY 2019 to be replaced with a new glovebox procured in FY 2018. The new Pyrochemistry R&D Glovebox will be available to support current development and troubleshooting of FCF fuel treatment processes, preparation of UCl_3 salt for the FCF electrorefiner, and advanced pyrochemical process development for programs such as the Joint Fuel Cycle Studies program and the Advanced Fuel Cycle program.



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. MATERIALS AND FUELS COMPLEX FACILITY DATA SHEETS

MATERIALS AND FUELS COMPLEX

Advanced Fuels Facility

Fuel and Material Fabrication

General Information:

The Advanced Fuels Facility (AFF) is a 4,920 square-foot facility located at Idaho National Laboratory's Materials and Fuels Complex (MFC). This less-than-hazard-category-3 radiological facility has been repurposed for nuclear fuel fabrication. AFF houses a wide range of material handling and fuel fabrication capabilities used for advanced manufacturing processes. Today, it supports INL's mission as lead nuclear energy lab for the nation.

The scope of operations in AFF involves research and development associated primarily with uranium-bearing fuels and associated surrogate materials in order to increase advanced fuel manufacturing capabilities at MFC.

Equipment and processes in AFF are used to support customers in the Department of Energy's Office of Nuclear Energy and private industry partners. AFF hosts a wide range of INL's new lab-scale capabilities for supporting the nation's need to develop advanced nuclear fuels.

The SPS glovebox provides the capability to press radiological and nonradiological powder compacts while passing electric current through the material being compacted.

Key Instruments:

Basic uses of AFF will include research and development of uranium-bearing fuels associated with the following processes:

- Spark plasma sintering (SPS) furnace system to press radiological/nonradiological powder compacts while passing an electrical current through the material being compacted.
- Advanced manufacturing feedstock preparation in conjunction with an additive manufacturing 3D printer to fabricate material shapes from constituent powders blown across a laser fusion zone.
- Dry bag isostatic press system to manufacture unique material shapes from constituent powders using a high-pressure fluid.
- Crystal growing system to produce lab-sized crystals from a melt of source materials.
- Laser welding system to provide laser weld closures of fuel cladding and capsules.
- Admatec 3D printer to manufacture shapes by fusing additive layers of constituent powders.

For more information

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MATERIALS AND FUELS COMPLEX

Analytical Laboratory

Technical Information

The current mission of the Analytical Laboratory (AL) is to (a) perform chemical, radiochemical and physical measurements; (b) provide nondestructive 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 the Materials and Fuels Complex and Idaho National Laboratory (INL). The mission is accomplished through a broad range of analytical chemistry capabilities.

As a result of this mission, AL receives a wide variety of samples from across INL, as well as from other outside entities. Sample types include liquids, solids, and irradiated/unirradiated fuel related to activities such as research and development, 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 (six - interconnected)
- Gloveboxes
    - Special form
    - Radiochemistry
    - Waste form testing
    - Casting lab
    - Wet prep
    - Fresh fuels
    - Carbon nitrogen oxygen hydrogen
    - Inductively coupled plasma – atomic emission (ICP-AES)
- Fume hoods
- Counting laboratory
    - Gamma
    - Alpha spec
    - Gas proportional counter
    - Scintillation
- Gas mass spectrometer
- Mass spectrometers
    - Inductively coupled plasma (ICP-MS)
    - ICP-AES
    - Multi-collector – inductively coupled plasma (MC-ICP-MS)
    - Thermal ionization
- Furnaces
- Glovebox advanced casting system (GACS) furnace
- Chemistry laboratory
- Bridge crane (5-ton, overhead, loading dock)

For more information

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MATERIALS AND FUELS COMPLEX

Engineering Development Laboratory

Fabrication, Assembly, and Testing of Research, Development, and Production Equipment

Technical Information

The Engineering Development Laboratory is used to fabricate, assemble, mock up, and test various research, development 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 Idaho National Laboratory 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 nondestructive examinations, e.g., radiography and film processing. Two mezzanines, which constitute the second floor, can be moved to accommodate tall equipment (30-foot 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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Experimental Fuels Facility

Technical Information

The Experimental Fuels Facility (EFF) houses a wide range of fuel fabrication capabilities, supporting customers in the Department of Energy's Office of Nuclear Energy and private industry partners through Idaho National Laboratory'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 2,000°C in vacuum, argon, air, hydrogen and nitrogen atmospheres
- Nonradiological 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
- Computer Numerical Control (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

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MATERIALS AND FUELS COMPLEX

Electron Microscopy Laboratory

Post-irradiation Examination

Technical Information

The Electron Microscopy Laboratory (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)

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MATERIALS AND FUELS COMPLEX

Fuels and Applied Science Building

Technical Information

In addition to the Gamma Irradiation Test Loop shown here, FASB contains inert atmosphere gloveboxes used for fuel development, treating waste from other glovebox operations, and testing equipment that will be used in other facilities.

