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Materials and Fuels Complex FY-22 – FY-26 Five-Year Mission Strategy

June 2022

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FY-22 – FY-26
Five-Year Mission Strategy

June 2022

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EXECUTIVE SUMMARY

The Idaho National Laboratory (INL), through its designated mission of advancing innovative nuclear energy solutions, is actively engaged in the research, development, demonstration and deployment of advanced nuclear technology. Key to the success of INL's mission is the Materials and Fuels Complex (MFC), the only complex in the U.S. that hosts a world-class assemblage of facilities, capabilities and instruments for handling, testing, and characterizing nuclear fuel and radioactive materials. Driven by its mission/vision of "Engineering and Experiments that Drive the World's Nuclear Energy Future," MFC is at the center of INL's – and indeed the Department of Energy's – advanced nuclear technology development initiatives, providing essential capabilities such as research-scale high-assay low-enriched uranium (HALEU) fuel production, reactor demonstration facilities, post-irradiation examination, and transient irradiation testing. Furthermore, MFC provides an ideal environment for test beds that are utilized for research, development and demonstration (RD&D) activities on used fuel treatment, nuclear non-proliferation, forensics, and nuclear power sources used for space exploration missions conducted by the National Aeronautics and Space Administration (NASA).

To accomplish the strategic objectives of the INL mission and prepare for upcoming RD&D needs, MFC will remain focused on delivering the following critical-to-success outcomes during the FY-22 – FY-26 timeframe:

1. Enable and accelerate the demonstration, testing, and operational deployment of advanced reactors, working in close collaboration with the National Reactor Innovation Center (NRIC), NASA and private partners
2. Fabricate and supply innovative nuclear fuels for demonstration and test reactors, and advance technologies and processes for the treatment of used fuel
3. Perform irradiation, analysis and testing of fuels and materials benefiting nuclear applications ranging from improved performance of operating reactors to radioisotope production
4. Provide components and/or technology to meet radioisotope power generation needs
5. Fulfill environmental stewardship commitments, including support for achieving net-zero carbon emissions on the INL site by 2031

The strategy to achieve these outcomes consists of:

- Striving for operational excellence and best-in-class safety performance via the execution of the MFC Operations Management Improvement strategy
- Continuing to develop the scientific and engineering expertise that underpins the MFC core competencies
- Executing the Five-Year Investment Strategy plan,
- Continuing to implement the MFC User Facility model

- Collaborating actively with other INL directorates, government agencies, private industry partners, other national laboratories, and academia to grow the MFC user base.

Significant progress on each of the five critical outcomes was accomplished through this strategy during the past year. Maintaining this momentum requires sustained discipline in strategy execution, focus on delivering the critical outcomes, and ensuring that risks to mission are effectively managed. By doing so, MFC will continue its pivotal role in helping DOE-NE and INL supply the world with safe, affordable, clean and reliable energy, combat climate change, and regain U.S. leadership in advanced reactor technology.

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1. INTRODUCTION

The Materials and Fuels Complex (MFC) is home to expert personnel and a unique infrastructure that serve the mission of the Idaho National Laboratory (INL). INL is a multi-program Department of Energy (DOE) laboratory. It is tasked by the DOE Office of Nuclear Energy (DOE-NE) with the core responsibility for leading and conducting nuclear energy research, development, and demonstration (RD&D) in support of DOE-NE's mission to advance nuclear energy science and technology to meet U.S. energy, environmental, and economic needs.[a] INL also contributes significantly to the advancement of national and homeland security-related technologies as well as technologies for non-nuclear energy generation. These responsibilities are all reflected in the mission and vision statements of INL:

- *Vision*: INL will change the world's energy future and secure our nation's critical infrastructure
- *Mission*: Discover, demonstrate, and secure innovative nuclear energy solutions, other clean energy options, and critical infrastructure.

The nuclear energy responsibility of the INL mission continues to benefit from strong bipartisan support for the role of nuclear energy in in reducing greenhouse gas emissions to combat climate change. Furthermore, the invasion of Ukraine by Russia exposed the vulnerability of relying on Russia for the supply of a significant share of the uranium needs of the U.S. nuclear industry. It also demonstrates the danger to national security posed by ceding U.S. leadership in nuclear technology development to countries such as Russia and China. The extensive bipartisan support for nuclear energy is driving federal investment in public-private partnerships aimed at maintaining the viability of the existing commercial nuclear reactor fleet in the U.S., and accelerating the deployment of advanced reactor designs that produce cost-competitive energy while continuing to subscribe to strong non-proliferation, safety, and security standards. In parallel, advanced reactor technology development continues to attract considerable investment from private sources.

These trends have resulted in some notable recent developments, namely:

- As part of the Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act) enacted in November 2021, the DOE will institute a $6 billion Civil Nuclear Credit (CNC) program to bolster the existing U.S. nuclear fleet, thus helping preserve the largest source of carbon-free electricity in the U.S.
- As part of the same Bipartisan Infrastructure Law, $2.5 billion in funding was allocated to continue the Advanced Reactor Development Program (ARDP). Under the ARDP, two advanced reactor designs, TerraPower's Natrium sodium-cooled fast reactor and X-Energy's Xe-100 high-temperature gas-cooled reactor, are progressing towards the demonstration phase. Furthermore, the ARDP is supporting five other companies towards risk reduction efforts in preparation for future demonstrations, including the Molten Chloride Reactor Experiment led by Southern Company Services.
- The U.S. Department of Defense (DOD), acting through the Strategic Capabilities Office (SCO), issued a Record of Decision (ROD) in April 2022 for the Final Construction and Demonstration of a Prototype Mobile Microreactor Environmental Impact Statement (Final EIS).[b] SCO has decided to implement the Proposed Action (the preferred alternative) as described in the Final EIS, which is to fabricate the prototype mobile microreactor and reactor fuel at existing off-site commercial facilities and demonstrate the microreactor at the INL site. The ROD is in support of Project Pele, which has a timeline of demonstrating a mobile microreactor by 2024.

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a. DOE Office of Nuclear Energy: Strategic Vision (January 2021).

b. Department of Defense, Office of the Secretary: "Record of Decision for the Final Construction and Demonstration of a Prototype Mobile Microreactor Environmental Impact Statement"; available at https://www.mobilemicroreactoreis.com/documentation.aspx

- With funding from the DOE Microreactor program, the MARVEL reactor remains on track to be the world's first contemporary microreactor fueled with high-assay low-enriched uranium (HALEU) to be built and demonstrated at MFC's Transient Reactor Test Facility.
- With funding from the National Reactor Innovation Center (NRIC), progress continues on repurposing the EBR-II dome and the Zero Power Physics Reactor (ZPPR) cell – both located at the MFC - into advanced reactor demonstration test beds. Critical Decision-0 (CD-0) was approved for the Safeguards Category I Advanced Reactor Demonstration Test Bed, to be located in the ZPPR cell, in March 2022.

As the designated nuclear energy laboratory for the DOE, INL is heavily engaged in these activities which will not only reestablish the U.S. as the leader in nuclear technology but also provide other countries[c] looking to reduce their carbon footprint with a clean, affordable, and safe energy choice.

As a source of expertise, facilities, and test beds related to the nuclear fuel cycle and nuclear materials development, MFC has an instrumental role in those INL activities involving nuclear energy RD&D. The capabilities available at MFC today have evolved from MFC's historical mission, and that context is summarized here.

1.1 MFC History

When the National Reactor Test Station was established in Idaho in 1949 to be a remote location for the testing of reactors, Argonne National Laboratory built and operated the Experimental Breeder Reactor, later known as Experimental Breeder Reactor I or EBR-I, there. Argonne established an Idaho Division and located other higher-risk facilities at the EBR-I site (rather than in the more populated Argonne location in Chicago suburbs). When the Atomic Energy Commission and Argonne agreed EBR-II would be built, the EBR-II site was selected to be closer to Idaho Falls, and Argonne had new facilities built there as well, such as the Transient Reactor Test Facility (TREAT) and the Analytical Laboratory. EBR-II and the associated Fuel Cycle Facility were built to demonstrate reprocessing of fast reactor spent fuel into new fuel recycled back into the reactor and to demonstrate reliable power generation from a fast reactor. That initial mission was accomplished during 1965-1969, after which the EBR-II mission evolved to irradiation testing, operational testing, and safety testing.[d] The desire to reduce EBR-II's operating cost as an irradiation facility led to new technology developments that are now central to many fast reactor concepts being proposed by private developers. Specifically, the burnup capability of metal fuel was improved to match that of mixed oxide fast reactor fuel initially as a means to reduce EBR-II fuel cost, and the advantages of a metal-fueled, sodium-cooled fast reactor with a pool-type primary system were demonstrated from a program initially intended to determine how to economically ensure EBR-II's operating safety.

Additional facilities were built at the EBR-II site, which became known as Argonne National Laboratory - West (ANL-W), most directly supporting the EBR-II irradiation testing mission, such as the Hot Fuel Examination Facility (HFEF), the Fuel Assembly and Storage Building (FASB), and the Fuel Manufacturing Facility (FMF). Other facilities otherwise supporting U.S. fast reactor development were placed there, such as the Zero Power Plutonium Reactor. After the shutdown of EBR-II, TREAT, and the Zero Power Plutonium Reactor in 1994, the ANL-W site served varied purposes, primarily nuclear materials stabilization but also some smaller research programs that reached beyond the historic fast

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c. Internationally, new nuclear plants are being actively explored in countries throughout Europe (ex: United Kingdom, France, Poland, Czech Republic), the Middle East (ex: Jordan, Egypt, Saudi Arabia), and Africa (ex: South Africa, Nigeria).

d. For additional information on the history of EBR-II and the Fuel Cycle Facility see Leonard J. Koch, *Experimental Breeder Reactor-II (EBR-II): An Integrated Experimental Fast Reactor Nuclear Power* Station (Argonne, IL; Argonne National Laboratory, n.d.), 1-1; Catherine Westfall, *Civilian Nuclear Power on the Drawing Board: The Development of Experimental Breeder Reactor-II,* Argonne National Laboratory report ANL/HISST-1-03/6 (Argonne, IL; Argonne National Laboratory, n.d.), 18; Charles E. Stevenson, *The EBR-II Fuel Cycle Story* (La Grange Park, IL; American Nuclear Society, 1987), 13.

reactor development mission and used site facilities for new purposes. During that period, the Space and Security Systems Power Facility (SSPSF) was built for assembly of Pu-238 radioisotope power sources, again broadening the programmatic capability of the site. With the establishment of INL in 2005, the newly renamed Materials and Fuels Complex benefitted from a mission focused again on nuclear energy RD&D but addressing a broad range of nuclear energy technologies. INL continued and expanded the effort to transition and re-equip legacy facilities for broader capabilities. The need for the Irradiated Materials Characterization Laboratory (IMCL) was articulated and the facility built in 2016. TREAT was restarted in 2017 with the mission to support fuel safety testing for a variety of reactor types. Through these transitions over 20 years, MFC expanded on a set of core capabilities and facilities that include fuel manufacturing, post-irradiation examination of fuel and structural materials, fuel reprocessing and waste disposal.[e] The investment in MFC by DOE-NE and INL accelerated in the 2017 – 2020 timeframe in expectation of MFC's enabling role in the RD&D of next-generation reactor technologies scheduled for deployment in the 2020s and 2030s. A recent photograph of the MFC site along with a map showing the location of key facilities are shown in Figure 1.

1.2 MFC Current State

The historical infrastructure of MFC combined with more recent upgrades and installations have resulted in a world-class assemblage of facilities, capabilities, and instruments for handling, testing, and characterizing radioactive materials such as nuclear reactor fuels, components, and structural materials. The principal source of investment in MFC is DOE-NE, as MFC primarily serves the nuclear energy science and technology advancement mission of DOE-NE. Users from other DOE and national security programs, NASA, private industry and academia also make use of the capabilities and radioactive materials available at MFC.

The mission/vision of MFC, "Engineering and Experiments that Drive the World's Nuclear Energy Future," is served by resources such as:

- The largest inert-atmosphere hot cell facilities in the U.S.
- A uniquely capable transient neutron-irradiation test reactor (TREAT)
- Capability to fabricate at bench-scale nearly all fuel types of interest to reactor designers and developers
- Facilities and equipment to produce high-assay low-enriched uranium (HALEU) fuel forms on an engineering scale (Fuels and Applied Science Building [FASB], Fuel Manufacturing Facility [FMF], Fuel Conditioning Facility [FCF])
- Facilities for treatment, recycling and storage of used fuel
- World class characterization capabilities at the Irradiated Materials Characterization Laboratory (IMCL), Electron Microscopy Laboratory (EML) and Analytical Research Laboratories Extensive suite of gloveboxes for handling transuranic and ceramic fuel, special nuclear materials and radioisotope power systems assembly
- Multiple furnaces with temperature capability up to 2,000°C in vacuum, argon, air, hydrogen, and nitrogen atmospheres (Experimental Fuels Facility)
- NRAD, a 250-kW TRIGA reactor optimized for neutron radiography
- The EBR-II dome and Zero Power Physics Reactor (ZPPR) cell that are being repurposed for hosting private-sector advanced reactor demonstration projects.

e. The Fuel Conditioning Facility at MFC was selected as an American Nuclear Society Historic Landmark on September 3, 2020, for its Historic Work Recycling EBR-II Used Nuclear Fuel.

Figure 1. Photograph of the INL Materials and Fuels Complex (top) and MFC map showing key facilities (bottom).

These MFC capabilities, supported by a dedicated staff of research and operations personnel, provide a platform for conducting RD&D activities related to nuclear energy technology. Examples of ongoing and planned activities at MFC include the following:

- Advanced reactor demonstration and testing
- Fuel fabrication for advanced reactors
- Irradiation, analysis and testing of fuel and structural reactor materials
- Radioisotope power systems for space missions
- Treatment of used fuel for recycling and disposal.

A summary of MFC's resources is provided in Table 1. Major accomplishments at MFC during the preceding year include:

- Completed a 3D reconstruction of irradiated TRISO fuel compact - The TRISO fuel compact is the first irradiated engineering scale fuel element to be imaged in 3D at high resolution, thanks to a new X-ray imaging technique.
- Achieved world's first fabrication of Uranium-10%Zirconium (U-10Zr) fuel pellets by additive manufacturing - Metallic U-10Zr fuel pellets were successfully 3D-printed, a world's first, using the powder-fed directed energy deposition additive manufacturing technique in the Advanced Fuels Facility (AFF).
- Delivered the Primary Coolant Acceptance Test (PCAT) assembly - The first-of-a-kind PCAT assembly was fabricated by the MFC Fabrication shop, and was an important milestone in the continued development of the Microreactor Applications Research Validation and Evaluation (MARVEL) reactor.
- Completed Sirius-2b transient test series in the TREAT facility as part of the NASA Space Nuclear Propulsion Program - These tests demonstrated that a high-temperature ceramic-metallic (cermet) fuel (molybdenum-tungsten/uranium mononitride) would maintain structural integrity under the ramp rates and operational temperatures expected during the startup of a nuclear propulsion reactor.
- Mars 2020 spacecraft and Perseverance rover landing - Following a seven-month journey, Perseverance touched down on Mars on February 18, 2021. Powered by a multi-mission radioisotope thermoelectric generator (MMRTG), this rover is exploring the red planet seeking signs of life.
- Completed milestone for shipment of excess Special Nuclear Material (SNM) - MFC personnel successfully shipped excess transuranic sources and legacy fuel fabrication scrap offsite, helping meet a Program Guidance milestone set by the Department of Energy's Idaho Facilities Management to complete at least one offsite shipment of excess special nuclear material.
- Added new capability to Hot Fuel Examination Facility (HFEF) to produce refabricated fuel rodlets – This capability enables the harvesting of material from previously irradiated fuel experiments to make refabricated fuel rodlets, which can then be utilized for the transient testing needed to support innovative reactor fuel development and qualification.
- Added new Gas Mass Spectrometer to analytical chemistry capability: A new quadrupole mass analyzer, used for the analysis of gaseous samples, has been installed in the Analytical Research Laboratory. This instrument can generate mass spectra faster than sector field mass spectrometers, and is equipped for both bulk and trace level detection of gases.

Table 1. MFC at a Glance.

1,229 employees onsite • 736 MFC • 493 other support organizations
29 mission facilities, including the following 21 nuclear & radiological facilities:
• Hazard Category 2: – Fuel Conditioning Facility (FCF) – Fuel Manufacturing Facility (FMF) – Hot Fuel Examination Facility (HFEF) – Irradiated Materials Characterization Laboratory (IMCL) – Material Security & Consolidation Facility (MSCF – INTEC) – Neutron Radiography Reactor (NRAD) – Radioactive Scrap & Waste Facility (RSWF) – Remote-Handled Low-Level Waste Disposal Facility (RHLLW) – Sample Prep Lab (SPL, future facility) – Space & Security Power Systems Facility (SSPSF) – Transient Reactor Test (TREAT) Facility – Zero Power Physics Reactor facility (ZPPR)
• Hazard Category 3: – Analytical Laboratory (AL)
• Less than Hazard Category 3: – Advanced Fuels Facility (AFF) – Electron Microscopy Laboratory (EML) – Experimental Fuels Facility (EFF) – Fuels and Applied Science Building (FASB) – Outside Radioactive Storage Area (ORSA) – Radioactive Liquid Waste Treatment Facility (RLWTF) – Radiochemistry Laboratory (RCL) – Sodium Components Maintenance Shop (SCMS)

1.3 Purpose

The purpose of this Mission Strategy plan is to identify the critical-to-success outcomes required from MFC during the FY-22 – FY-26 timeframe in support of the INL and DOE missions, as well as the mission/vision of MFC, namely "Engineering and Experiments that Drive the World's Nuclear Energy Future." The plan also describes the underlying strategic activities needed to accomplish these critical outcomes and includes a section on the risks and challenges related to mission execution. The MFC Mission Strategy plan references the DOE-NE Strategic Vision and the INL Laboratory Plan.

The MFC Five-Year Mission Strategy plan is complementary to the MFC Operations Management Improvement (OMI) Strategy and the MFC Five-Year Investment Strategy. The relationships between these documents can be summarized as follows:

- The MFC Five-Year Mission Strategy defines the MFC outcomes and strategies required to meet DOE and INL Laboratory objectives identified in the INL Laboratory Plan and DOE-NE programs.
- The MFC Five-Year Investment Strategy defines infrastructure needs, cost, and timeline necessary to meet the MFC mission strategy.
- The OMI Strategy identifies barriers to MFC success in terms of people, processes, and additional equipment needs not identified in the investment strategy. The OMI Strategy defines actions and timelines to remove those barriers.

Last, annual budget development is done through the Integrated Resource Planning Tool which identifies and allocates resources and funding required to meet mission objectives.

2. MFC ORGANIZATION

A current version of the MFC organization chart is shown in Figure 2. The MFC divisions, led by the Associate Laboratory Director (ALD), are grouped into two categories: Research and Production and Engineering, Operations, and Maintenance. The science mission of MFC is carried out primarily by the Research and Production Divisions. The Engineering/Operations/Maintenance Divisions ensure that MFC facilities are properly operated, maintained and upgraded to fulfill their respective mission functions in a manner that complies fully with applicable safety and environmental regulations. Table 2 shows the breakdown of the MFC divisions according to these two categories. Brief descriptions of the divisions are provided in Appendix A.

Figure 2. MFC Organization Chart

Table 2. MFC Divisions.

Engineering/Operations/Maintenance[a]	Research/Production[b]
MFC Business	Analytical Research Laboratories
MFC Engineering	Characterization and Advanced PIE
MFC Maintenance, Infrastructure & Fabrication	Fuel Fabrication & Nuclear Material Management
MFC Operations	MFC Production Facilities
MFC Projects	Space Nuclear Power and Isotope Technologies
MFC Safety & Compliance	Transient Reactor Test Facility (TREAT)

a. Includes the MFC Chief Operating Officer.
b. Includes the MFC Chief Scientist.

3. MFC FACILITIES

As discussed in Section 1, MFC's facilities and infrastructure support a comprehensive range of experiments and testing related to nuclear technology RD&D. Information on several MFC facilities is provided in Appendix B. Descriptions of some facilities are also available on the web, and the applicable website links are listed in Table 3. Figure 3 shows how the extensive MFC capabilities are mapped to individual facilities.

Table 3. Principal MFC facilities (website links are listed when available).

Research/Production Division	Facilities
Analytical Research Laboratories	Analytical Laboratory: https://mfc.inl.gov/SitePages/Analytical%20Laboratory.aspx#mfc-instruments Radiochemistry Laboratory
Characterization and Advanced PIE	Electron Microscopy Laboratory: https://mfc.inl.gov/SitePages/Electron%20Microscopy%20Laboratory.aspx Irradiated Materials Characterization Laboratory: https://mfc.inl.gov/SitePages/Irradiated%20Materials%20Characterization%20Laboratory.aspx Sample Preparation Laboratory (under construction): https://mfc.inl.gov/SitePages/Sample%20Preparation%20Laboratory.aspx
Fuel Fabrication & Nuclear Material Management	Advanced Fuels Facility (AFF) Experimental Fuels Facility: https://mfc.inl.gov/SitePages/Experimental%20Fuels%20Facility.aspx Fuel Manufacturing Facility: https://mfc.inl.gov/SitePages/Fuel%20Manufacturing%20Facility.aspx Fuels and Applied Science Building: https://mfc.inl.gov/SitePages/Fuels%20and%20Applied%20Science%20Building.aspx Zero Power Physics Reactor: https://mfc.inl.gov/SitePages/Zero%20Power%20Physics%20Reactor.aspx
MFC Production Facilities	Fuel Conditioning Facility: https://mfc.inl.gov/SitePages/Fuel%20Conditioning%20Facility.aspx Sodium Components Maintenance Shop (SCMS) Radioactive Scrap and Waste Facility (RSWF) Remote Handled Low Level Waste (RHLLW) Facility
Post-Irradiation Examination	Hot Fuel Examination Facility: https://mfc.inl.gov/SitePages/Hot%20Fuel%20Examination%20Facility.aspx
Space Nuclear Power and Isotope Technologies	Space and Security Power Systems Facility: https://inl.gov/research-program/space-power-systems/
Transient Reactor Test Facility	Transient Reactor Test Facility (TREAT): https://mfc.inl.gov/SitePages/Transient%20Reactor%20Test%20Facility.aspx https://transient.inl.gov/SitePages/Home.aspx

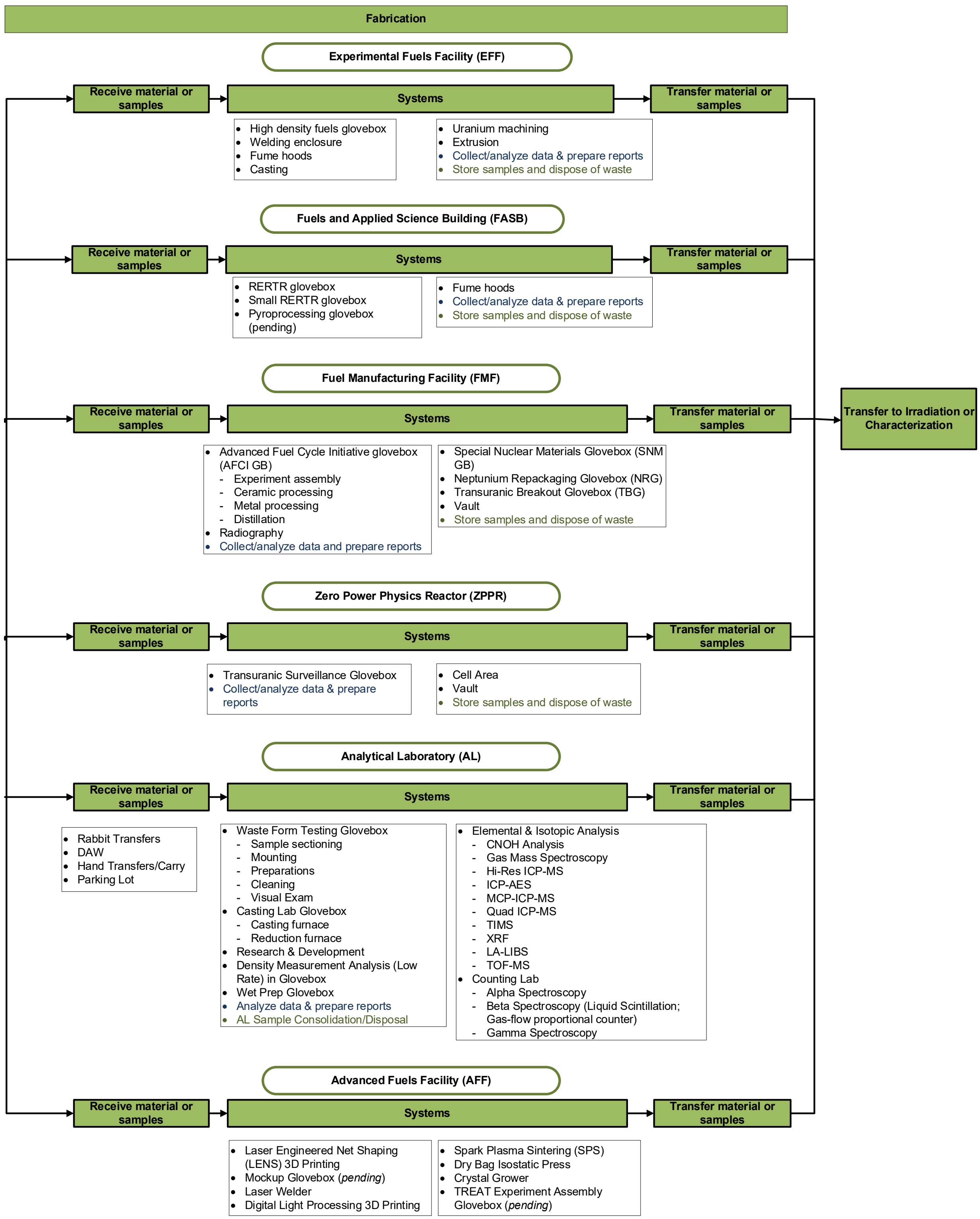

Figure 3a. Existing nuclear RD&D capabilities at MFC: Fabrication.

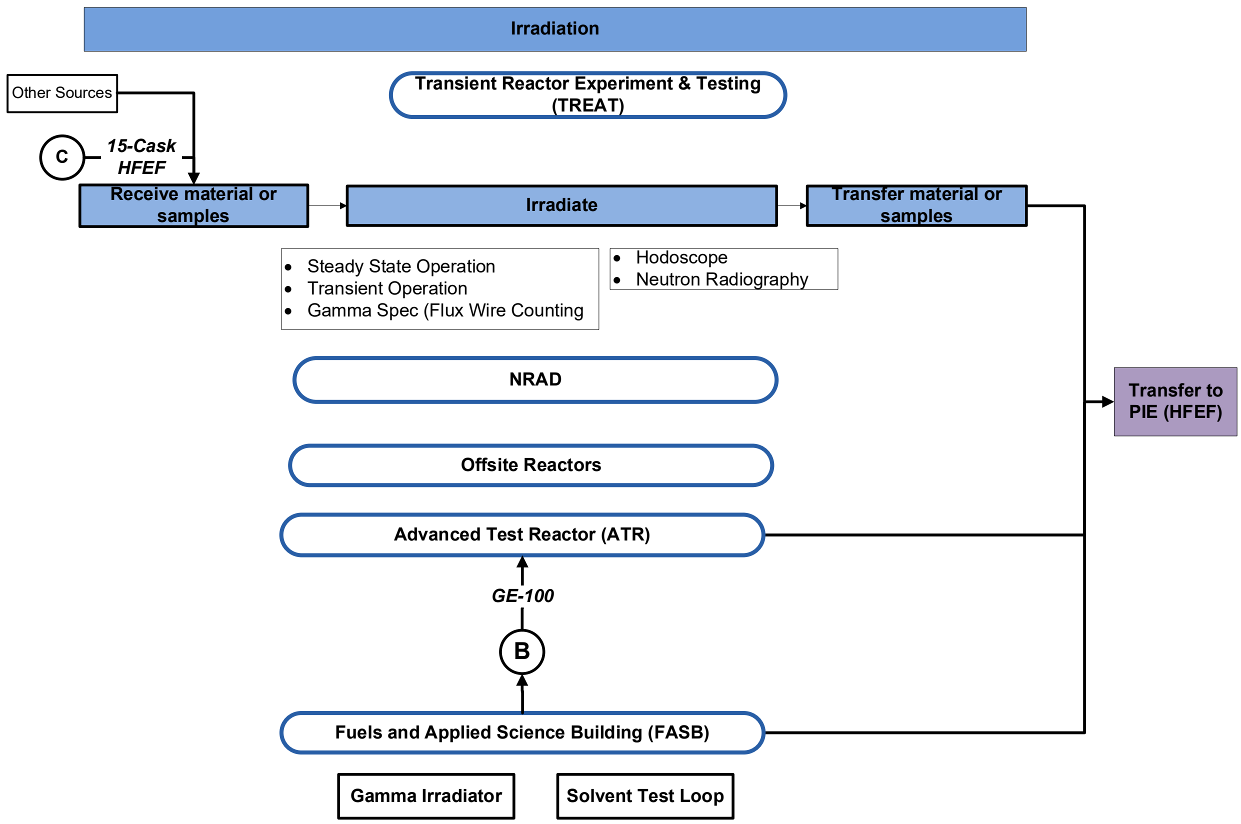

Figure 3b. Existing nuclear RD&D capabilities at MFC: Irradiation.

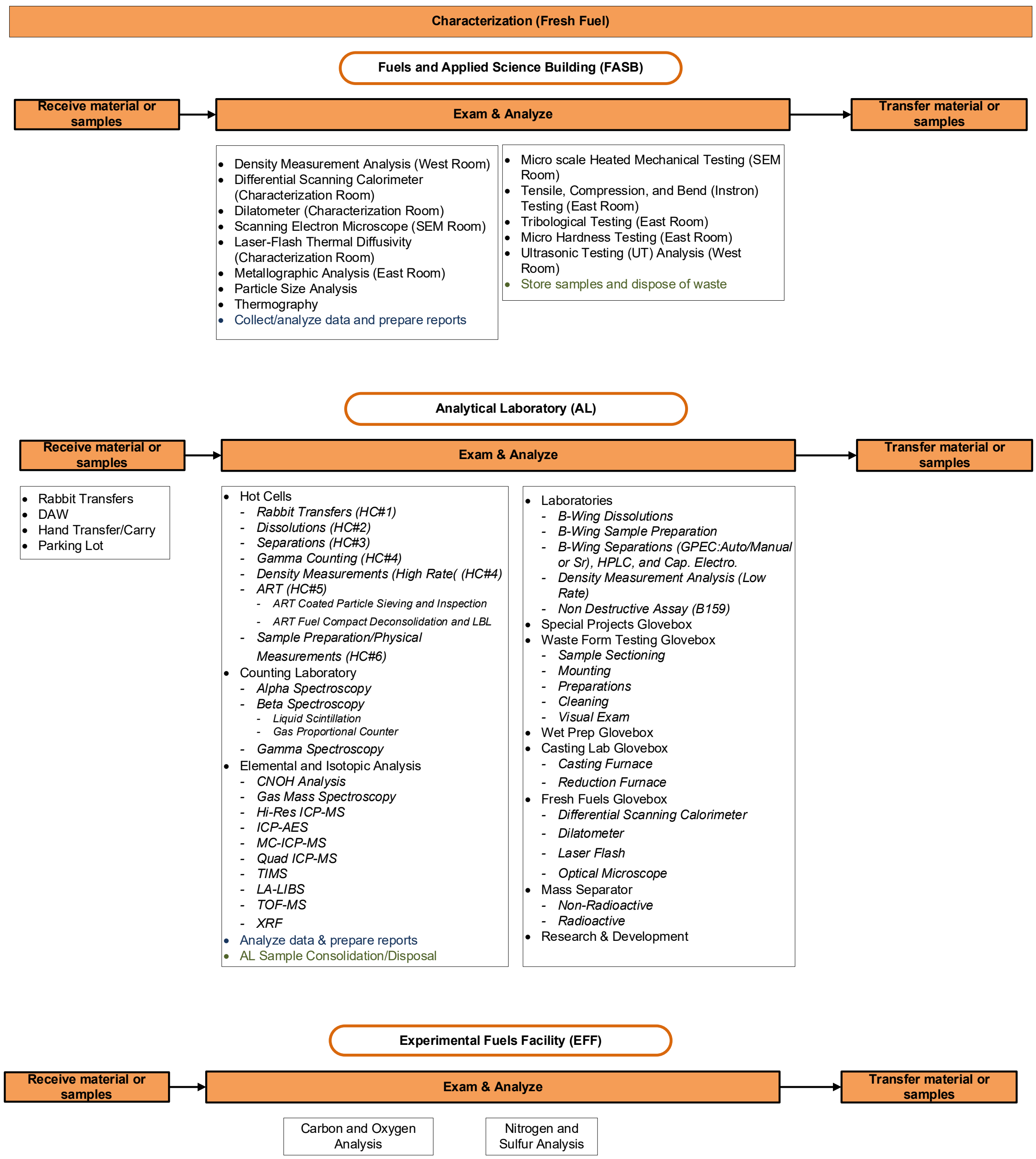

Figure 3c. Existing nuclear RD&D capabilities at MFC: Fresh Fuel Characterization.

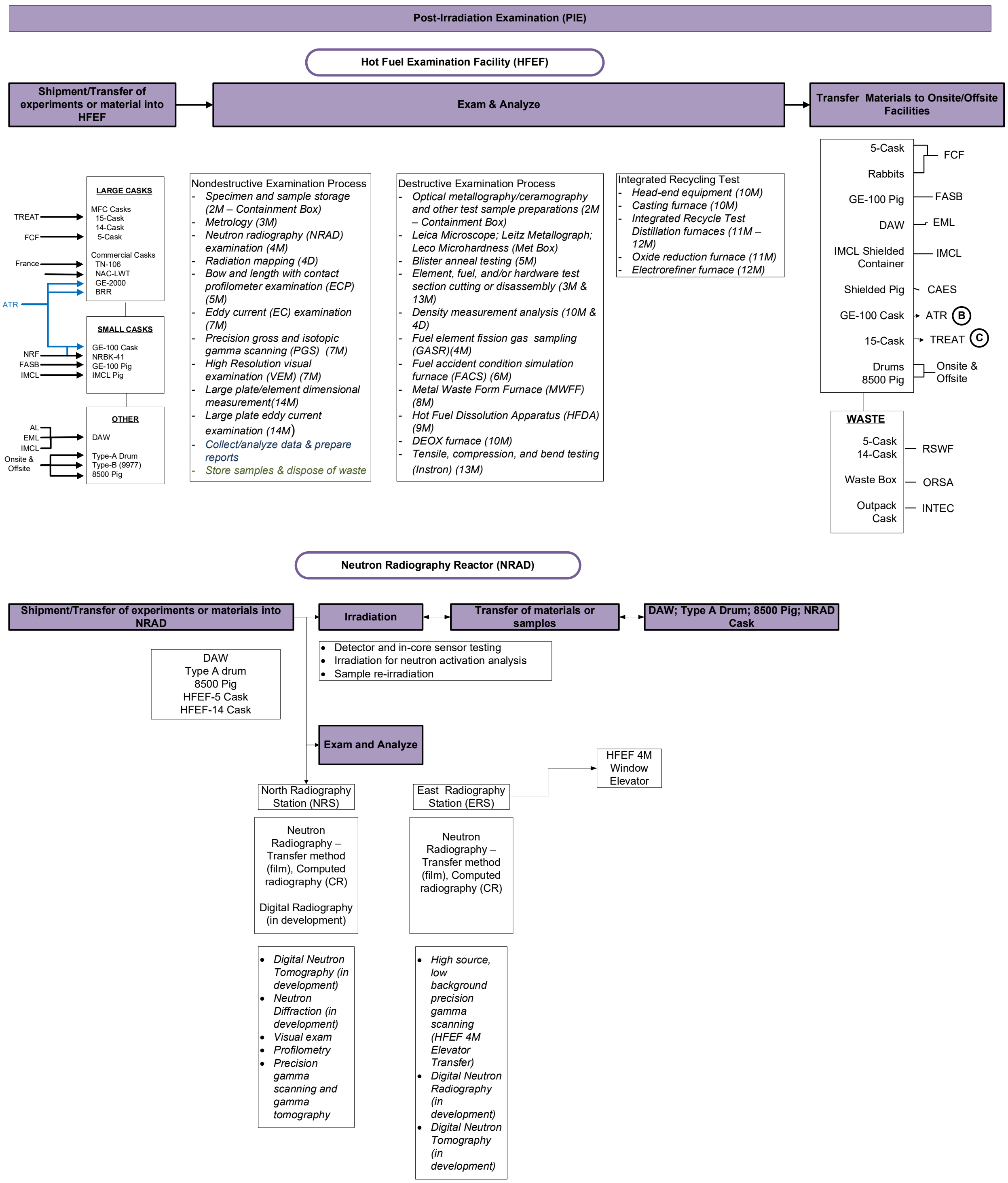

Figure 3d. Existing nuclear RD&D capabilities at MFC: PIE at HFEF/NRAD.

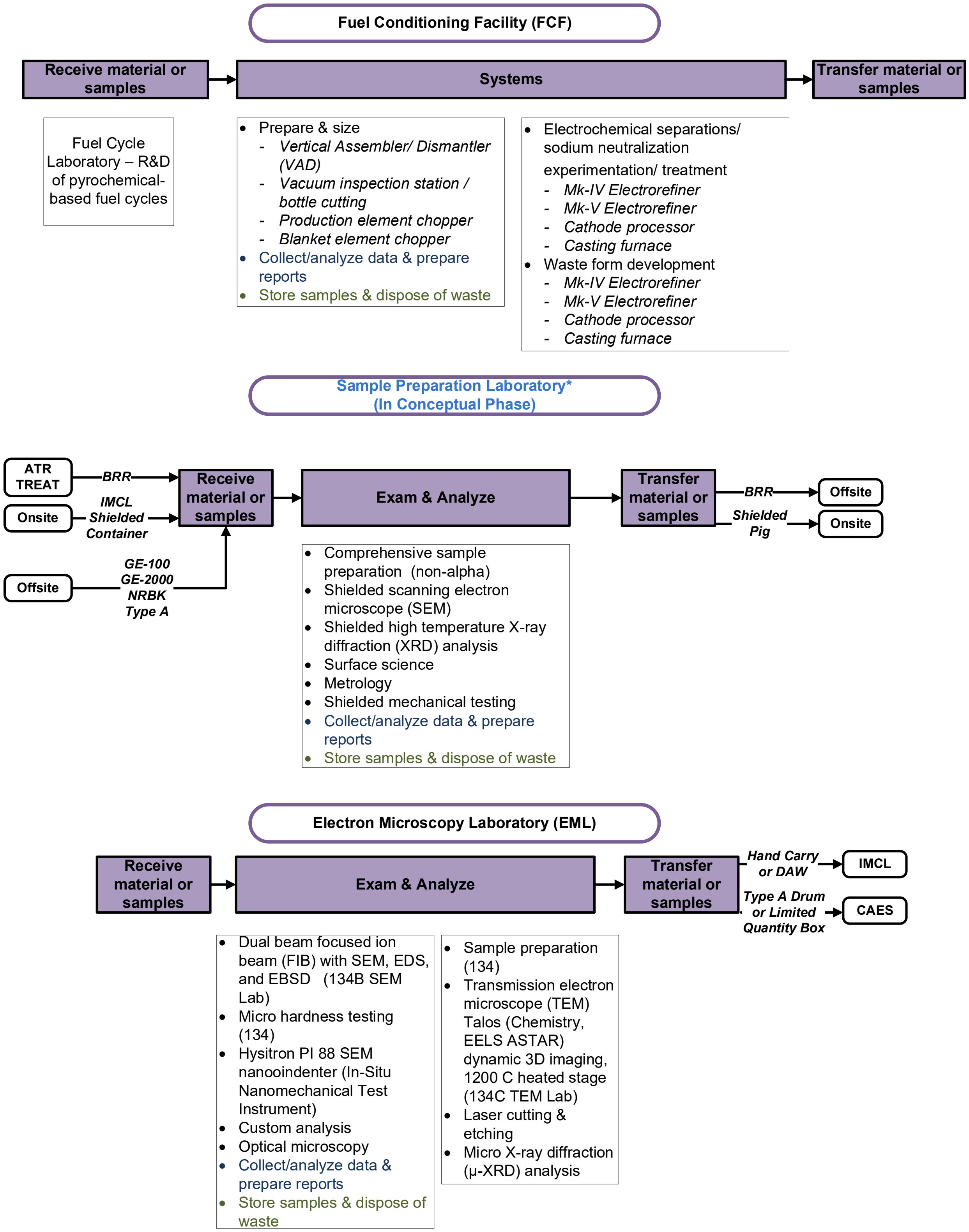

Figure 3e. Existing nuclear RD&D capabilities at MFC: PIE at FCF, SPL (planned), and EML.