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 (helium 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

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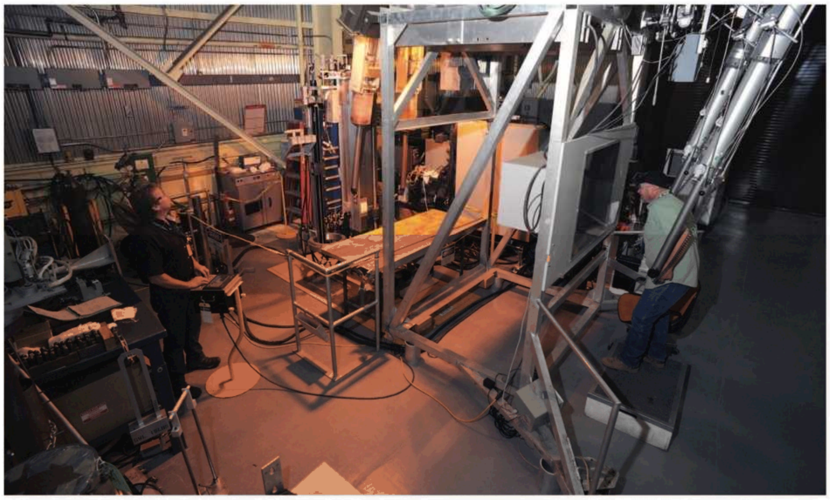
Fuel Conditioning Facility

Technical Information



FCF includes a mock-up shop where technicians can build and test new hot cell equipment before installing it into the hot cell.

The Fuel Conditioning Facility (FCF) supports nuclear energy research and development for the U.S. Department of Energy (DOE) 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 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

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Fuel Manufacturing Facility

Technical Information

Material processing in the special nuclear material (SNM) glovebox is part of an ongoing material disposition program that supports work at INL and other DOE labs.

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

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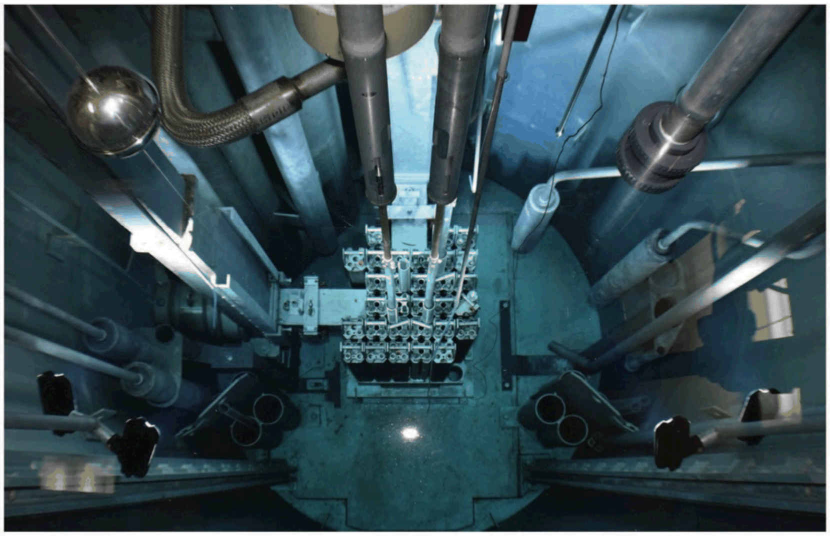
Hot Fuel Examination Facility

Technical Information



The HFEF TRIGA reactor, known as NRAD, enables neutron-radiography irradiations to verify materials behaviors.

The Hot Fuel Examination Facility (HFEF) is a multi-program hot cell facility. There are two adjacent shielded hot cells (the main cell and decontamination cell), a shielded metallography box, an unshielded hot repair area, and a waste-characterization area. HFEF provides shielding and containment for remote examination, processing, and handling of highly radioactive and TRU-bearing materials in its argon-atmosphere hot cells, unshielded labs, support areas and special equipment for handling, examining, and testing of highly radioactive materials.

Basic Capabilities:

- Nondestructive and destructive post-irradiation examination of irradiated samples in two large, heavily shielded hot cells
  - Machining and disassembly of fuel and material experiments
  - Neutron radiography/neutron tomography
  - Visual examination and dimensional examination
  - Gamma scanning/gamma tomography
  - Fission-gas-release measurement
  - Sample preparation for metallography, chemical and isotopic analysis, and optical 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 assemblies up to 13 feet long
- Furnaces for simulating accident conditions at temperatures up to 2,000° C for extended periods of time

Key Instruments:

Nondestructive instruments include:

- 300 kW TRIGA Neutron Radiography Reactor (NRAD)
- Eddy Current probe for measurement of oxide thickness
- Precision gross and isotopic gamma spectrometer
- Element contact profilometer

Destructive instruments include:

- Laser puncture gas collection and analysis system
- Fuel Accident Condition Simulator (FACS) furnace
- Metal waste form furnace