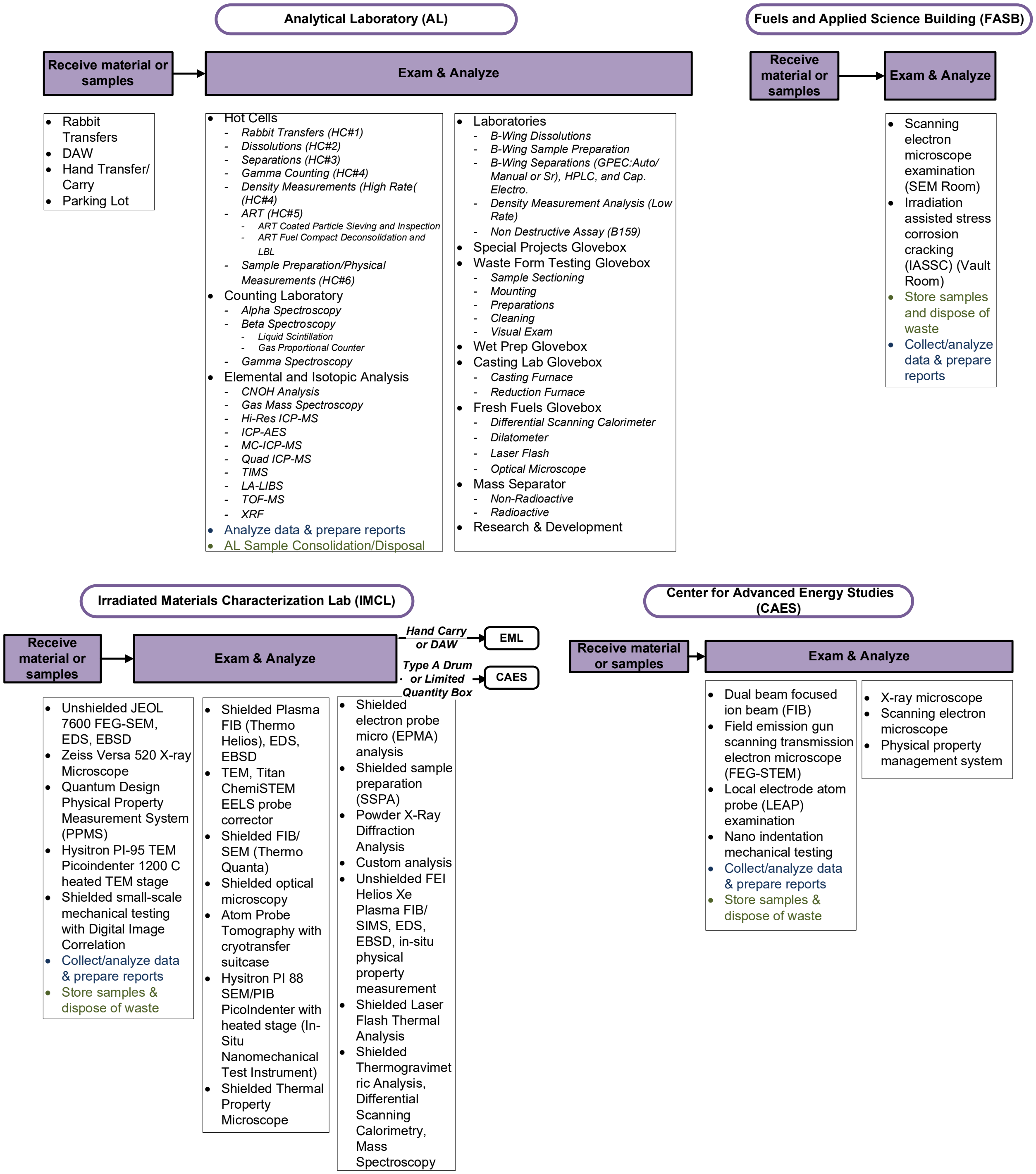

Figure 3f. Existing nuclear RD&D capabilities at MFC: PIE at AL, FASB, IMCL, and CAES.

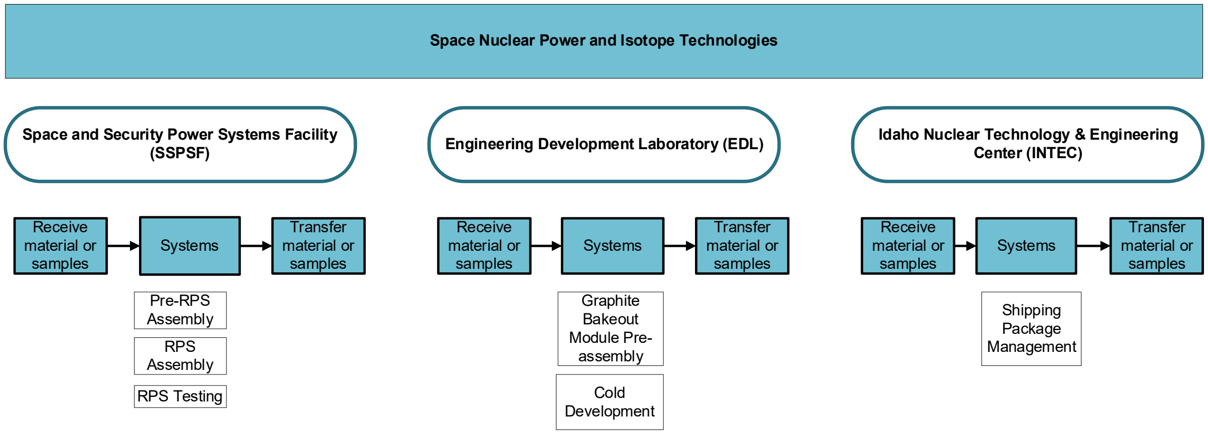

Figure 3g. Existing nuclear RD&D capabilities at MFC: SSPSF, EDL, and INTEC.

4. DESCRIPTION OF MFC CORE COMPETENCIES

MFC offers the following core competencies:

- Nuclear fuels fabrication
- Fuel characterization
- Materials characterization: Radiation damage in cladding and reactor components
- Fuel recycling and nuclear material management
- Transient irradiation testing
- Radioanalytical chemistry
- Space nuclear power
- Focused basic research
- Isotope production
- Nuclear nonproliferation and nuclear forensics.

A short description of each of these competencies is provided in this section. Additional information is provided in Appendix C, including proposed areas of research to advance the knowledge base of the competencies. It should be noted that new competencies can be added to the current core over time as needed to support the mission of MFC. This section concludes with a discussion on the connection between the MFC core competencies and the INL core capabilities.

4.1 MFC Core Competencies

4.1.1 Nuclear Fuels Fabrication

Fuel fabrication facilities at MFC allow fabrication process development for nearly any nuclear fuel form of interest today, including production of fuel test samples to be incorporated into ATR and TREAT irradiation tests. Also available are facilities, instrumentation and personnel to perform both pre- and post-radiation characterization of fuel material. MFC has previously operated engineering-scale fuel production capabilities (i.e., FMF) in support of EBR-II. These capabilities support continuing advances in light water reactor (LWR) fuel technology that have been critical to increasing performance of the current fleet and improving tolerance to severe accidents. They also support development of advanced nuclear fuels 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. Many fuel development needs associated with advanced reactors include adaptation of fast reactor fuel technology to new reactor concepts. MFC is also researching and demonstrating advanced manufacturing techniques for fuel fabrication and experimentation.

4.1.2 Fuel Characterization

MFC hosts facilities, instrumentation and expertise to perform both pre- and post-irradiation characterization of fuel material. The Hot Fuel Examination Facility (HFEF) is equipped to receive radioactive materials and irradiated components in a range of sizes, and provides shielded space and equipment for disassembly, nondestructive examination, size reduction, and destructive examination. The Irradiated Materials Characterization Laboratory (IMCL) is specially designed to apply state-of-the-art instrumentation for microstructural and thermal characterization of irradiated fuel. The facilities of the Analytical Research Laboratories receive a wide variety of samples from across INL and from outside entities, including irradiated and unirradiated fuels and materials. Last, fresh fuel characterization can be performed in the FASB and EFF.

4.1.3 Materials characterization: Radiation Damage in Cladding and Reactor Components

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 therefore instrumental in maintaining the current fleet and developing advanced reactors. MFC capabilities for sample characterization on the nano and atomic scales, as well as sample preparation and storage, are key to this research. Also important 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.

4.1.4 Fuel Recycling and Nuclear Material Management

Nuclear fuel cycles that increase uranium resource utilization and reduce nuclear waste are required to reduce long-term waste disposition risk, induce 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 Fuel Conditioning Facility (FCF) mission for fuel cycle demonstrations if appropriate. Laboratory space in FASB and FCF supports fuel processing and treatment R&D. FCF hot cells are used for processing and treatment of used nuclear fuel, resulting in waste materials suitable for disposal in a deep geologic repository.

The Fuel Fabrication and Nuclear Material Management (FFNMM) Division manages a substantial inventory of contact-handled accountable nuclear material at MFC. The major quantities of contact-handled nuclear material are associated with ZPPR fuel, unirradiated fast reactor fuel and associated fabrication scrap, and feedstock materials. The overarching nuclear material management goal is to maintain and enhance the capability to efficiently support excess material disposition and programmatic missions while minimizing the number of facilities and locations that are required to manage significant quantities of special nuclear material. To this end, FFNMM continues to support programmatic planning efforts to ensure nuclear material is available to meet anticipated needs while minimizing the inventory of excess nuclear material stored at MFC. Prior efforts have resulted in tons of excess special nuclear material and approximately 170 metric tons of excess source nuclear material being removed from MFC. Current excess material management efforts focus on monitored safe storage of the existing material inventory, along with continued processing and shipment of legacy highly enriched uranium (HEU) scrap materials. These efforts facilitate transition of the HEU to beneficial reuse where practical, produce a more stable and better characterized material form, free up vault storage space to support new RD&D missions, and demonstrate progress towards responsible removal of excess nuclear material from the state of Idaho. Future efforts will focus on developing new equipment capabilities needed to process and disposition the legacy plutonium-bearing scrap materials.

4.1.5 Transient Irradiation Testing

Transient testing of nuclear fuels is needed to develop and prove the safety basis for advanced reactors and new fuel designs for operating reactors. With resumption of operations at the TREAT facility, state-of-the-art transient irradiation capabilities along with the requisite operational expertise have been re-established for development of advanced nuclear fuel systems, the study of high intensity neutron interactions with materials, and the testing of nuclear instrumentation under reactor transient conditions. TREAT is capable of neutron irradiation of a variety of experiment configurations at time scales and neutron-flux pulses not attainable in reactor facilities such as the Advanced Test Reactor (ATR). The co-location of TREAT at MFC greatly facilitates efficiencies in assembly of experimental modules, pre- and post-irradiation characterization, and access to other essential support services. The TREAT facility is a significant asset for carrying out important programs ranging from accident-tolerant fuel qualification to startup of one or more DOE-authorized demonstration reactors by 2025.

4.1.6 Radioanalytical Chemistry

Building on MFC's experience for applied and developmental research in radiochemical separations for the nuclear fuel cycle, MFC has developed significant expertise and measurement capabilities in analytical chemistry in support of programs that include advanced nuclear fuel design, nuclear waste management, and nuclear nonproliferation. MFC can provide modern instrumentation and subject-matter expertise for analyses in the areas of radionuclide separations, mass spectrometry, elemental analysis, and radio-analytical measurement (alpha, beta and gamma counting).

4.1.7 Space Nuclear Power

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. Specifically, INL fuels, performs acceptance testing (vibrational testing, mass properties, magnetic field testing and thermal vacuum testing), delivers to NASA and provides ground support at NASA site for radioisotope power systems. The ground support includes efforts such as safety basis work for ground facilities and launch safety, hurricane plans, security plans and upset condition planning. The NASA facilities are essentially made into DOE nuclear facilities during the stay of the RPS at the NASA facilities. Long-term planning working with DOE and NASA is a featured activity to provide for a clear understanding on which NASA missions can be supported with nuclear power capabilities and the interconnectedness.

INL also actively supports NASA's efforts in two space-related reactor development projects. The first is a surface fission power demonstration for a lunar application slated for 2030. This is a reactor for unmanned demonstration in the 40 kWe range. The second project is a reactor for space propulsion which would be necessary for future travel to locations such as Mars. This would be a fission-based system that would be in the ~100 MWth range and provide for the generation of a very hot hydrogen stream for propulsion. An actual system is likely a 2030's application goal.

Development of advanced radioisotope power systems is an ongoing effort with activities in the advanced thermo-electric and dynamic conversion systems underway. These activities are joint ones with NASA-Glen Research Center. The goal of the dynamic power conversion system is a lunar demonstration mission in the 2030 timeframe. The systems under consideration are Stirling and Brayton based. The advanced thermo-electric systems are working towards a goal of a qualification unit by 2028 to support a mission by 2030.

4.1.8 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. MFC occupies a unique position for performing this type of basic research through the availability of facilities with state-of-the-art instrumentation and expert instrument scientists, relevant materials, and scientists who are experts in the behavior of materials in the nuclear environment. MFC is particularly adept at conducting basic research on radioactive materials that require remote handling. In addition to performing basic research using its own assets, MFC can also enable research by other national laboratories and universities by providing samples with low levels of contamination that fit within the acceptable radioactive permit limits of these entities.

4.1.9 Isotope Production

There are two customers for the Isotope production side of the business, the Office of Science (DOE-SC) and DOE-NE. The production of the medical isotope, Co-60, is for the DOE-SC and takes place in the Advanced Test Reactor (ATR). Other isotopes are under investigation for future production for DOE-SC. Pu-238 is also produced in ATR for DOE-NE on the behalf of NASA for use in radioisotope power systems (see previous section).

4.1.10 Nuclear Nonproliferation and Nuclear Forensics

Critical initiatives that support national security programs include preparation of measurement standards that support verification measurements for 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, DOD, and the Department of Homeland Security (DHS). This capability can be extended to develop and demonstrate safeguards technology appropriate for inclusion in the design of new facilities.

4.2 Alignment of MFC Competencies with INL Core Capabilities

It is worthwhile noting how the MFC core competencies map against the designated INL core capabilities that enable the Laboratory's mission[f]. Of the twenty-four DOE-designated core capabilities shared across DOE's science and applied energy laboratories, INL focuses on thirteen core capabilities and two emerging core capabilities shown on Figure 4. Seven of those INL core capabilities are supported by MFC's competencies and facilities:

- Applied materials science and engineering
- Chemical engineering
- Condensed matter physics and materials science (emerging)
- Large-scale user facilities/R&D facilities/advanced instrumentation
- Mechanical design and engineering
- Nuclear and radiochemistry
- Nuclear engineering.

A few principal examples of how MFC supported the INL core capabilities during FY-21 include

Applied materials science and engineering – TRISO particle fuel is the chosen fuel for several advanced gas-cooled reactor and micro-reactor designs. Understanding the microstructure of unirradiated TRISO fuel is critical to form a baseline for evaluating its properties and performance following irradiation. As part of DOE-NE's Advanced Gas Reactor Program, INL researchers are applying a combination of scanning and transmission electron microscopy techniques to determine the chemical composition and crystal structure of unirradiated uranium oxycarbide (UCO) TRISO fuel kernels. This research – performed using instrumentation located at MFC's EML and IMCL - will contribute to an understanding of how irradiation affects the microstructure of UCO TRISO fuel, and help inform performance characteristics of TRISO fuel under irradiation.

f. INL/LTD-21-62463, Annual Laboratory Plan 2021.

Chemical engineering – INL continues to develop electrometallurgical and hybrid zirconium removal processes (ZIRCEX), prior to uranium recovery, to facilitate the supply of HALEU. The first ZIRCEX instantaneous reaction rate test was successfully completed on unirradiated zirconium fuel in FY-22 in the Material Recovery Pilot Plant (MRPP) at MFC's INTEC facility. This is a critical step needed to inform integrated testing of decladding, oxidation and elutriation of the uranium product. The next step will involve work on irradiated zirconium fuel.

Condensed matter physics and materials science (emerging) – Atomic resolution imaging of ThO_2 was conducted at IMCL to provide dislocation loop information as part of a Thermal Energy Transport under Irradiation (TETI) and Nuclear Science User Facilities (NSUF) program. The thermal transport in oxide fuels affects fuel burnup efficiency, as well as reactor safety. It is important to understand irradiation-induced defects such as dislocation loops and their effects on thermal transport in oxide fuels. The Center for TETI at INL, an Energy Frontier Research Center (EFRC), was funded by the Office of Basic Energy Sciences to understand the fundamental sciences of radiation damage and thermal transport, and their relationships. Atomic resolution imaging characterization revealed the nature and characteristics of extremely small radiation induced dislocation loops in ThO_2. This information will help to explain thermal transport under irradiation in ThO_2, UO_2 and Th1-xUxO_2.

Large-scale user facilities/R&D facilities/advanced instrumentation – A new capability has been established in HFEF to harvest material from previously irradiated fuel experiments and produce refabricated fuel rodlets. This effort required the design, fabrication, installation, and demonstration of significant new systems in HFEF, including two new welding systems. The new capability will be critical for making pre-irradiated rodlets from larger commercial fuel rods, which will then be utilized for the transient testing needed to support innovative reactor fuel development and qualification.

Mechanical design and engineering – MFC Fabrication delivered the Primary Coolant Acceptance Test (PCAT) assembly, supporting continued development of the Microreactor Applications Research Validation and Evaluation (MARVEL) reactor. Fabrication of the first-of-a-kind PCAT assembly represented one of the largest fabrication projects executed by the MFC Fabrication shop. The PCAT assembly was delivered on time and was of outstanding quality, with every weld passing either dye penetrant or radiography analysis. The PCAT assembly will be used to validate modeling and simulation flow and heat transfer characteristics of the MARVEL reactor.

Nuclear and radiochemistry – Two new instruments were added to the capabilities of MFC's Analytical Research Laboratories (ARL) during FY-2021:

1. Acceptance testing of a state-of-the-art inductively coupled plasma time-of-flight mass spectrometer (ICP-TOF-MS) was completed. This instrument, equipped with a customized enclosure that enables analysis of radiological samples, is ideal for transient signals such as laser ablation, liquid chromatography-mass spectrometry (LC-MS), and size-limited samples such as nanoparticles. Research planned with this instrument includes developing methods for LC-MS applications and coupling with laser ablation-laser induced breakdown spectroscopy (LA-LIBS) to provide elemental and isotopic information on solid samples.

2. A new quadrupole mass analyzer, used for the analysis of gaseous samples, was installed. The compact design of this instrument allows cart mounting and thus mobility. The instrument can generate mass spectra faster than sector field mass spectrometers, and is equipped for both bulk and trace level detection of gases. Instrumental detection limits range from parts per billion for most noble gases to parts per million for hydrogen. Research planned with this instrument includes indirect analysis of metallic sodium fuel/cladding bonding via hydrogen generated during water immersion; entrained hydrogen analysis for experiments supporting the NASA Space Nuclear Propulsion Program; volatile species analysis of irradiated chloride salts; analysis of plenum fission gases captured by the gas analysis and sample recharge (GASR) system; and fission gas compressibility studies.

Nuclear engineering – A major reactor control system upgrade to extend experimental capabilities at the Transient Reactor Test Facility (TREAT) is in progress. TREAT has the unique ability to control reactor power using a feedback loop. This ability allows the generation of specific power versus time histories designed to meet specific experiment requirements. Historically, the TREAT Automatic Reactor Control System (ARCS) required power to be above a certain threshold before entering closed loop feedback control due to the limitations of a single nuclear instrument to cover the full power range of TREAT (0 – 20,000 MW). ARCS software updates being implemented in FY-2022 will eliminate the need for this power threshold by including low power nuclear instruments in the feedback loop, providing a wider range of operation in closed loop feedback control. This upgrade, when complete and fully implemented, will allow TREAT to perform transient experiments at lower reactor power levels, which is needed for upcoming experiments. Operators at TREAT are testing the upgraded ARCS by completing several trial transients to validate performance ahead of actual experiments.

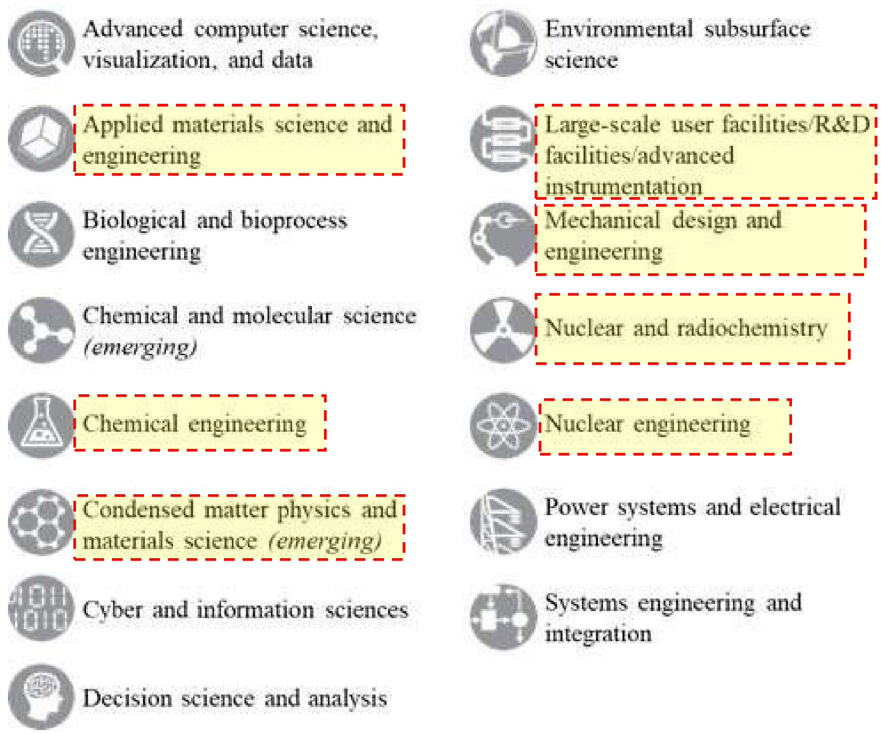

Figure 4. INL’s 13 existing and 2 emerging core capabilities from the INL Annual Laboratory Plan 2021. MFC-supported core capabilities are highlighted.

5. MFC USER FACILITY MODEL

Given the wide range of RD&D performed at MFC and the multiple users of MFC facilities and instrumentation, a MFC user facility model is being implemented to ensure that adequate and reliable base funding is available for compliant nuclear facility operations and scientific infrastructure sustainment. The funding, coming on a continual annual basis from a single fund source (Idaho Facilities Management) establishes a base level of funding that ensures personnel expertise is available to operate and maintain both operations and scientific infrastructure and be available to support RD&D activities at MFC. As illustrated in Figure 5, the user facility model is intended to build and maintain the DOE-NE RD&D capability required for the test bed concept, which is especially relevant to MFC's role in NRIC. The 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. It 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.

The addition of new demonstration platform capabilities will require increased base operations and mission operations levels of IFM funding to maintain the facilities and research infrastructure. Experimenters would pay for any use of the facilities through other NE program funds or through the Strategic Partnership Projects (SPP) or Cooperative Research and Development Agreement (CRADA) processes.

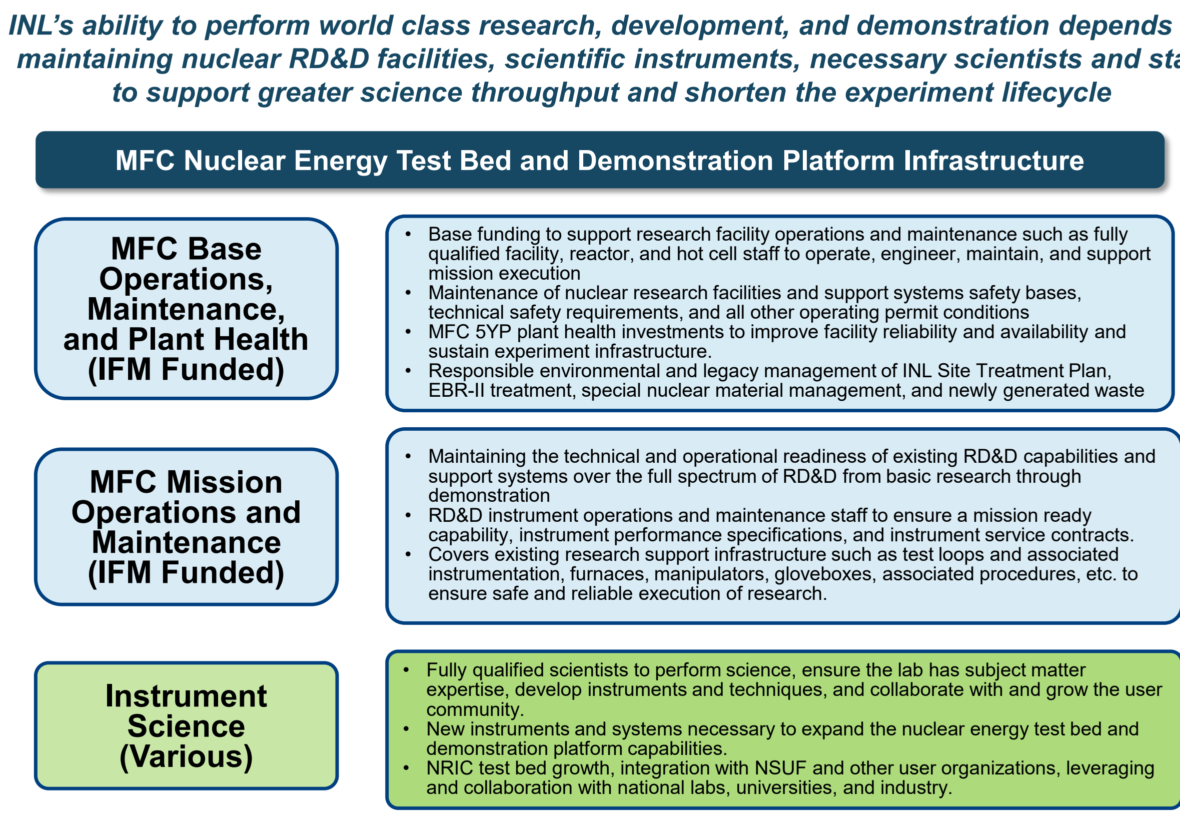

Figure 5. DOE-NE Test Bed and Demonstration Platform Funding Strategy.

The user facility model uses a consistent and simplified approach to funding (see Figure 5) that aligns with the operation of MFC as an RD&D test bed. The proposed model accounts for three key lines of asset funding: (1) MFC Base Operations, Maintenance and Plant Health, (2) MFC Mission Operations and Maintenance, and (3) Instrument Science.

- MFC Base Operations, Maintenance, and Plant Health provides compliance-level support to operate and maintain MFC nuclear and radiological facilities in a safe, stable, and compliant state of readiness to accept work. It includes funding for staff to operate, engineer, maintain, and support mission execution in reactors and hot cells. Plant health refers to additional investment beyond basic preventative and corrective maintenance that addresses revitalization and refurbishment activities focused on improving facility reliability and accelerating research throughput. This supports DOE-NE programmatic objectives by maintaining and improving existing test bed infrastructure and constructing new support infrastructure, as needed, to ensure the safe operation of MFC.
- MFC Mission Operations and Maintenance provides predictable and reliable funding to support a core team of expert RD&D support staff and critical RD&D systems and infrastructure (including instruments), thus ensuring qualified personnel and systems are ready to support important research missions. Activities funded under Mission Operations and Maintenance include instrument performance specifications and service contracts; and maintaining existing support infrastructure such as experiment loops, manipulators, and associated equipment and instrumentation. These are distinct from Base Operations activities, which focus on systems and infrastructure associated with building operations (heating, ventilating, and air conditioning [HVAC], electrical, safety systems, building roofs and shells, etc.) and maintain facility safety bases and compliance requirements.
- Instrument Science supports a staff of fully qualified scientists, engineers and technicians to perform R&D and ensures the laboratory has subject matter expertise to develop instruments and techniques, and collaborate with and grow the user community. Activities include collaborating with the Nuclear Scientific Users Facility, INL Nuclear Science and Technology (NS&T) programs, National Homeland Security (N&HS) programs, NRIC, and others to prioritize and pursue funding for construction or enhancement of future or current capabilities where national gaps exist. This can also include indirect laboratory investment in scientific capabilities.

Details of proposed investments in facility and instrument infrastructure are available in the companion document “Materials and Fuels Complex FY-22 – FY-26 Five-Year Investment Strategy” (INL/RPT-22-65722).

6. MFC FY-22 – FY-26 CRITICAL OUTCOMES

As mentioned earlier, MFC supports the INL mission to discover, demonstrate, and secure innovative nuclear energy solutions, other clean energy options, and critical infrastructure. Each INL Directorate – including MFC –maintains a 5-year strategy for supporting the INL mission based on the respective Directorate's mission responsibilities and capabilities. These strategies are documented in Directorate-level strategic or mission plans and are updated annually.

Because of the RD&D assets and capabilities available within the MFC complex, the MFC Directorate contributes to the accomplishment of the INL mission both directly and by supporting the mission of other INL Directorates, especially the NS&T and N&HS Directorates[g]. MFC also supports important research for NASA. Hence, the needs of these Directorates and programs are a significant input to the MFC mission plan. In order to effectively serve the INL mission and support the entities just described, MFC must achieve the following critical-to-success outcomes during the FY-22 – FY-26 5-year term:

1. Enable and accelerate the demonstration, testing, and operational deployment of advanced reactors, working in close collaboration with NRIC, NASA and private partners
2. Fabricate and supply innovative nuclear fuels for demonstration and test reactors, and advance technologies and processes for treatment of used fuel
3. Perform irradiation, analysis and testing of fuel and materials benefiting nuclear applications ranging from improved performance of operating reactors to radioisotope production
4. Provide components and/or technology to meet radioisotope power generation needs
5. Fulfill environmental stewardship commitments.

Accomplishments of these critical outcomes while excelling in safety and operational performance will advance the following three (of the five) INL S&T initiatives documented in the FY-21 INL Laboratory Plan:

- Nuclear Reactor Sustainment and Expanded Deployment - Sustain and expand nuclear energy leadership to advance a low-carbon energy future.
- Integrated Fuel Cycle Solutions - Develop effective and integrated fuel cycle solutions to sustain the current reactor fleet and enable its replacement and expansion with advanced reactors.
- Advanced Design & Manufacturing for Extreme Environments - Leverage advanced manufacturing to reduce nuclear power plant capital cost, operating cost, and advance process applications matched to nuclear reactor energy properties.

Additional information on how these INL S&T initiatives flow down to the MFC critical outcomes is provided in Appendix D, along with how the MFC critical outcomes relate to DOE-NE strategic goals. The rest of this section describes the MFC critical outcomes in more detail.

1. Enable and Accelerate the Demonstration, Testing, and Operational Deployment of Advanced Reactors, Working in Close Collaboration With NRIC, NASA and Private Partners

MFC's unique expertise, experience and facilities make it the premier location in the US for enabling the demonstration of advanced reactors planned within the next decade. Specific strategic initiatives include

g. Information on the NS&T and N&HS strategies can be found in the *2020 – 2025 NS&T Strategic Plan and Implementing Framework* (currently under revision) and the *2018-2023 N&HS Strategic Plan*, respectively.

- Project Pele – MFC capabilities are well-suited to assist the Strategic Capabilities Office (SCO) of the DOD in achieving the objective of Project Pele to perform power testing of a microreactor by the end of 2024. Facilities such as TREAT, HFEF and the EBR-II dome are being considered for initial fueling and start-up testing of the microreactor.
- MARVEL – MFC is actively supporting the MARVEL project being developed through the DOE Microreactor Program. In addition to successfully delivering the Primary Coolant Acceptance Test (PCAT) assembly during FY-21, MFC personnel are engaged in the procurement of the MARVEL fuel, the engineering modifications at the TREAT facility needed to host microreactor demonstrations (including, but not limited, to MARVEL), and the design of the reactor system.
- Molten Chloride Reactor Experiment (MCRE) – MFC has significant scope in the MCRE project (led by Southern Company Services in partnership with TerraPower, INL and others), which is funded through the DOE's ARDP Risk Reduction program. MCRE will be the world's first demonstration of a fast-spectrum molten salt fuel in a critical low-power nuclear reactor, and is intended to inform the design, licensing and operation of TerraPower's Molten Chloride Fast Reactor.
- NRIC Support – MFC plays a crucial role in the success of a key component of the NRIC strategy to provide a network of test beds and sites that can accommodate a wide variety of demonstration reactors with a Congressionally-mandated objective of demonstrating advanced reactor concepts by 2025.
- NASA Surface Fission Power – This is a collaborative effort with NASA and private firms for a demonstration mission to the lunar surface. The goal is an autonomous reactor of approximately 40 kWe size to operate for several years. The three commercial contracts for phase I will be in place in the latter part of 2022.
- NASA Nuclear Thermal Propulsion – This is a collaborative effort with NASA and private industry to provide for a system that can allow human travel to Mars. The system will likely be complete in the 2030s and consist of a ~100 MWth reactor capable of supplying a stream of very hot hydrogen gas to provide thrust for a spacecraft. The three commercial contracts for phase I were started in late 2021.

The success of these and other demonstration initiatives will rely on an efficient collaboration framework between MFC, NS&T, NRIC, DOD-SCO, private advanced reactor developers, and other national laboratories.

Key Stakeholder(s): DOE-NE, DOD-SCO, NS&T, NRIC, NASA, advanced reactor developers (Southern Company, TerraPower)

MFC Divisions with Applicable Facilities and Resources: Fuel Fabrication and Nuclear Material Management (FFNMM); Transient Reactor Test (TREAT) facility; Space Nuclear Power & Isotope Technologies; MFC Production Facilities, including the Fuel Conditioning Facility (FCF); MFC Engineering, which in FY-22 set up a new department, Reactor Projects, to support NRIC and reactor test beds and demonstrations.

Applicable MFC Competencies: Nuclear fuels fabrication; Fuel recycling and nuclear material management; Space nuclear power

Table 4. FY-22 – FY-26 Activities: Enable and accelerate the demonstration, testing, and operational deployment of advanced reactors.

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome[h]	Related FY-22 Lab Plan Initiative
Support Project Pele microreactor demonstration	Complete preparation of the Experimental Breeder Reactor-II facility to host microreactor demonstration in 2023-24		Nuclear reactor sustainment and expanded deployment
	Prepare plans for fuel loading the Pele microreactor in the TREAT South Highbay (if needed)		
Support MARVEL demonstration	Continue to provide engineering and fabrication support for MARVEL design and testing		
	Ensure that modifications at TREAT to support microreactor demonstrations generically encompass MARVEL requirements		
	Support procurement of fuel elements for the MARVEL reactor		
Support MCRE project	Complete preparation of the ZPPR facility to host MCRE operations		
	Support NS&T in the MCRE fuel salt production tasks, including the establishment of a new fuel salt synthesis production line in FMF		
Continue to support the NRIC mission	Continue preparation to re-establish the Experimental Breeder Reactor-II facility as the NRIC Demonstration of Microreactor Experiments (DOME); and the ZPPR facility cell as a Security Category I Test Bed for advanced reactor demonstrations	Notable Outcome 1.1.B – National Reactor Innovation Center	Nuclear reactor sustainment and expanded deployment
	Support N&ST in the design of the Molten Salt Thermophysical Examination Capability (MSTEC) and in related procurement activities, and prepare for installation in FCF		
			Nuclear reactor sustainment and expanded deployment
	Support as needed private companies awarded funding under the Advanced Reactor Demonstration Program		
			Nuclear reactor sustainment and expanded deployment

h. FY 2022 INL Performance Evaluation and Measurement Plan (PEMP)

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome[h]	Related FY-22 Lab Plan Initiative
Support NASA fuel-development plan for ceramic-metallic and ceramic-ceramic fuel for a nuclear thermal propulsion system	Complete the Sirius 3 irradiation cycle in TREAT during FY-22	Notable Outcome 1.4.A – NASA Programs	Nuclear reactor sustainment and expanded deployment Advanced materials and manufacturing for extreme environments
	Design, build, install, and complete readiness of flowing hydrogen test vehicle for TREAT		
Support design and testing efforts for a fission surface power system planned for 2030 launch			Nuclear reactor sustainment and expanded deployment
Support development of waste management strategies, interim storage, funding strategies and disposition	Provide input to CRADA with OKLO on terms and conditions governing HALEU fuel back-end disposition		
Prepare the MFC organization to accommodate training and qualification of reactor operators for testing and demonstration reactors			
Engage with private entities planning to use MFC facilities and test beds to ensure mutual understanding of capabilities and requirements			

2. Fabricate and Supply Innovative Nuclear Fuels for Demonstration and Test Reactors, and Advance Technologies and Processes for Treatment of Used Fuel

Several of the promising advanced reactor and microreactor designs employ high-assay low-enriched uranium (HALEU) fuel. There is currently no commercial supply chain for HALEU fuel in the U.S., and one is not expected in time to support the fueling of demonstration reactors scheduled within the 2023-2025 period. MFC will leverage its expertise and facilities to address this gap by developing and implementing more efficient engineering-scale processes for downblending existing high-enriched uranium inventory into an interim HALEU supply for advanced reactor developers.

MFC expertise and assets will also support R & D for the secure transportation, storage, and disposition of radiological materials generated by these advanced reactor technologies, including used fuel. Furthermore, MFC will assist in developing an integrated civilian nuclear fuel cycle test bed capability that includes the ability to process both U and Pu as well as testing of new nonproliferation technologies.

Key Stakeholder(s): DOE-NE, DOE-NNSA, NS&T, N&HS, advanced reactor developers.

MFC Divisions with Applicable Facilities: MFC Production Facilities; Fuel Fabrication and Nuclear Material Management (FFNMM); Hot Fuel Examination Facility; Characterization and Advanced Post Irradiation Examination (CAPIE); Analytical Research Laboratories.

Applicable MFC Competencies: Nuclear fuels fabrication and characterization; Fuel recycling and nuclear material management; Nuclear nonproliferation and nuclear forensics; Radioanalytical chemistry; Focused basic research.

Table 5. FY-22 – FY-26 Activities: Fabricate and supply innovative nuclear fuels for demonstration and test reactors, and advance technologies and processes for treatment of used fuel.

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome	Related FY-22 Lab Plan Initiative
Produce an interim supply of HALEU from treatment of EBR-II spent fuel in the Fuel Conditioning Facility (FCF) and recasting in regulus form in HFEF	Continue processing and process enhancement as defined in PLN-6098[i]	Notable Outcome 2.3.B – Maximize EBR-II driver SNF receipts at MFC in support of the 2019 Supplemental Agreement milestone.	Integrated fuel cycle solutions
Prepare MFC buildings for installation of fuel fabrication and production equipment for campaign-style, engineering-scale fuel production	Develop and demonstrate cutting-edge, fabrication techniques and processes, including the development of Advanced Manufacturing techniques for nuclear fuel		
	Continue planning for the establishment of a reactor fuels research capability (see Appendix C)		
Continue to develop and demonstrate capabilities for nuclear fuel-related basic and applied science research	Develop U/Pu process test bed (Project Beartooth)		Integrated fuel cycle solutions
Develop innovative solutions for the processing, storage, transportation, and treatment of used fuel	Obtain data to support transportation safety case for various HALEU forms.		
	Assist in fuels R&D for proliferation resistance		
	Continue testing on zirconium/aluminum-cladding removal with a chloride volatility process (Zircex)	Notable Outcome 1.1.C – Fuel Cycle	Integrated fuel cycle solutions Nuclear reactor sustainment and expanded deployment
Support N&HS Mission to advance security solutions that prevent, detect, and counter nuclear and radiological threats			Integrated fuel cycle solutions

i. PLN-6098 Revision 1, "Treatment Plan for Irradiated Sodium-Bonded Driver Fuel and the Production of High-Assay Low-Enriched Uranium," November 2020

3. Perform Irradiation, Analysis and Testing of Fuel and Materials Benefiting Nuclear Applications Ranging from Improved Performance of Operating Reactors to Radioisotope Production

When combined with the thermal irradiation available at the ATR, MFC through the TREAT and NRAD reactors, hot cells, and analytical laboratories, provides a comprehensive suite of capabilities that can foster the R&D needed to deploy nuclear-reactor components and fuels with revolutionary performance improvements and cost competitiveness. These would benefit both operating reactors and advanced reactors, including the pre- and post-irradiation analysis of accident-tolerant fuel for commercial reactors and the evaluation of material properties of advanced-manufactured components subjected to the temperature and radiation environments expected in advanced or operating reactors. Several of these tests and evaluations are planned within the FY-22 – FY-26 period.

The MFC and ATR capabilities will also be utilized to assist with the mission of the DOE Office of Science (DOE-SC) for U.S.-based production of radioisotopes such as cobalt-60 that have important medical and industrial applications.

Key Stakeholder(s): DOE-NE; NS&T; commercial reactor operators; advanced reactor developers; DOE-SC

MFC Divisions with Applicable Facilities: Hot Fuel Examination Facility; Characterization and Advanced Post Irradiation Examination (CAPIE); Analytical Research Laboratories; Transient Reactor Test (TREAT) facility; Space Nuclear Power & Isotope Technologies; Fuel Fabrication and Nuclear Material Management (FFNMM)

Applicable MFC Competencies: Nuclear fuels fabrication and characterization; Transient irradiation testing; Assessing radiation damage in cladding and in-core structural materials; Radioanalytical chemistry; Space nuclear power and isotope technologies; Focused basic research

Table 6. FY-22 – FY-26 Activities: Perform irradiation, analysis and testing of fuel and materials benefiting nuclear applications.

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome	Related FY-22 Lab Plan Initiative
Complete establishment of new irradiation testing and fabrication capabilities at INL to support Accident Tolerant Fuel (ATF) deployment	Execute the TREAT test program to provide results needed to evaluate and demonstrate safety-related behavior of nuclear fuel and nuclear reactor concepts		Nuclear reactor sustainment and expanded deployment
	Prepare rodlets for the ATF-2C experiment in ATR	Notable Outcome 1.1.D – Advanced Fuels	
	Complete the Experiment Preparation and Inspection Cell (EPIC) to add capability to install instrument sensors onto test rods refabricated from shortened pre-irradiated fuel rods		
Characterize and test advanced-manufactured fuel and components	Complete applicable Laboratory-Directed Research and Development (LDRD) projects		Advanced materials and manufacturing for extreme environments

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome	Related FY-22 Lab Plan Initiative
Continue examination of TRISO fuel	Support TRISO R&D for microreactor designs and high-temperature gas reactors		Nuclear reactor sustainment and expanded deployment
Reduce the time required for engineering-scale post irradiation examination by a factor of ten or more	Collaborate with N&ST Directorate to demonstrate effective coupling of modeling and simulation with experiment		Nuclear reactor sustainment and expanded deployment
	Expand the use of online instrumentation to accelerate the analysis of irradiation experiments		
	Re-evaluate post irradiation examination instruments and workflow for optimization		
	Invest in hardware for the application of Artificial Intelligence/Machine Learning to accelerate data analysis		
	Expand the use of robotics to automate and accelerate the examination of irradiated materials		
	Complete applicable LDRD projects		
Leverage TREAT to address some of the capability gaps resulting from the closure of the Halden research reactor	Complete the EPIC to add capability to install instrument sensors onto test rods refabricated from shortened pre-irradiated fuel rods		
Support DOE-SC isotope production strategy.	Continue to support DOE-SC initiative on cobalt-60		
Continue R & D in support of Naval Reactors program			Nuclear reactor sustainment and expanded deployment
Attract external users from industry and academia for collaborations to perform innovative R & D related to nuclear technology applications	Partner with industry and academia to pursue funded collaborations through programs such as GAIN, NEUP, NSUF and FY-22 Industry FOA (iFOA)		Nuclear reactor sustainment and expanded deployment
	Finalize the establishment of the SPL External Advisory Committee		
	Increase outreach to a broader set of universities, including minority-serving institutions (MSI)		All

4. Provide Components and/or Technology to Meet Radioisotope Power Generation Needs

Nuclear-sourced power – whether from radioisotopes or from fission reactors – is expected to play a vital role in NASA's upcoming missions such as the Dragonfly mission to explore Saturn's moon Titan and the establishment of human outposts, first on the moon and then on to other heavenly bodies, such as Mars. MFC's Space Nuclear Power & Isotope Technologies division, in collaboration with the ATR and other national laboratories, will continue to lead DOE-NE activities to supply Pu-238 for the radioisotope power systems used for NASA's deep-space exploration needs.