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MATERIALS AND FUELS COMPLEX

Irradiated Materials Characterization Laboratory

Technical Information

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 3D 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

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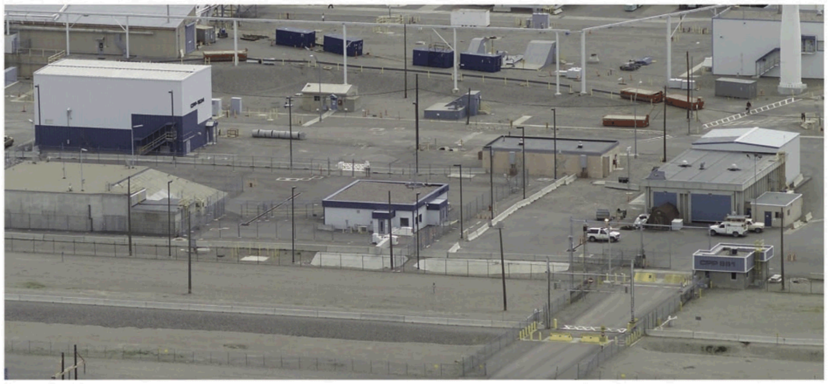
MATERIALS AND FUELS COMPLEX

Idaho Nuclear Technology & Engineering Center

Waste Forms and Separations



Technical Information

The Idaho Nuclear Technology and Engineering Center (INTEC) was established in the 1950s as the Idaho Chemical Processing Plant (ICPP) to recover usable uranium in spent nuclear fuel used in government reactors. In 1998, the plant was renamed INTEC. Expanded capabilities will be determined by the Department of Energy (DOE) funding and repurposing 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 Buildings:

- Material Security and Consolidation Facility (MSCF) - CPP-651
  - MSCF provides 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.
- CPP-653 - Fuel Cycle Research and Development
  - The Material Recovery Project aims to design a material recovery fluidized bed system for scoping tests of the ZIRCEX process.
  - Support Homeland Security in developing decontamination techniques

Key Instruments:

- Hood in CPP-653
- Inductively coupled plasma-mass spectroscopy (ICP-MS) in CPP-653
- Decontamination tent in CPP-653
- ZIRCEX process (under development)

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MATERIALS AND FUELS COMPLEX

Radiochemistry Laboratory

Characterization, Post-irradiation Examination

Technical Information

The Radiochemistry Laboratory (RCL) houses several laboratories for aqueous separations science and technology, actinide chemistry, radiochemistry research, and metals and isotopic analyses on radioactive materials. The RCL contains two radiochemistry laboratories, an instrumentation laboratory, a counting laboratory and a glovebox laboratory, as well as necessary chemical and source storage areas. RCL supports work from various outside entities and federal agencies, including the Department of Homeland Security and the Department of Energy.

Basic Capabilities:

- Analysis and characterization of nuclear fission products using aqueous chemistry
- Radioisotope separation
- Element dissolution of radioisotopes using advanced chemistry techniques
- Ability to create unique organic solvents for use in separations type work

Key Instruments:

- Counting Laboratory (gamma counters, liquid scintillation, nuclear magnetic resonance)
- Gas chromatograph/ion chromatograph
- Spectrometers (inductively coupled plasma-mass spectrometer and inductively coupled plasma-optical emission spectrometer)
- Spectrophotometer
- Argon separations glovebox
- Air separations gloveboxes
- Fume hoods
- Furnaces

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MATERIALS AND FUELS COMPLEX

Sample Preparation Laboratory

Post-irradiation Examination

Technical Information

The Sample Preparation Laboratory (SPL) will, beginning in 2022, 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

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MATERIALS AND FUELS COMPLEX

Transient Reactor Test Facility

Technical Information

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 was placed on standby in 1994. TREAT was restarted in 2018 and is currently supporting experiment programs. TREAT provides a valuable capability to support efforts to develop accident-tolerant fuels for light-water reactors as well as the advanced reactor fuels, both of which will allow nuclear power to remain the primary source of emission-free baseload energy in the future.

Basic Capabilities:

- High-intensity (20 GW), short-duration (<100 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 suitable to instrument experiments during testing

17-50292 TREAT R1

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Zero Power Physics Reactor Facility

Technical Information

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 the Materials and Fuels Complex and other Idaho National Laboratory locations.

Basic Capabilities:

- Transuranic and enriched-uranium materials storage
- Transuranic and enriched-uranium material inspection/repackaging
- Transuranic and enriched-uranium material handling for experiments/training

Key Instruments:

- Transuranic surveillance glovebox line
- Vault storage
- Cell area that can be reconfigured as necessary for experiment/training activities

The Zero Power Physics Reactor was placed in nonoperational standby in 1992, and has since been dismantled, which frees the space for nuclear material storage, inspection, and repackaging.

ZPPR operators performing material inspections in the transuranic surveillance glovebox.

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