Key Stakeholder(s): DOE-NE, NASA

MFC Divisions with Applicable Facilities: Space Nuclear Power & Isotope Technologies; Fuel Fabrication and Nuclear Material Management (FFNMM)

Applicable MFC Competencies: Space nuclear power and isotope technologies; Nuclear fuels fabrication and characterization; Transient irradiation testing

Table 7. FY-22 – FY-26 Activities: Provide components and/or technology to meet NASA objectives.

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome	Related FY-22 Lab Plan Initiative
Radioisotope Power Development	Continue work on a customized Multi-Mission Thermal Electric Generators (MMRTG) version for the Dragonfly mission		Nuclear reactor sustainment and expanded deployment
	Evaluate the use of skutterudite materials as replacement for the current MMRTG's PbTe-based thermoelectric materials		
	Continue preparation for target insertion in ATR for the Constant Rate Production: Pu-238 Fuel Services Program	Notable Outcome 1.4.A – NASA Programs	
	Partner with NASA to develop a Next Generation RTG (NGRTG) and a Dynamic Radioisotope Power System (DRPS)		
Continue duties as National Technical Director for Space Nuclear Power	Work with other national laboratories as members of the Space Nuclear Power Advisory Board to provide support for DOE and NASA in several key areas: -Replanning of launch safety planning -Provide for better coordination and vetting of alternative technologies for space nuclear applications such as new proposed power systems, power conversion systems or radioisotopes.		

5. Fulfill Environmental Stewardship Commitments

INL shares the responsibility for the DOE's legacy nuclear waste and fuel on the INL site with the Idaho Cleanup Project. This responsibility involves the fulfillment of Regulatory Milestone Commitments to the State of Idaho as described in the Idaho Site Treatment Plan (STP), 1995 Settlement Agreement between the state of Idaho and the DOE, and in subsequent supplemental agreements signed in 2019 and 2020. MFC is playing a key role in fulfilling several of these commitments, including the reprocessing of EBR-II fuel by 2028. INL and MFC plan to leverage capabilities and expertise in treatment and disposition of sodium and NaK components and the processing of sodium-bonded fuel to develop treatment technologies and disposition options for the legacy EBR-II fuel, as well as for the future inventory of used sodium-bonded fuel generated by advanced reactor technologies.

Coincident with the January 2021 issuance of Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, INL committed to reducing carbon emissions and achieving net-zero carbon emissions on the INL site by 2031. In support of this goal, MFC has initiated Net Zero (NZ) long-range planning that is being integrated into the FY-21 – FY-26 MFC Five-Year Infrastructure Maintenance Plan. The INL NZ team is leading a comprehensive facility by facility review of MFC mission and support structures based on vulnerability and resiliency criteria provided by DOE-NE. This DOE-NE sponsored infrastructure assessment is designed to forecast where the MFC site is either unprepared or at risk for climate-induced physical impacts throughout MFC. Additionally, MFC is taking steps to categorize potential NZ gains when planning for HVAC upgrades, standby power diesel generator replacements, and when looking at aging building's roofs, windows, doors, and exteriors. As an example of net-zero preparation, a design change was instituted when constructing the new MFC parking lot in 2021 to provide conduit to multiple parking lot rows for future expansion of electric vehicle (EV) charging stations, in anticipation of an increasing number of electric vehicles. The conduit added will also allow MFC to add EV charging stations for the bus fleet should the need arise. Another example is MFC's plan for light-emitting diode (LED) replacement of all perimeter lights.

Key Stakeholder(s): DOE-NE Idaho Facilities Management, DOE Office of Environmental Management, DOE-NNSA, State of Idaho

MFC Divisions with Applicable Facilities and Resources: MFC Production Facilities, Fuel Fabrication and Nuclear Material Management, Analytical Research Laboratories; MFC Maintenance, Infrastructure & Fabrication

Applicable MFC Competencies: Fuel recycling and nuclear material management; Radioanalytical chemistry, sodium treatment capabilities and permitted storage capabilities

Table 8. FY-22 – FY-26 Activities: Fulfill environmental stewardship commitments.

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome	Related FY-22 Lab Plan Initiative
Develop treatment technologies and disposition options for sodium-bonded fuels	Maximize the number of treated batches of sodium bonded Experimental Breeder Reactor-II Driver Fuel (EBR-II) in the Fuel Conditioning Facility (FCF) Mark IV electro-refiner	Notable Outcome 2.3.B – Maximize Experimental Breeder Reactor-II (EBR-II) driver spent nuclear fuel (SNF) receipts at MFC in support of the 2019 Supplemental Agreement milestone.	Integrated fuel cycle solutions

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome	Related FY-22 Lab Plan Initiative
	Within available funding, develop alternate treatment methods for non-candidate EBR-II driver SNF to facilitate a successful outcome of the December 31, 2028 Supplemental Agreement milestone Continue alternative analysis, R&D and regulatory strategies for EBR II blanket material within available funding		
Continue active nuclear material management & excess disposition of MFC inventories	Demonstrate disposal of legacy and newly generated waste at commercial facilities		
Support INL net-zero carbon emissions goal by 2031	Engage with the INL Net-Zero team to ensure their input and assistance with design and functional requirements associated with future upgrades at MFC		

7. STRATEGY FOR ACHIEVING CRITICAL OUTCOMES

Achieving the outcomes described in the preceding section relies on a strategy consisting of five principal elements:

- Maintaining operational excellence and best-in-class safety performance through the execution of the MFC OMI strategy
- Continuing to develop the scientific and engineering expertise that underpins the MFC core competencies
- Executing the 5-Year Investment Strategy plan
- Continuing to implement the MFC User Facility model, and
- Collaborating actively with other INL directorates, government agencies, private industry partners, other national laboratories, and academia to grow the MFC user base.

The actions contained in the OMI Strategy are intended to improve the effectiveness of MFC's facility operations and provide for overall improvement of the MFC organization. MFC will continue to implement an enhanced operations model focused on increasing facility reliability and shortening the experiment lifecycle. To this end, existing facilities will be modernized, and new infrastructure capability added, consistent with the MFC Five-Year Investment Strategy plan. Furthermore, operations and maintenance processes such as engineering design approval, procurement, and equipment reliability will be continually assessed for simplification or upgrading, with the goals of improving reliability and, when appropriate, reducing administrative burden. Technologies that are already widely used in the non-nuclear industry such as robotics, artificial intelligence (AI), and augmented/virtual reality will continue to be evaluated for their potential to improve efficiency at MFC. For example, MFC can accelerate the rate of scientific discovery and innovation by developing a digital framework around its characterization and analysis capabilities. By connecting data streams, defining ontology, and streamlining correlative processes, MFC can drastically reduce the time required between characterization and data analysis as well as develop a world class framework to leverage advanced data analytics and artificial intelligence.

INL works to embed safe conduct of research principles and human performance improvement (HPI) principles in its holistic culture of safety, based on the tenet that personnel and public safety is foundational to mission accomplishment[j]. As a nuclear facility complex, MFC must address the unique characteristics and hazards associated with nuclear technology. In addition, MFC must mitigate the standard industrial hazards present in the systems, structures, and components which are utilized to perform work at MFC. Maintaining a healthy safety culture along with good processes and an environment that promotes continuous learning and improvement are therefore paramount to the ability of MFC to fulfill its mission.

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j. Fundamental expectations relative to Nuclear Safety Culture, Human Performance Improvement, and Just Culture are codified in HBK-104, "MFC Human Performance and Nuclear Safety Culture Pocket Guide."

A vibrant research culture is also an important enabler of the MFC mission. Efforts to improve the MFC research culture have already been initiated, mainly directed at encouraging R&D staff to value RD&D principles embodied in technical integrity, inquisitiveness, professional growth, and collaboration. In FY-21, MFC launched the Technical Leadership Council (TLC), consisting of researchers tasked to advise the MFC Chief Scientist on matters related to the research culture of MFC and on the performance of research work at MFC. The TLC efforts in FY-22 include tracking metrics related to research performance and rollout in FY-22 of an MFC Mentor/Mentee program that focuses on personnel in science research roles. Another major effort in FY-22 will be the implementation at MFC of the ten (10) principles of a strong research culture that INL is adopting as a blueprint to guide current and future researchers at INL in their daily work. These 10 principles are

1. All employees are engaged in the success of the science and technology mission.
2. An environment of creativity, inquisitiveness, and constant questioning is fostered.
3. The highest level of scientific integrity is expected.
4. Staff members aspire to generate scientific products at the forefront of their field.
5. Scientific successes are celebrated and actively promoted.
6. Scientific failure is valued as a mode of learning.
7. Professional development and mentoring are encouraged and valued.
8. Diversity of backgrounds, an inclusive environment, and teamwork lead to innovation.
9. Independent input and review are sought and valued to improve research quality and impact.
10. Our research tools and facilities are recognized globally as unique and state-of-the-art in our fields of study.

Table 9. FY-22 – FY-26 Activities: Strategy for achieving critical outcomes.

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome
Maintain and execute the MFC OMI Strategy	Continually update and improve MFC processes for greater safety, effectiveness, and efficiency	
	Continue to fully leverage Asset Suite capabilities	
Maintain and execute the MFC Five-Year Investment Strategy	Make progress on SPL construction	Notable Outcome 2.2.A – Construction and Commissioning of new facilities/capabilities Notable Outcome 2.3.A – Advanced Test Reactor (ATR) and Materials and Fuels Complex (MFC) Infrastructure Investment for reliability improvement
	Continue activities to provide offices, shop space, and warehouse space capable of supporting the increasing amount of activities at MFC	
	Update plan to ensure sufficient space and facilities for Security Category I & II activities	
	Ensure facility reliability and availability	

Activity	Sub-Task (if applicable)	Related FY-22 PEMP/Notable Outcome
Develop technical expertise and capability	Maintain current state-of-the art scientific instruments and R&D equipment	
	Implement plans to hire and develop staff with necessary skillset to use MFC instruments and equipment	
	Develop and apply new techniques and processes that make new technology increasingly available for nuclear R&D	
Enhance research culture	Implement INL's 10 Principles of a Strong Research Culture at MFC	
	Support MFC researchers' participation in the INL Young Researcher Association (YRA)	
Expand and improve the implementation of the MFC User Facility model	Influence decision makers toward broader funding of MFC as a user facility	
	Deliver on commitments made to external users, including those in the private sector, other government agencies, and universities	
Encourage a collaborative culture among MFC R&D staff, facility operators and support personnel, and external users	Continue to work on the implementation of the instrument scientist concept across MFC mission organizations	
	Develop an improved approach to facilitate more streamlined work processes	
	Pursue initiative to ensure alignment of priorities between Research and Operations staff	
	Apply to the International Atomic Energy Agency for renewal of International Centre based on Research Reactors (ICERR) designation for INL	
Develop process to prioritize and coordinate demands for MFC resources	Continue to engage with NS&T on the use of the IRPT to plan and staff work at MFC	

8. RISKS AND CHALLENGES

Accomplishing the mission outcomes of MFC requires the mitigation, elimination and/or avoidance of challenges and risks

The major risks (and related response actions) include in order of priority:

- Maintaining and upgrading aging facilities (such as HFEF) at MFC while coordinating, scheduling and executing mission work
  - MFC is developing and executing a Utilities and Infrastructure Systems (U&IS) FY-22 – FY-26 Five-Year Infrastructure Management Plan to address facilities' needs proactively starting in FY-22. This plan will be updated annually.
  - MFC is executing an equipment reliability maintenance program and a plant health execution strategy utilizing facility/complex health committees to enable higher levels of facility reliability.
- Challenges to successfully recruit, engage, develop and reward top talent presents a serious risk to mission accomplishment
  - An INL Nuclear Staffing Executive Board consisting of the ALDs of the ATR, MFC and NS&T directorates is being set up to provide a strategic outlook to enterprise-wide nuclear staffing and development. The board will address, among other items, cross organization development, staff development plans that could include directed transfers to grow the nuclear staff, supervisors, and leaders of the future, and coordination of recruiting efforts. The charter for the board should be finalized in FY-22, and approval sought from Laboratory Directory by FY-23.
  - MFC has developed a university engagement plan for each MFC division to establish collaborations and/or recruiting pipelines with targeted universities and vocational technical institutes.
- Sustaining the facility investment needs captured in the MFC Five-Year Investment Strategy plan while growing the operations and maintenance (O&M) budget for new facilities and capabilities.
  - Proactively identify and develop funding strategies for O&M costs of new facilities / capabilities
- Limited availability of office space and of laboratory space, especially in Security Category I and II and Hazard Category 2 facilities, that can lead to conflicts between projects competing for the same space
  - Continually seeking to identify activities in these facilities that can be transferred to non-nuclear facilities and relocating equipment that is no longer needed for mission support to free up space
  - Developed a mission need statement to establish a reactor fuels research capability that provides appropriate space and fuel fabrication/research capabilities for development and engineering-scale demonstration of nuclear fuel fabrication
  - A Mission Need Statement for the MFC West Campus Office Building (PLN-6416), an institutionally funded investment in key infrastructure at MFC with a total estimated cost < $25M, was issued March 6, 2022. Functional and operational requirements have been developed with a design/build-to-cost acquisition strategy envisioned.
- Lagging data management and analysis capabilities to collect data.
  - Invested, through Indirect Priorities List (IPL) funding, in a large, centralized data server for data storage within the Irradiated Materials Characterization Laboratory (IMCL) to enable large volumes of data to be stored in one centralized location.

In FY-22, MFC management instituted a risk management process to identify, prioritize and address risks that could compromise mission performance. High-priority risks, ranked according to probability of occurrence and severity of impact, are assigned to individual owners who are expected to engage key stakeholders and develop a strategy to address the risks. Progress on dispositioning high-priority risks is tracked using a Risk Control Summary matrix, which is reviewed by MFC leadership regularly. A snapshot of the Risk Control Summary matrix is shown in Table 10. Once all associated actions identified by the risk owner to address a particular risk are completed, the risk will be re-evaluated by MFC leadership to confirm that its level has been reduced adequately. New risks are captured in the matrix as they are identified.

Table 10. Snapshot of Section of Risk Control Summary Matrix.

Risk Item	Description	Risk Level	Response Strategy	Response Actions[a]	Status
Major equipment failure in the facilities	Reliability Program implemented, but needs maturing	High	Mitigate	Checking that OMI actions are adequate to mature the program. May need to review and update actions for FY22.	In progress
Engineering Modification Implementation, including Asset Suite Implementation	Powerful tool, capabilities, but new or very different. Training required.	High	Mitigate	Training review required to assure right audience/staff are given the training.	In progress
Lack of a comprehensive management process accounting for project related materials, new and legacy equipment	Needed to ensure research programs pay for management, storage, and where applicable, timely disposal of project related research materials/equipment at MFC	High	Mitigate	Evaluating an MFC pricing strategy for management and disposition of research related materials and equipment	In progress
Hazardous and mixed hazardous waste management performance maturity	Raise level of knowledge and practices with handling hazardous and mixed hazardous wastes	High	Mitigate	Reviewing OMI actions, MFC training, Lab-Wide training and refresher training	In progress

a. Response Strategy options: Accept; Transfer; Mitigate; Avoid

9. CLOSING

Over the next five years, INL and MFC will remain focused on helping DOE-NE achieve its mission to advance nuclear energy science and technology to meet U.S. energy, environmental, and economic needs. MFC's personnel, facilities and infrastructure are playing an important role in supporting the R&D efforts and demonstration test beds needed to underpin the next generation of nuclear technologies. Executing the strategy described in this document will ensure that MFC continues to maintain and expand upon these capabilities, including addition of the Sample Preparation Laboratory (Figure 6). It will drive the accomplishment of the five critical outcomes that will position MFC to contribute to the success of the DOE-NE mission, and play a pivotal role in supplying the world with safe, affordable, clean and reliable energy, combating climate change, and regaining U.S. leadership in advanced reactor technology.

Figure 6. Construction of the MFC Sample Preparation Laboratory (SPL). When completed, SPL will provide INL with a central point for collaborations with universities, industry partners, and other DOE user facilities on research involving irradiated structural and cladding materials.

Appendix A

MFC Divisions

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Appendix A

MFC Divisions

The mission and key objectives for each of the twelve MFC divisions are provided in this appendix.

A-1. MFC BUSINESS

Mission: Understand and respond to mission, program, and facility needs regarding processes and tools for performance analysis, training, document management, strategic planning, financial tracking, communications, and human resources.

Key Responsibilities:

- Provide metrics and analysis, assessment, issues management and causal analysis services
- Provide training design and delivery to improve employee knowledge, skills, and behaviors
- Use configuration management practices to create, revise, issue, and preserve MFC documents
- Develop strategy that identifies how MFC will support laboratory mission and vision; updates five-year plan annually
- Optimize funding sources to align resources to mission
- Provide timely information to MFC employees and provide general facts to those interested in MFC capabilities through tours, fact sheets, and on-line resources
- Recruit key talent and retain remarkable employees while fostering diversity and inclusion. Assist management team with performance management
- Provide technical troubleshooting for PCs, installation of standard software, remote access setup and support for travel, request access to accounts, and desktop backup

A-2. MFC ENGINEERING

Mission: The MFC Design Authority, responsible for the processes to design, create and secure modifications to MFC facilities and to ensure their sustained reliability. Develop unique equipment, processes, and systems to enable and protect research and experimentation. Maintain, control, and update MFC safety basis and design basis.

Key Responsibilities:

- Evaluate and resolve operational, maintenance, and programmatic engineering needs for systems, structures, and components at MFC facilities and ensure safety and defense-in-depth systems are reliable and meet design and safety analysis requirements
- Develop hot-cell operated systems and components in support of research experiments and processes and provide the technical interface between the nuclear facility and principal investigators responsible for the operation and maintenance of these systems
- Provide facility modification and new equipment design and drafting services based on best-practice engineering principles, codes, standards, and guidelines to support safe, efficient, quality research
- Provide safety analysis and nuclear safety regulatory processes to support safe, efficient, and compliant facility operations that enable quality research outcomes

- Procurement engineering, supplier management and oversight, ordering, tracking, kitting, and staging of materials for nuclear facilities
- Provide instrumentation and control, network, cyber security, and software engineering/development for control, data acquisition, and research systems

A-3. MFC MAINTENANCE, INFRASTRUCTURE & FABRICATION

Mission: Maximizing facility availability through reliability-centered maintenance of our facilities and support systems, fabricating one-of-a-kind components that support research outcomes, and operations and management of our support infrastructure.

Key Responsibilities:

- Nuclear and facility systems corrective and preventative maintenance
- Equipment Reliability Program: predictive maintenance
- Component machining and fabrication services
- Utility systems operation and infrastructure management
- Strategic Infrastructure Planning: space planning, infrastructure upgrades, and capability improvements

A-4. MFC OPERATIONS

Mission: MFC Operations Division provides safe and consistent operations ensuring successful implementation and delivery of preeminent research focused on nuclear energy, science, and technology.

Key Responsibilities:

- Provide leadership and technical oversight to ensure all MFC facilities are operating within their defined safety analysis (DSA)
- Provide strategic recommendations to MFC leadership team and operational personnel to ensure consistent management and compliance to Conduct of Operations (ConOps) in all Nuclear and Radiological facilities
- Provide mentoring and oversight to Nuclear Facility Manager (NFM), Facility Management (FM) and first-line management
- HPI Program implementation
- Lead event critiques and cause analysis
- Emergency management interface
- Safeguards & Security interface
- Advanced Reactor Demonstration and Deployment for DOME/PELE and LOTUS/MCRE

A-5. MFC PROJECTS

Mission: Successful completion of all projects and critical facility and mission activities using appropriate project management principles.

Key Responsibilities:

- Enable demonstration of advanced reactor concepts
- Deliver line item capital construction projects that enhance Laboratory capabilities within approved budget and schedule

- Apply tailored project management principles in support of critical facility and mission activities
- Effectively complete construction projects that provide enhanced facility reliability and enable R&D mission outcomes
- Establish and maintain a structured cask management program that ensures functionality and enables successful completion of mission outcomes
- Implement a structured approach to management of projects that helps ensure successful project completion through effective planning, monitoring and control, and reporting

A-6. MFC SAFETY & COMPLIANCE

Mission: Ensuring our workplace and our communities are safe; our workers are healthy and have a sense of well-being; and our environment is sustained for future generations.

Key Responsibilities:

- Provide mission-focused environmental, safety and health, quality, and radiological support services
- Influence the regulatory climate to support specific mission and operation needs
- Provide the expertise needed to assist in the anticipation, recognition, evaluation, prevention, and control of those environmental factors or stresses arising in or from the workplace which may cause sickness, impaired health and wellbeing, or significant discomfort among workers
- Provide radiation protection services to workers, facilities, and the public to ensure exposures are as low as reasonably achievable and comply with all regulatory requirements
- Implement Nuclear Quality Assurance (NQA-1) requirements across MFC activities
- Evaluation of personnel injuries
- Serve as cross-cutting subject matter experts or technical points of contact for INL in specific environment, safety and health, radiological controls, and quality disciplines
- Oversee MFC waste management functions

A-7. ANALYTICAL RESEARCH LABORATORIES

Mission: Provide high quality analytical measurements, operate reliable nuclear facilities, conduct world class research, and provide unique educational experiences to INL, U.S. colleagues and our world-wide partners.

Key Responsibilities:

- Conduct analytical chemistry on nuclear fuels and materials in support of INL research programs and outside customers including advanced nuclear fuel design, nuclear waste management and nuclear nonproliferation
- Conduct analytical chemistry on environmental samples for regulatory compliance
- Provide data analyses on samples that meets or exceeds the requirements of the customer
- Develop cutting edge chemical methods to meet the growing analytical challenges of the nuclear fuels community
- Provide modern instrumentation and subject-matter expertise for analyses in the areas of radionuclide separations, mass spectrometry, elemental analysis, and radio-analytical measurement (counting)
- Foster development of scientific and operational talent

A-8. CHARACTERIZATION AND ADVANCED PIE

Mission: Examination and data analysis that drive innovation in nuclear fuels and materials.

Key Responsibilities:

- Perform non-destructive and destructive post-irradiation examination of experimental fuels and materials for the advancement of nuclear energy
- Operate the Neutron Radiography Reactor to perform neutron imaging of irradiated fuels and materials, in-core irradiation of test samples, and provide neutron beams for advanced examination techniques
- Design, fabricate, and perform developmental testing of new instruments, fixtures, and tools to perform PIE
- Develop new remote examination techniques to support nuclear fuels and materials research
- Plan, manage, and execute key mission and infrastructure upgrades to support continued programmatic and facility availability and reliability
- Maintain and upgrade facility systems and equipment to support facility compliance and programmatic needs
- Provide the capabilities, data, and analysis of nuclear fuels and materials that shorten the development/deployment cycle for advanced nuclear energy systems
- Develop an active and diverse user community, inclusive of DOE laboratories, universities, industry, and international researchers
- Ensure that the quality of data produced meets or exceeds requirements for its intended purpose
- Publish knowledge gained in peer-reviewed journals
- Drive improvements to PIE and characterization capabilities, methods, and facilities at INL, nationally, and internationally
- Collaborate to provide validation data for modeling and simulation

A-9. FUEL FABRICATION & NUCLEAR MATERIAL MANAGEMENT

Mission: Support the advancement of nuclear energy by providing exceptional nuclear fuel fabrication, process development, experiment fabrication, feedstock development, instrument testing, and nuclear material management.

Key Responsibilities:

- Support the fabrication and development of improved fuels for LWRs, fast reactors, micro reactors and other advanced reactor concepts
- Develop advanced manufacturing capabilities for nuclear applications
- Plan, manage, and oversee the special nuclear material program

A-10. MFC PRODUCTION FACILITIES

Mission: Provide production environment that enables future R&D capabilities and supports our environment commitments

Key Responsibilities:

- RD&D advanced pyro chemical separations concepts

- Treatment of irradiated sodium bonded fuels and materials
- R&D for disposition alternatives for spent-fuel product
- Management, treatment, storage, and disposal of waste
- Ensures Site Treatment Plan compliance

A-11. SPACE NUCLEAR POWER AND ISOTOPE TECHNOLOGIES

Mission: Develop the use of nuclear power in its various forms (heat, radioisotope, electric power, reactor driven) to provide energy needs (or nuclear power solutions) in remote or hostile environments for NASA or other U. S. governmental customers.

Key Responsibilities:

- Develop and enable nuclear power and isotope technologies for space and terrestrial applications
- Maintain knowledgeable and experienced staff to support radioisotope-power-system infrastructure and missions for fueling, testing, storing, transporting, and supporting ground operations at customer locations. This includes qualified staff in, for example, program and project management, engineering, material science, quality assurance, material control, fabrication, shipping-cask management, nuclear safety, and operations disciplines
- Provide leadership and coordination for INL's isotope production efforts for DOE-SC
- Support DOE-NE Nuclear Infrastructure Programs by staffing their National Technical Director Office to provide coordination among the DOE and other customer interfaces for:
    - Mission planning capabilities (long-term and detailed, as needed)
    - Technical issue resolution
    - Scope, budget, and schedule integration among participants

A-12. TRANSIENT REACTOR TEST FACILITY (TREAT)

Mission: Provide state-of-the-art transient irradiation capabilities for development of advanced nuclear fuel systems and the study of high intensity neutron interactions with materials

Key Responsibilities:

- Develop and enable transient capabilities for advanced reactor fuels and materials testing.
- Provide testing capabilities to qualify existing reactor fuel designs for baseload and load following operations.
- Implement new fuel transient testing capabilities, such as the sodium and hydrogen test loops.
- Support updating of the Fuel Motion Monitoring System for assessing fuel transient effects and radiography capabilities for pre- and post-irradiation imaging of irradiated fuels and materials in support of transient testing.
- Support cutting edge instrumentation development and integration to provide real time data during postulated nuclear accident scenarios in support of transient testing.

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Appendix B

MFC Facility Data Sheets

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Advanced Fuels Facility

Fuel and Material Fabrication

The laser welder allows for high precision closure welding on materials that are difficult to weld.

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 features a range of material handling and fuel fabrication capabilities used for advanced manufacturing processes. It supports INL's mission as the nation's lead nuclear energy lab.

AFF's operations involve research and development primarily with uranium-bearing fuels and associated surrogate materials to increase MFC's advanced fuel manufacturing capabilities.

Equipment and processes in AFF 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.

ENGINEERED SPACES

AFF is a radiological space where uranium nuclear fuel is routinely handled. This material is safely contained in gloveboxes, hoods, and other contamination areas where the equipment and processes are protected from contamination spread by engineered systems. Inert gloveboxes are also employed to prevent metal fuels from oxidizing in air. The equipment includes:

- 2 fume hoods, one radiological
- Inert radiological gloveboxes
  - Experiment vehicle assembly glovebox to provide a large inert volume for experiment assembly. It can maintain an atmosphere of helium, argon, and helium/argon mixtures to aid in targeting specific irradiation conditions.
  - Spark plasma sintering glovebox
  - Laser welding glovebox containing a 700W laser and capable of helium, argon, or mixed helium/argon environments.
  - Advanced manufacturing machine glovebox housing the LENS laser 3-D printer
  - Advanced manufacturing feedstock glovebox which houses powder handling and powder processing equipment
- Inert, non-radiological glovebox
  - Mockup glovebox providing a test bed to evaluate equipment prior to installation in a radiological glovebox

Idaho National Laboratory

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

ADVANCED MANUFACTURING

AFF employs new fabrication technology for nuclear fuel and other nuclear components. This results in materials that have properties and geometries that cannot be achieved through traditional fabrication methods. The manufacturing is done through advanced powder metallurgy in the case of the SPS and the dry bag isostatic press and through 3D printing with the various systems in the facility. Key equipment includes:

- Spark plasma sintering (SPS)/field assisted sintering (FAS) system
- Dry bag isostatic press system to manufacture unique material shapes from constituent powders using a high-pressure fluid.
- Feedstock preparation and processing
- LENS laser 3D printer
- Direct energy deposition (DED) additive manufacturing system
- Digital light processing (DLP) additive manufacturing system

EXPERIMENT ASSEMBLY

AFF is also used to assemble irradiation experiments that will be tested in various nuclear reactors. The experiments range from rodlet specimens consisting of fuel and cladding to capsule assemblies which often integrate a suite of instrumentation and fuel specimens of various types and geometries. This involves tightly controlled tolerancing, complex assembly of the sample and the various instrumentation needed for monitoring, targeted atmospheric control, and novel welding methods to ensure proper closure and specimen atmosphere. The key equipment supporting this work includes:

- Laser welding system for fuel cladding and irradiation test vehicles.
- Micro-TIG welding system for assembly of delicate capsule instrumentation
- Leak testing equipment to support helium leak checks of specimens up to 7 ft long and 5.5″ in diameter
- Weld under pressure system (WUPS) used to seal-weld rodlet and capsule specimens pressurized up to 500psig with any inert gas.
- Capsule assembly pressurization system (CAPS) used to pressurize experiment capsules through a one-way valve integral to experiment assemblies
- Custom lathe welder for rodlet instrumentation and development of techniques applicable to pre-irradiated fuel specimens.

OTHER EQUIPMENT/ PROCESSES

- Small metallographic station for optical analysis
  - » Medium speed saw
  - » Hot mount press
  - » Rotary polisher
  - » Leica optical microscope for examination of metallography mounts or other specimens
- Plunge EDM for processing fuel specimens requiring a high degree of precision.
- Czochralski method crystal puller to obtain pure, single crystals for scientific analysis

FOR MORE INFORMATION

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An analyst works with the gas manifold in a laboratory.

Analytical Research Laboratories

The Analytical Research Laboratories (ARL) at Idaho National Laboratory's Materials and Fuels Complex provide the chemical, radiochemical, physical and analytical data needed for various research and engineering development programs, and for applied research and engineering development activities supporting advanced nuclear fuel design, waste management, environmental and other INL programs.

The laboratories receive samples from across INL, as well as outside entities. These samples include irradiated and unirradiated fuels and materials, and samples needed for testing related to material accountability, radiation monitoring, process monitoring and environmental monitoring. The laboratories also support engineering development activities such as the preparation of samples for irradiation testing.

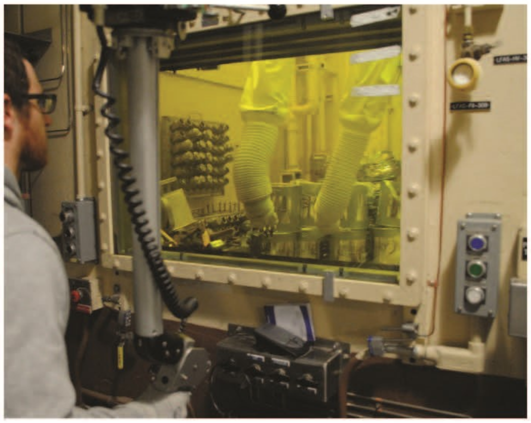
The main features and equipment in the labs' A-wing include six interconnected hot cells, gloveboxes, a chemistry laboratory, a 5-ton overhead bridge crane and other cask handling equipment. The primary features of the B-wing include state-of-the-art analytical instrumentation, general chemistry laboratories, air and inert atmosphere gloveboxes, fume hoods, counting rooms and assay equipment.

The ARL maintain equipment typical of a standard chemistry laboratory, including furnaces, X-ray diffractometers and equipment to test fundamental physical properties. The laboratories also host several unique fuel fabrication capabilities in the Casting Laboratory, including the INL-designed glovebox advanced casting system (GACS) furnace. This furnace casts metallic fuel samples containing transuranic elements with greater efficiency and less waste than previous designs.

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 forms, and samples.
- Analytical chemistry support for nuclear forensics.
- Determination of stable and radioisotopic content in a variety of matrices.
- Radioisotope separation.
- Characterization of engineered materials.
- Expertise in characterization of engineered materials and the nuclear fuel life cycle.

Idaho National Laboratory



An analyst receives samples in hot cell 1.

TECHNICAL INFORMATION

The mission of the ARL is to perform chemical, radiochemical and physical measurements, provide nondestructive analysis measurements and conduct applied research and engineering development activities that support advanced reactor design, waste management, environmental and other programs at MFC and INL. Our mission is accomplished through a broad range of analytical chemistry capabilities.

The ARL receive a variety of samples from across INL, as well as from outside entities. Sample types include liquids, solids, gases and irradiated/unirradiated fuels/materials related to research and development activities, material accountability, radiation monitoring, process monitoring and environmental monitoring. The labs also support engineering development and testing activities by creating unique standards and preparing samples for irradiation testing. ARL scientists possess a broad range of expertise as outlined below.

KEY EXPERTISE:

- Analysis and characterization of as-built and post-irradiated nuclear fuels, materials and reactor components
- Analysis of hazardous, mixed, or highly radioactive wastes, other waste forms and samples
- Analytical chemistry support for nuclear forensics.
- Burnup analyses.
- Determination of stable and radioisotopic content in a variety of matrices.
- Elemental/isotopic separation.
- Characterization of engineered materials and the nuclear fuel life cycle.
- Method development/ experimental design.

KEY CAPABILITIES/ INSTRUMENTATION:

- Six interconnected air atmosphere hot cells
- Gloveboxes
  - Hot cell #1
  - Shielded ICP-OES at hot cell #6
  - Special projects
  - Radiochemistry
  - Waste form testing
  - Casting lab
  - Wet prep
  - Fresh fuels
  - CNO (carbon/ nitrogen/oxygen)
- Fume hoods
- Counting laboratories
  - Gamma
  - Alpha spec
  - Gas flow proportional counters
  - Liquid scintillation
  - Low background counting laboratory in pre-WWII steel vault using low-background concrete
- Gas chromatograph
- Gas pressurized extraction chromatography (GPEC) (manual and automatic)
- Gas mass spectrometer (portable)
- High resolution multi-collector fission gas mass spectrometer (MC-GMS) (2022)
- Mass spectrometers
  - Inductively coupled plasma (Quad-ICP-MS)
  - High-resolution inductively coupled plasma (HR-ICP-MS)
  - Multi-collector inductively coupled plasma (MC-ICP-MS)
  - Inductively coupled plasma time of flight (ICP-TOF)
  - Thermal ionization mass spectrometer (TIMS)
- Elemental analysis
  - Optical emission (ICP-OES)
  - Femtosecond laser-induced breakdown spectrometer (fs-LIBS)
- Light element (CSONH) combustion and inert fusion analyzers
- Capillary electrophoresis (CE)
- High performance liquid chromatography (HPLC)
- X-ray fluorescence (XRF)
- Microwave-assisted digestor
- 3D laser scanning confocal microscope
- 4K digital microscope
- Hot cell particle picking microscope
- Hot cell entrained gas collector
- Mass separator (rad and non-rad)
- Non-destructive barrel scanner
- Hot uniaxial press (HUP), muffle, well, and tube furnaces
- Glovebox advanced casting system (GACS) furnace
- Wet chemistry laboratories

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Engineering Development Laboratory

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

The Engineering Development Laboratory is used for fabrication, assembly, mock-up and testing for the Space Nuclear Power & Isotope Technologies Division.

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The Engineering Development Laboratory (EDL) 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

Idaho National Laboratory

21-50083

Experimental Fuels Facility

Fuel Fabrication, Process Development

EFF includes uranium metal forming equipment, including a computer numerical control (CNC) lathe, electrical discharge machine, a cold rolling mill, and other fabrication equipment, which enable the creation of virtually any fuel type.

The Experimental Fuels Facility (EFF) is a 5,000-square-foot nuclear fuel fabrication facility at Idaho National Laboratory's Materials and Fuels Complex. EFF houses a wide range of fuel fabrication and material handling capabilities. Established in 2012, EFF supports INL's mission as the lead nuclear energy research lab for the nation.

Equipment and processes in EFF support customers in DOE's Office of Nuclear Energy and private industry partners. EFF hosts a wide range of INL's new lab-scale capabilities for supporting the nation's need to develop even safer, more reliable nuclear fuels.

Basic uses of EFF include uranium and uranium alloy casting and extrusion, processing uranium metal and ceramics at all enrichments, fabrication and handling of alloys and powders, and a machine shop with radiological and non-radiological areas.

KEY EQUIPMENT:

- 4 fume hoods (3 radiological)
- Inert atmosphere uranium processing glovebox line for fabrication and handling of alloys and powders
- High-temperature applications (arc melting furnace, molten salt bath, billet casting furnace, high-temperature annealing furnace)
- Cold crucible gas atomizer with a 5kg capacity able to process uranium alloys
- Fuel experiment assembly equipment (annealing quench furnace, sodium glovebox, sodium settling furnace, orbital capsule, and cladding welding)
- Various other mills, presses, and other fabrication capabilities to support advanced fuels development
- Machine shop for machining encapsulated fuel components
- 150-ton extrusion press system (including a molten salt furnace and a straightener/draw bench)

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The Experimental Fuels Facility supports customers in the Department of Energy's Office of Nuclear Energy and private industry partners.

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 processing (all enrichments):
- Alloying
- Casting
- Extrusion
- Atomization
- Machining
- 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
- Machine shop with both radiological and non-radiological areas to support advanced fuel development

KEY INSTRUMENTS:

- Radiological fume hoods (3)
- 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) lathes and mills
- Electrical discharge machine
- Centerless grinder
- Rolling mill
- Shears and punches
- 150-ton extrusion press
- Hydraulic straightener/ draw bench
- Gas atomizer
- Arc-melting furnaces
- Molten salt bath
- Billet-casting furnace
- High-temperature annealing furnace

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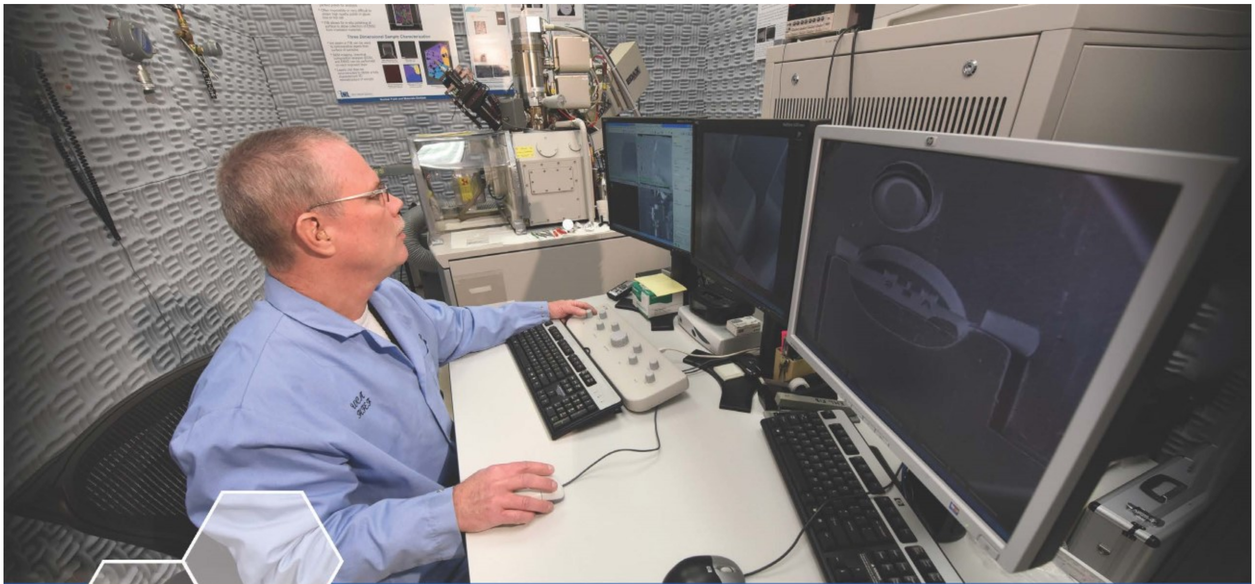

Electron Microscopy Laboratory

Post-irradiation Examination

Researchers at the Electron Microscopy Laboratory use electron and optical microscopes to characterize materials as well as prepare high quality samples from radioactive materials.

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:

- JEOL JSM-7000f SEM with energy dispersive X-ray spectroscopy (EDS), wavelength dispersive spectroscopy (WDS) and electron backscatter diffraction (EBSD) detectors
- Gatan precision ion polishing systems (PIPS-2)
- Gatan precision etching and coating system (PECS)
- LYRA 3GM is a FIB/SEM workstation from TESCAN. The system is equipped with Aztec Oxford Instruments suite for EDS/EBSD characterization, LEICA cryo-stage, and Alemnis nanomechanical testing. The microscope has the Omniprobe200 manipulator for in-situ sample lift out, and two gas injection systems for carbon and platinum deposition. The integration of complementary analytical tools will allow researchers to characterize complex samples and rapidly solve analytical problems.
- FEI Talos F200x S/TEM equipped with Super-X EDS, Gatan Quantum electron energy loss spectroscopy (EELS) and ASTAR/TOPSPIN systems, enabling high-resolution/high-speed imaging and chemical analysis and grain orientation and strain mapping

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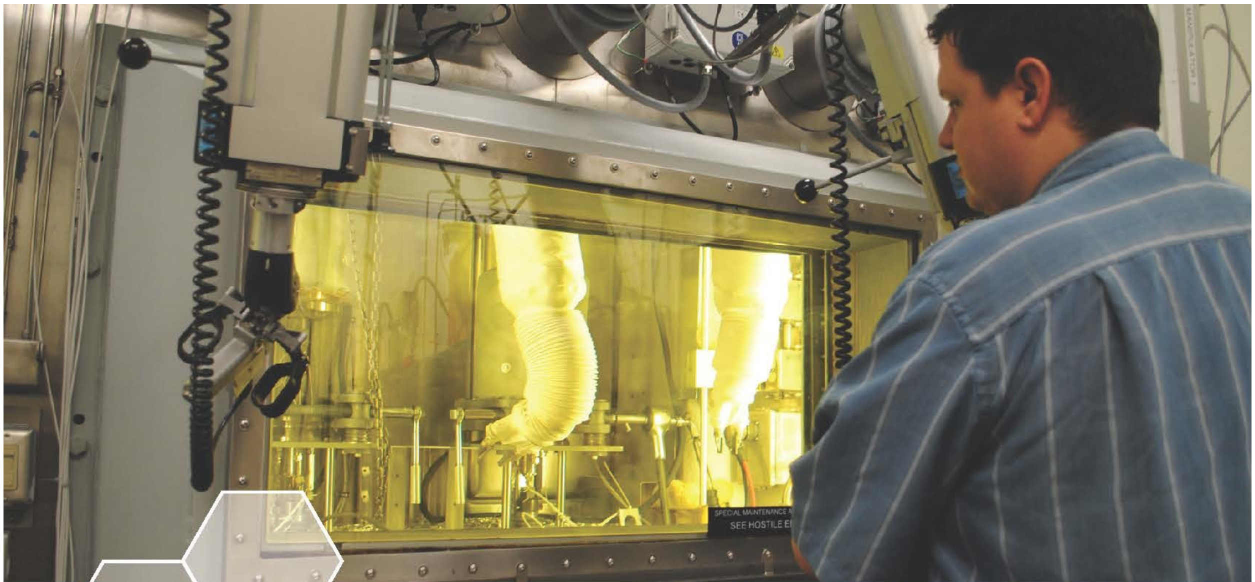

Fuels and Applied Science Building

Fuel Fabrication, Irradiation, Characterization, Post-irradiation Examination, Process Development

The Irradiation-Assisted Stress Corrosion Cracking hot cells are located in FASB's west room.

The Fuels and Applied Science Building (FASB) is a radiological facility that houses small hot cells, gloveboxes, hoods, and a variety of equipment that supports nuclear energy research and development. This facility is a key part of the fuel development mission of the Materials and Fuels Complex at Idaho National Laboratory. FASB's capabilities include research and development related to nuclear fuel fabrication, used fuel treatment options, nuclear waste management, and other scientific activities.

The FASB west room contains inert atmosphere gloveboxes used for development of various nuclear fuels, treating waste from glovebox operations, working with corrosive materials and testing equipment that will be used in other facilities. A set of small hot cells houses an irradiation-assisted stress corrosion cracking system used for evaluating structural material for nuclear light water reactor life extension.

The east room contains material processing areas, a thermal properties laboratory, a sample preparation area and a characterization area that contains electron and optical microscopes and X-ray diffraction X-ray fluorescence equipment.

KEY CAPABILITIES:

- Irradiation-assisted stress corrosion cracking hot cells
- Two inert fuel development gloveboxes
- Pyrochemistry glovebox
- 3 radiological hoods and one non-radiological hood
- Thermal properties characterization instruments (laser flash, dilatometer, differential scanning calorimeter)
- Cobalt-60 gamma irradiator
- Lab-scale fabrication equipment (hot isostatic press, arc melting furnace)
- Metal and ceramic powder processing equipment (atomizer, milling, mixing, pressing/sintering)
- Numerous heat treating and sintering furnaces

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.

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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 building houses laboratory scale fuel fabrication capability for both dispersion and foil bearing nuclear fuel plates, a pyrochemistry glovebox housing a laboratory scale electrorefiner and other furnaces to perform separations experiments. It also has a set of hot cells, including one that houses an irradiation assisted stress corrosion cracking system that measures corrosion and crack propagation in nuclear reactor structural materials as part of the light water reactor life extension program.

The building also contains a sample preparation and characterization suite with optical and electron microscopes, thermal properties and other characterization equipment.

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:

- Two inert fuel fabrication gloveboxes
  - Arc-melting furnace with casting capability
  - Hydraulic press
  - Gram-scale atomizer
  - Hydriding/nitriding apparatus
  - Inert box welding station
- Inert pyrochemistry glovebox
  - Molten salt electrorefiner
  - Oxide reduction furnace
  - Sodium distillation furnace
  - Fuel form casting
  - Multi function furnace
- Three radiological fume hoods
- Irradiation assisted stress corrosion cracking
  - Decontamination station
  - In-cell imaging microscope
  - Pressurized water reactor testing rig
  - Boiling water reactor testing rig
- Fabrication equipment
  - Hot isostatic press
  - Hot rolling mill
  - Multiple furnaces
- Sample preparation and characterization
  - High- and low-speed saws
  - Auto polisher
  - Three scanning electron microscopes
  - X-ray diffractometer
  - X-ray fluorescence
  - Optical microscopes
  - Particle-size analysis
  - Microhardness testing
  - Density measurement (helium pycnometer)
  - Differential scanning calorimeter
  - Dilatometer
  - Laser-flash thermal diffusivity
  - Positron-annihilation spectroscopy
  - Tensile, compression and bend testing
  - Ultrasonic testing
- Cobalt-60 gamma irradiator
- Solvent test loop

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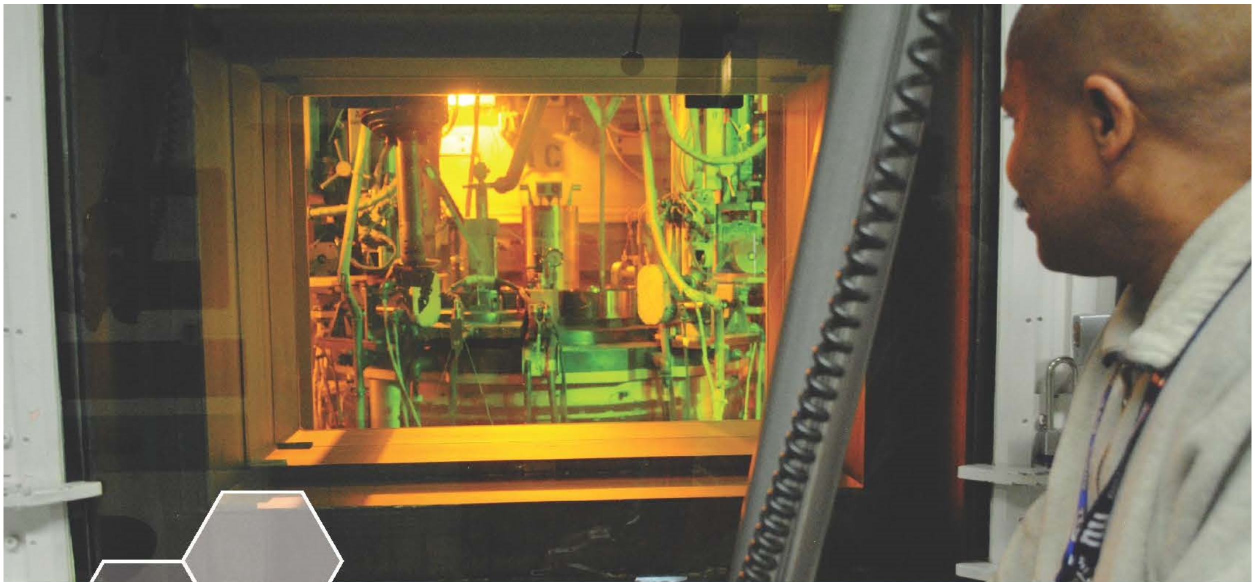

Fuel Conditioning Facility

Advanced Fuel Cycle Research On Material Separations and Waste Form Development

INL's Fuel Conditioning Facility supports work to demonstrate the technical feasibility of a nuclear recycling technique called pyroprocessing.

The Fuel Conditioning Facility (FCF) at Idaho National Laboratory's Materials and Fuels Complex supports nuclear energy research and development for the U.S. Department of Energy and other customers. FCF's unique capabilities make it an ideal facility for its primary mission to support treatment of DOE-owned sodium-bonded metal fuel.

In a secondary role, FCF also supports multi-program work related to integrated fuel cycle research and development with a focus on material recovery and waste form development.

FCF consists of two hot cells, one having an air atmosphere and the other having an inert argon gas atmosphere, which enables technicians to work safely with radioactive nuclear materials from behind 5-foot-thick shielding walls.

KEY CAPABILITIES

- Two heavily shielded hot cells equipped with remotely operated manipulators to safely handle irradiated fuels and materials
- Instruments used to prepare and size elements for treatment, such as element chopper, vacuum inspection, and the vertical assembler/dismantler
- Engineering-scale equipment including molten salt electrorefiners and high temperature furnaces capable of sodium neutralization and uranium recovery
- Systems to support handling of heavily shielded shipping casks for fuel receipt and water disposal
- Pneumatic "rabbit" system for transfer of material samples to and from MFC's Analytical Laboratory (AL) or its Hot Fuel Examination Facility (HFEF)
- Mock-up area to allow thorough testing of new remotely operated systems prior to their installation into FCF, HFEF, or AL hot cells
- Advanced Fuel Cycle R&D argon atmosphere glovebox

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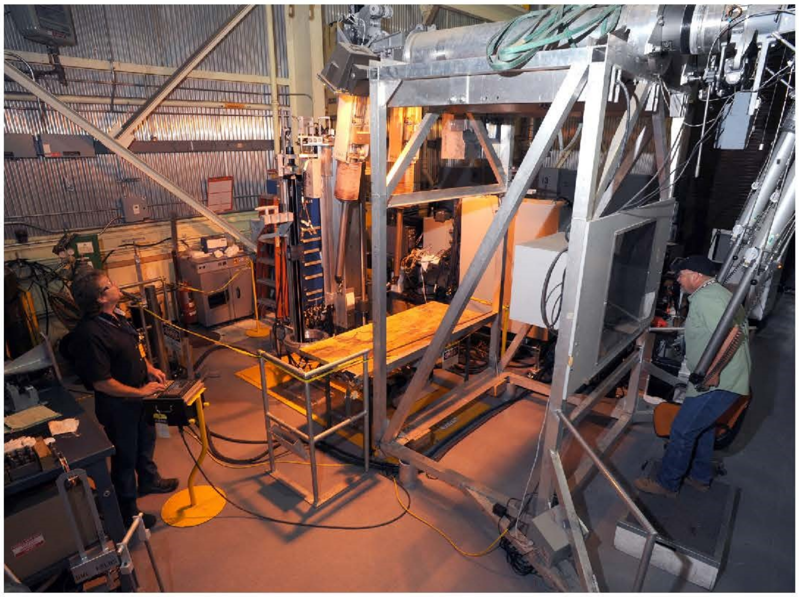

FCF includes a mock-up shop where technicians can build and test new hot cell equipment before installing it into the hot cell.

TECHNICAL INFORMATION
The Fuel Conditioning Facility's (FCF) primary mission is to support pyroprocessing treatment of DOE-owned sodium-bonded metal fuel.

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
- Lab-scale process development in inert atmosphere gloveboxes

KEY INSTRUMENTS:

- Electrochemical separations/sodium neutralization experimentation/ treatment via two molten salt electrorefiners
- High temperature vacuum atmosphere furnaces (cathode processor, casting furnace, & multi-function furnace)
- Pneumatic rabbit transfer system
- Canister-cutting machine
- Manipulator repair glovebox
- Vacuum inspection station/bottle cutting, production element chopper
- Air & argon atmosphere hot cells
- Suited entry repair area
- Mock-up shop

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Arc melting in the Advanced Fuel Cycle Initiative (AFCI) glovebox supports fabrication of experiments for irradiation at reactors such as the Advanced Test Reactor.

Fuel Manufacturing Facility

Fuel Fabrication, Nuclear Material Management

The Fuel Manufacturing Facility (FMF) is a nuclear facility that consists of multiple workrooms and a material storage vault. This facility complements a host of capabilities within the Materials and Fuels Complex at Idaho National Laboratory, the nation's lead nuclear energy research lab.

FMF was constructed in 1986 for the purpose of housing binary (i.e., uranium and zirconium) fuel and its associated equipment to fabricate the driver fuel for the Experimental Breeder Reactor-II (EBR-II). With the shutdown of the EBR-II reactor, this equipment was removed and the focus at FMF transitioned to research and development (R&D) of transuranic metallic and ceramic fuels. Additionally, the material storage vault contains and supplies various INL and off-site facilities with feedstock materials

KEY EQUIPMENT/ CAPABILITIES:
4 inert gloveboxes

- Advanced Fuel Cycle Initiative (AFCI) glovebox
  - Provides the capabilities to develop transuranic metallic and ceramic fuel experiments for irradiation
  - Feedstock production/ purification
  - Characterization sample fabrication
  - Equipment includes:
    - Arc melter
    - Distillation/ tube furnace
    - Sintering furnace
    - Orbital welder
    - Ceramic powder mixing/pressing equipment
- Neptunium repackaging glovebox (NRG):
  - Provides the capability to recertify neptunium packages for transport to other DOE facilities
  - Supports material inspection/inventory
- Special nuclear materials (SNM) glovebox:
  - Provides the capability for legacy uranium material recovery for reuse
  - Supports uranium material inspection/ inventory/breakouts
  - Uranium roasting and casting capabilities

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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.

- Transuranic breakout glovebox (TBG)
  - » Supports transuranic material inspection/ inventory/breakouts

Radiography

- Provides the capability for verification of experiment fabrication requirements such as fuel placement and rodlet/capsule welding

Vault storage

- Receipt and storage of programmatic materials

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
    - Roasting
    - Casting
    - Feedstock breakout
  - » 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

Post-irradiation Examination of Fuels and Materials

The Hot Fuel Examination Facility is the largest hot cell dedicated to radioactive material research at Idaho National Laboratory.

The Hot Fuel Examination Facility (HFEF) is Idaho National Laboratory's flagship facility for conducting post-irradiation examinations of fuels and materials. HFEF, located at the Materials and Fuels Complex, is a national research asset with the largest inert atmosphere hot cell dedicated to nuclear materials research in the U.S.

HFEF provides the ability to remotely handle and perform detailed nondestructive and destructive examination of highly irradiated fuel and material samples. Its argon-atmosphere hot cell, labs and special equipment handle a variety of fuel forms, including tiny particles, four-foot research reactor plates and full-sized commercial rods. HFEF supports INL's mission of research and development of safer and more efficient fuel designs.

KEY CAPABILITIES:

- HFEF has two large, shielded hot cells. The main cell, which is 70 by 30 feet, is stainless steel-lined. It's fitted with two 5-ton cranes and 15 workstations, each with a 4-foot-thick window of oil-filled glass and a pair of remote manipulators. The second hot cell is an air cell used to decontaminate materials and equipment.
- Laser puncture and gas collection with the gas assay sample and recharge (GASR) from fuel samples helps researchers gain needed information on fission gas and helium release.
- Precision gamma scanning (PGS) allows scientists to precisely determine the location of radioactive elements in fuel and material samples.
- The fuel accident condition simulator (FACS) furnace enables fuel and material sample testing under worst-case scenarios involving temperatures of up to 2,000 C for extended periods. This allows scientists to understand performance and improve the safety of fuel designs.
- The Neutron Radiography Reactor is a 250 kW steady state Training Research Isotopes General Atomics (TRIGA) reactor co-located within and adjacent to HFEF. It is equipped with two separate radiography stations for neutron radiography of fuel and materials.
- Fuel refabrication for testing in the Transient Reactor Test (TREAT) facility.

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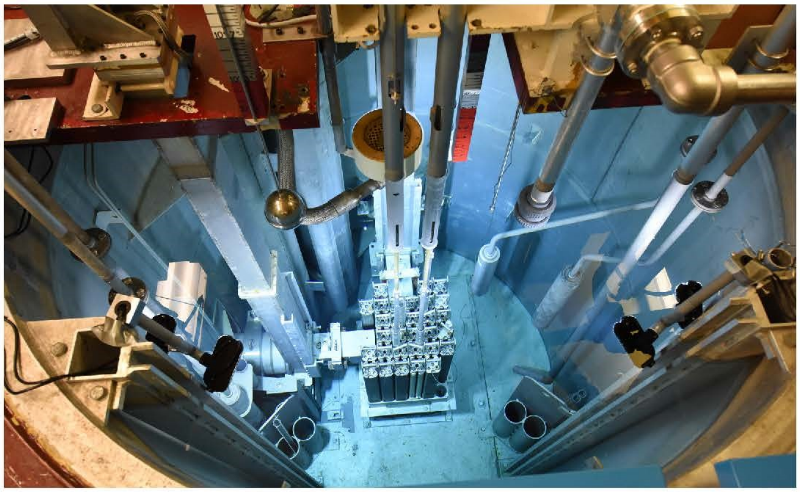

The NRAD reactor provides a neutron source for indirect-film and digital radiography of irradiated fuels and materials, neutron computed tomography and neutron diffraction

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 film and digital radiography
  - » Neutron tomography
  - » Neutron diffraction
  - » 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.
- Precision milling, welding, and machining.
- 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.

KEY INSTRUMENTS:

Nondestructive instruments include:

- NRAD reactor
- Autoradiography
- Visual examination machine
- Eddy current probe for measurement of oxide thickness
- Precision gross and isotopic gamma spectrometer
- Element contact profilometer bow & length machine (fuel rods)
- Profilometry and eddy current measurement bench (fuel plates)
- Pycnometer

Destructive instruments include:

- Laser puncture gas collection and analysis system
- Fuel accident condition simulator (FACS) furnace
- Metal waste form furnace
- Remote load frame

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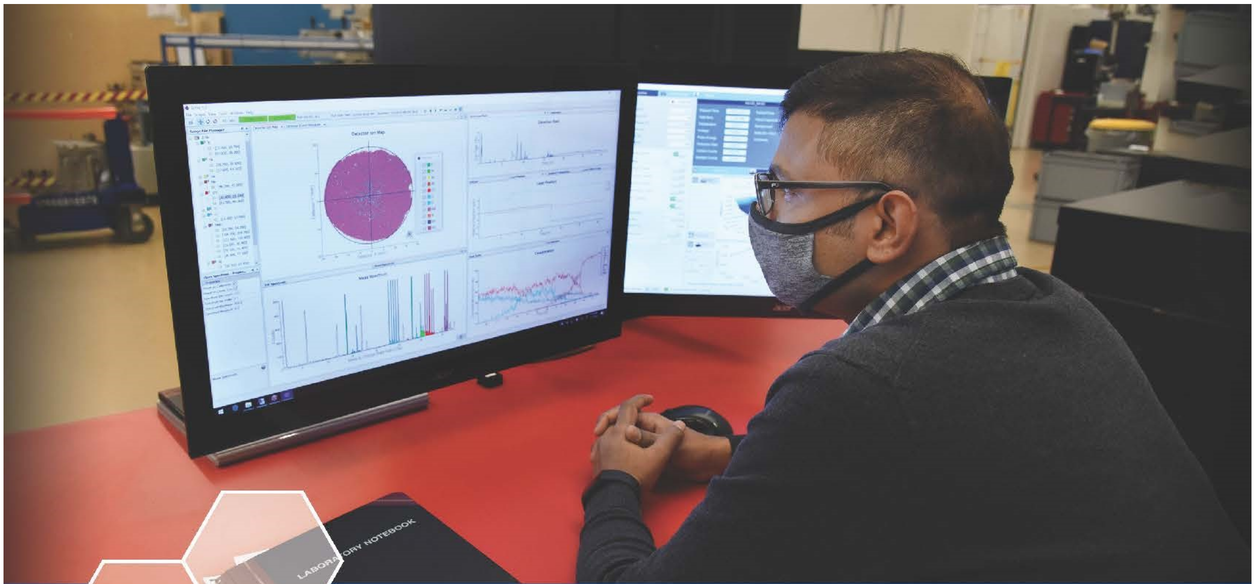

Irradiated Materials Characterization Laboratory

Advanced Post-Irradiation Examination

The Irradiated Materials Characterization Laboratory is home to a variety of high-end instruments that allow researchers to study irradiated fuels and materials at the micro, nano and atomic levels, which is where irradiation damage occurs.

The Irradiated Materials Characterization Laboratory (IMCL) is a unique, 12,000-square-foot facility located at Idaho National Laboratory's Materials and Fuels Complex. The hazard category 2 facility incorporates many features designed to allow researchers to prepare and conduct microstructural-level investigations on irradiated fuel safely and efficiently.

IMCL focuses on microstructural, microchemical, and micromechanical analysis and thermophysical 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 for the study of nuclear fuel and materials.

Combined with INL's advanced computer modeling techniques, this understanding will enable advanced fuel designs, and reduce the time needed for fuel development and licensing.

BASIC CAPABILITIES:

- Preparation of high-activity samples
- Optical microscopy
- Electron probe microanalysis (EPMA)
- Dual-beam focused ion beam (FIB)
- Transmission electron microscopy (TEM)
- Local electrode atom probe (LEAP)
- Scanning electron microscopy (SEM)
- Measurement of material physical and thermal properties
- X-ray microscopy (XRM)
- X-ray diffractometer (XRD)

Idaho National Laboratory

KEY CAPABILITIES/INSTRUMENTS:

Application	Instrument	Capabilities	Configuration
Sample Preparation	SSPA - Shielded sample preparation area	Optical microscope, polishing and grinding, sample cutting in hot cell, glovebox, and hood	Shielded
Advanced Microscopy, Microchemistry, Micromechanical Testing	SEM - JEOL 7600	High-resolution scanning electron microscope (SEM) equipped with electron back-scatter diffraction, energy dispersive X-ray spectroscopy (EDS) and wavelength dispersive spectroscopy (WDS) detectors	Benchtop
	EPMA - Shielded Cameca SX100R	Quantitative compositional analysis of solid specimens on a micrometer spatial scale. Detectors and electronics are shielded to 3 Ci of 137 Cs to allow for trace element detection. Measures elements from B to Cm.	Shielded
	STEM - FEI Titan Scanning Transmission Electron Microscope	Equipped with probe corrector, super-X EDS, electron energy loss spectroscopy (EELS), DENSolutions D6 heating holder (1573 K), tomography holders, vacuum transfer holder, Hysitron PI-95 PicoIndenter	Benchtop
	APT - LEAP 5000 Atom Probe	3D imaging and chemical analysis at sub-nanometer scale	Benchtop
	FIB - FEI Quanta 3D FEG Focus Ion Beam	Preparation of minute samples for TEM, APT, and micromechanical testing	Shielded
	FIB - Thermo G3 Plasma Focus Ion Beam	Preparation of block samples for rapid 3D reconstruction, micromechanical testing, and microscale thermal property testing	Shielded
	FIB - Thermo G4 Helios Hydra Plasma Focus Ion Beam with TOF-SIMS	Equipped with secondary ion mass spectrometer (SIMS), EDS, and electron backscatter diffraction (EBSD) for sample preparation, imaging, microstructural, and chemical analysis	Benchtop
Thermophysical property measurement	LFA - Netzsch LFA 427 laser flash analyzer	Thermal diffusivity, contact resistance from room temperature to 2000 C, specific heat, thermal conductivity (under development)	Shielded
	TGA/MS - Simultaneous TGA/DSC+MS Netzsch STA 409C Skimmer	Measure specific heat, phase transformation temperatures and enthalpies, fission off-gas composition, mass change from room temperature to 2000 C	Shielded
	TCM - Thermal conductivity microscope	Spatial resolved thermal diffusivity, thermal conductivity with a spatial resolution of 50 µm from room temperature to 300 C	Shielded
	PPMS - Quantum Design Physical Property Measurement System	Electrical, thermal, thermodynamic and magnetic property measurement at temperatures from 1.8 K to 400 K and magnetic field range 0-9 T	Benchtop
Structure analysis and tomography	XRD - PANalytical powder X-ray diffractometer	Bulk X-ray diffraction with heating stage	Benchtop
	XRM - ZEISS Xradia 520 Versa X-ray microscope	Nondestructive 3D imaging of materials over 4 orders of magnitude in length scales (0.1-100 cm)	Benchtop
Mechanical testing	Mini-tensile tester	Tensile testing with digital image correlation (DIC)	Shielded

FOR MORE INFORMATION

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21-50083_IMCL_R2 (Updated: 2021)

Materials Security and Consolidation Complex

Waste Forms and Separations

The Materials Security and Consolidation Complex supports radioactive material storage and repackaging, developing contamination techniques for Homeland Security and developing fuel cycle research capabilities.

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The Materials Security and Consolidation Complex (MSCC) is located at the Idaho Nuclear Technology & Engineering Center (INTEC) and managed by the Materials and Fuels Complex Production Facilities and Infrastructure Division.

BASIC CAPABILITIES:

- Radioactive material storage and repackaging capabilities
- 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.

KEY INSTRUMENTS:

- ZIRCEX process equipment

21-50083_MSCC_R2 (Updated: 2022)

Research Collaboration Building

The Research Collaboration Building, completed in 2019, provides a landing spot, collaborative working space and training areas for the growing number of students, visiting researchers and postdoctoral researchers at MFC.

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Idaho National Laboratory

The Research Collaboration Building (RCB) provides dedicated space for visiting researchers to interact with INL research staff at the Materials and Fuels Complex.

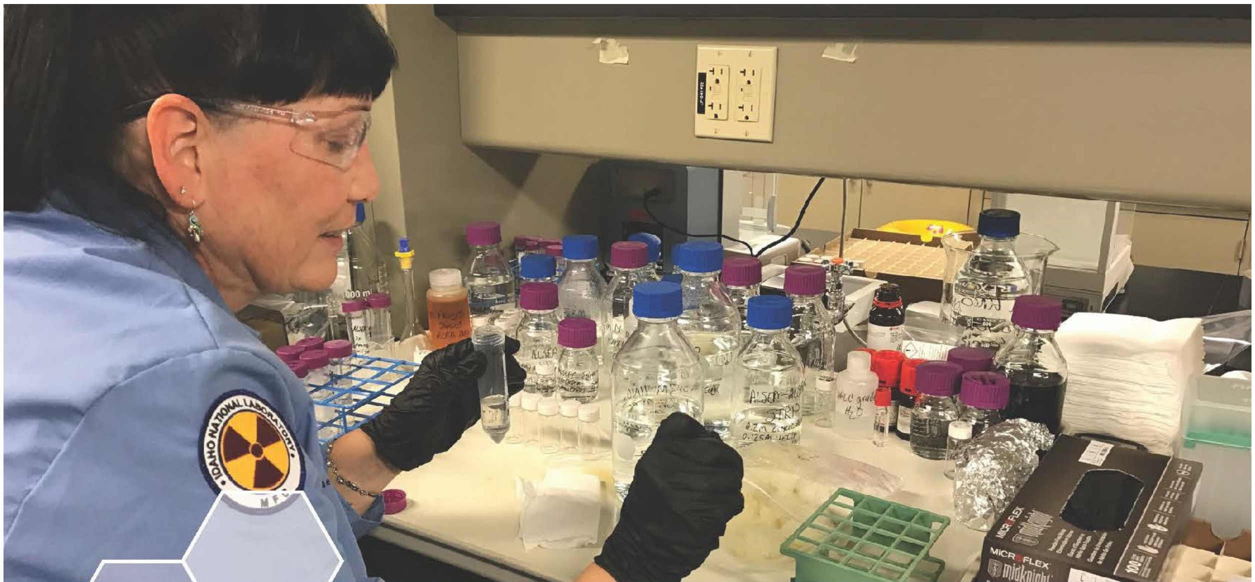
The two-story, 13,901-square-foot RCB is located outside of MFC's perimeter security fence west of the entrance, providing a landing spot, collaborative working space and training areas for the growing number of students, visiting researchers and postdoctoral researchers at MFC.

Funding for the RCB was provided through the Nuclear Science User Facilities (NSUF), which facilitates the advancement of nuclear science and technology by providing nuclear energy researchers access to world-class capabilities at no cost to the researcher.

BASIC CAPABILITIES:

- 28 offices for MFC researchers, NSUF staff and long-term visitors.
- 23 researcher work stations and five collaboration spaces where INL scientists can host and work with their research partners and analyze data.
- A 1,000-square-foot laboratory (non-radiation) that will be used to develop and test instrumentation before it is installed in a radiological facility.
- The ability for researchers to monitor research equipment at the Irradiated Materials Characterization Laboratory (IMCL), which focuses on microstructural, thermal, and mechanical characterization of irradiated nuclear fuels and materials.

21-50083_RCB_R1 (Updated: 2021)



Radiochemistry Laboratory

Characterization, Post-irradiation Examination

The Radiochemistry Laboratory is located adjacent to the Analytical Research Laboratories and focuses on analysis and characterization of nuclear fission products, radioisotope separation and element dissolution.

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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

Idaho National Laboratory

21-50083_RCL_R0 (Updated: 2021)

Space Nuclear Power and Isotope Technologies Division at INL

Providing Unique Capability for Enabling Deep Space Exploration

Workers in the Space and Security Power Systems Facility assemble, test and deliver power systems for NASA deep-space missions.

Idaho National Laboratory (INL) hosts a unique capability for enabling deep space exploration that spans the limits of our own solar system and beyond. Located at the Materials and Fuels Complex, the Space Nuclear Power and Isotope Technologies (SNPIT) division manages the Space and Security Power Systems Facility (SSPSF), where assembly and testing capabilities for radioisotope power systems (RPSs) reside.

Two-dozen RPSs have provided electricity to space missions since 1961. RPSs provide safe, reliable power where alternative power sources are not possible. Both Pluto New Horizons (flew by Pluto in 2015) and Curiosity rover (currently on Mars) were assembled and tested at INL. The Mars 2020 rover mission, which landed on Feb. 18, also uses an INL RPS.

RPSs provide the power to operate spacecraft or rover systems, such as scientific instruments, robotic arms, computers, radios, and drive systems. They are fueled with plutonium-238, which gives off a steady supply of heat as the material decays. Thermocouples are used to create voltage from the temperature difference between the hot interior and the cold exterior in deep space. The power supply created using an RPS is steady, reliable, and lasts for decades – the systems launched in 1977 are still operating and sending back data from well beyond the edges of the solar system.

At SSPSF, personnel complete RPS assembly operations, involving placement of fueled clads into graphite components to form general purpose heat source modules. Next, assembly starts when modules are placed into a converter that houses thermocouples, together comprising the RPS. Following RPS assembly, a series of acceptance testing is completed. After successful completion of acceptance testing, INL transports the RPS to Kennedy Space Center. The SNPIT division staff members provide ground operations support involving the RPS at Kennedy Space Center and Cape Canaveral Air Force Station until after launch.

The SNPIT division also performs unique isotope production for medical and NASA applications. The division uses the Advanced Test Reactor to produce cobalt-60 for the Department of Energy-Office of Science. The cobalt-60 is used for medial purposes. ATR, in collaboration with Oak Ridge National Laboratory, is also used for producing plutonium-238 for NASA applications.

Idaho National Laboratory

Space and Security Power Systems Facility

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

BASIC CAPABILITIES

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

KEY INSTRUMENTS

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

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21-50083_SNPIT-SSPSF_R3 (Updated: 2021)

Sample Preparation Laboratory

Post-irradiation Examination

The Sample Preparation Laboratory is under construction at the Materials and Fuels Complex. The facility is designed for high-throughput characterization of gamma-emitting materials.

Idaho National Laboratory's Sample Preparation Laboratory (SPL) is designed as a Hazard Category 3 facility to serve as a national center for accelerated research, development, and qualification of nuclear materials. SPL's nuclear materials analysis capabilities will increase the understanding of nuclear materials, leading to advancements that will extend the life of the current fleet of reactors and development and deployment of materials for advanced reactors.

Construction of SPL began in June 2020.

SPL will play an important role in America's energy future. Extending the life of the current reactor fleet requires a deeper understanding of the degradation mechanisms and service life of the in-core structural materials used in these systems. Likewise, the economic and safety performance of advanced reactor technologies relies on the development and qualification of improved fuel cladding and structural materials. The national infrastructure for mechanical testing, detailed microstructural examination, and surface characterization of high-activity irradiated material in the U.S. is limited. This limited infrastructure constrains critical material development and qualification activities; SPL is designed to fill this gap.

SPL provides dedicated high-throughput sample preparation, mechanical testing, surface science, and microstructural analysis that address these limitations. Its automated operations in fourth-generation shielded cells will efficiently generate information on material mechanical performance, microstructure, and environmental effects over eight orders in length scales. Coupled with modeling and simulation, the increased quality and volume of information available will greatly reduce the time required for development of new radiation-resistant materials. SPL is designed as a user facility to allow visiting researchers access to scientific instruments while minimizing exposure to radiological environments. Instruments are operated from control consoles outside of facility radiological boundaries or remotely from the Research Collaboration Building on the MFC site.

Idaho National Laboratory

Construction of the Sample Preparation Laboratory began in June 2020.

The capability to handle medium-sized and small casks typically used for material shipments allows direct material shipment to and from other sites, removing a significant barrier to cooperation with industry, universities, and other U.S. and international laboratories. Electrical Discharge (EDM) and conventional machining allow fabrication of samples appropriate for testing from larger sections of structural materials retrieved from operating or decommissioned reactors. These materials can then be reinserted into INL's Advanced Test Reactor to further accumulate irradiation damage at an accelerated rate, allowing accurate predictions of material properties.

BASIC CAPABILITIES

- Hazard Category 3 nuclear facility
- Fatigue and fracture toughness testing
- Tensile testing at ambient and elevated temperature
- Charpy impact testing
- X-ray photoelectron spectroscopy (XPS)
- Electron microscopy
- Hardness testing
- Shielded x-ray diffraction
- High throughput sample preparation Receipt of mediumsized casks (BRR, NRBK, GE-100, etc.)
- Automated sample transfers to instruments
- Heat treatment of irradiated materials
- Receipt of medium-sized casks (BRR, NRBK, GE-100, etc.)
- Remote operation of instruments
- Long-term storage of critical material samples
- Research space for user-defined instruments

PROJECT STATUS

- DOE Mission Need Approval – June 2015
- Critical Decision (CD)-1, Approval of Alternative Analysis and Cost Range – September 2016
- Completion of Facility Design – October 2018
- CD-2/3, Approve Performance Baseline and Start of Construction – January 2020
- Construction Start – June 2020
- Construction Completion – 3Q FY 2023 (forecast)
- Start of Operations – 2Q FY 2025 (forecast)

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A U.S. Department of Energy National Laboratory

21-50083_SPL_R2 (Updated: 2022)

Transient Reactor Test Facility

Irradiation

The Transient Reactor Test (TREAT) Facility allows researchers to test nuclear fuels and materials in off-normal and accident conditions, providing key data that helps improve safety and efficiency.

The Transient Reactor Test (TREAT) Facility at Idaho National Laboratory is a national asset that provides unique test results in an essential nuclear research field. It will foster the development of new ways to provide baseload and load following electrical power. Transient testing is an essential component of the United States and international efforts to develop robust, safer nuclear fuels, and to bring innovative reactor technologies to the market.

Transient testing involves the application of controlled, short-term bursts of intense neutron flux directed toward a test specimen in order to study fuel and material performance under off-normal operational conditions and hypothetical accident scenarios. After the transient test, the fuel or material is analyzed at a post-irradiation examination (PIE) facility. The results of these examinations are then evaluated and used in advancing fuel or material design and qualification.

TREAT is a highly capable test reactor. Detailed real-time monitoring of the specimens during a test is possible via the hodoscope, a system that detects fast neutron signatures from experiments, and other experiment and core instrumentation. This instrumentation, coupled with PIE, allows scientists to determine the appropriate safety limits for the fuels and materials in nuclear power reactors. TREAT's simple, self-limiting, air-cooled design can safely accommodate multipin test assemblies, enabling the study of fuel melting, metal-liquid reactions, overheated fuel and coolant reactions, and transient behavior of fuels for high temperature system applications.

The TREAT facility operated from 1959 through 1994, when it was placed in standby mode. A resurgence of interest in developing innovative nuclear technologies has driven demand for transient testing. TREAT was restarted in 2017 and is currently supporting experiment programs.

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 was restarted in 2017 after being placed on standby in 1994.

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 those used in 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 2017 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 up to several minutes duration)
- 120 kW steady state operation
- Testing capability for static capsules, sodium loops, water loops, and hydrogen 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

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21-50083_TREAT_R4 (Updated: 2022)

Zero Power Physics Reactor Facility

Nuclear Material Management, Nonproliferation Activities

The east and west transuranic surveillance gloveboxes are used for material inspections and packaging. They were placed into service in 2014.

The Zero Power Physics Reactor (ZPPR) is a nuclear facility at Idaho National Laboratory's Materials and Fuels Complex. The reactor portion of ZPPR was operated by Argonne National Laboratory-West between 1969 and 1992. In 1992, the ZPPR reactor was placed into nonoperational standby. The ZPPR reactor and auxiliary equipment have since been removed from the facility. The current capabilities of the ZPPR facility include storage, inspection, and repackaging of transuranic elements and enriched uranium. The facility also provides suitable areas and material handling capabilities to support homeland security material detection experiments and the training of military and first responders to deal with nuclear materials.

The ZPPR facility consists of a workroom, cell area, and material storage vault. Current facility activities are material inspections and packaging in the workroom/vault, National and Homeland Security testing and detection training in the cell area, and transuranic and uranium material storage in the vault. This includes routine activities conducted in the ZPPR vault/workroom to monitor and maintain the integrity of the ZPPR fuel plates and other fissile materials in storage.

Planning is underway to modify the cell area to host reactor demonstrations and other nuclear projects.

KEY EQUIPMENT:

- Workroom hood
- East and west transuranic surveillance glovebox
- Vault storage for special nuclear material
- Cell area with very low radiation background environment

Idaho National Laboratory

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.

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

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21-50083_ZPPR_R0 (Updated: 2021)

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Appendix C

MFC Core Competencies

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Appendix C

MFC Core Competencies

Additional information on the core competencies supplied by the MFC Research and Production Divisions (Section 4) is provided in this appendix, including proposed areas of research to advance the knowledge base of the competencies. To recap, these core competencies are

- Nuclear fuels fabrication
- Fuel characterization
- Materials characterization: Radiation damage in cladding and reactor components
- Fuel recycling and nuclear material management
- Transient irradiation testing
- Radioanalytical chemistry
- Space nuclear power
- Focused basic research
- Isotope production
- Nuclear nonproliferation and nuclear forensics.

C-1. NUCLEAR FUELS FABRICATION

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. These advanced reactors cannot function without advanced fuels, however, and 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 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.[k] This 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 re-instrumentation 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 and supporting these LWR irradiation testing capabilities is elaborated in different ways throughout the rest of this section. In addition, research on fuel systems presents a number of scientific and engineering challenges that are discussed in the following subsections.

C-1.1 Fuel Research and Development Focus Areas

C-1.1.1 Advanced Technology Fuels

High uranium-density advanced technology fuels like uranium mononitride (UN), uranium diboride (UB_2), uranium monocarbide (UC), and triuranium disilicide (U_3Si_2) can improve nuclear fuel performance by allowing higher burn-up, leading to lower waste volumes and longer cycle lengths. Increased power uprates are possible due to the increased power density ATFs provide due to their increased uranium loading as compared to UO_2. These fuels can provide better performance in extreme temperatures due to their higher thermal conductivities, which results in reduced fuel failures and more efficient plant operation. A comparison of uranium loading and thermal conductivities as compared to other uranium-bearing fuel forms is shown in Figure C-1A, and microstructure of conventionally sintered UN and a UO_2/UB_2 composite structure is seen in Figures C-1B and C. These fuels will allow for the use of advanced cladding materials that may have neutronic penalties but provide increased safety margins. Obtaining other experimental data on these less well-studied fuels (compared to UO_2) will help build the database of knowledge for and confidence in these ATFs, which are necessities required by the rigorous qualification process of new nuclear technology. Expanding and maturing the knowledge base of ATFs will develop fundamental insight to the nature of advanced nuclear fuels. This increased knowledge will assist in promoting the integration of ATFs with advanced cladding and coolant materials being proposed for use in the existing LWR fleet and next generation reactor designs. The understanding of fuel behavior, synthesis, fabrication, performance under irradiation, and long-term storage of the spent fuel, can be achieved through a combination of experimentation and multiscale modeling. Awareness and understanding of the complexities involved with synthesis, fabrication, and sintering of ATF single phase and composite fuel concepts will bring needed insight to the challenges involved in bringing these ATFs to commercial use. Understanding performance under corrosion conditions coupled with strategies to mitigate hydrothermal corrosion is also important for providing a fundamental understanding of the behavior of these ATF concepts. Research involving improvements upon thermophysical characteristics of UO_2 and development of capabilities to manufacture HALEU fuel will help enable higher power experiments in ATR. These tests will provide insight to limiting operational margins for LWR fuels and will be used to expand the operating envelope of current and next generation LWR fuel rods.

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

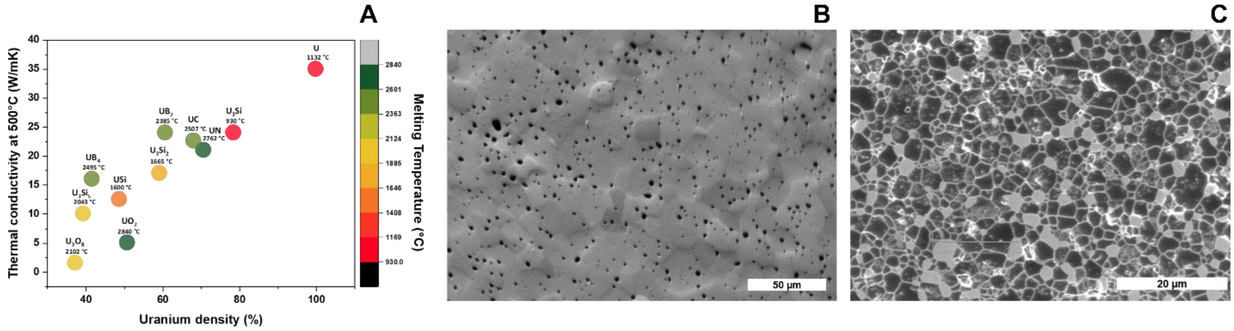


Figure C-1. A) Comparison of uranium loading versus uranium density color mapped to melting temperature for various ceramic uranium bearing fuel forms, B) Micrograph of conventionally sintered UN microstructure, C) Micrograph of a conventionally sintered UO_2/UB_2 fuel composite.

C-1.1.2 Metallic Fuel

Metallic fuels are fuel that contain only metallic materials and alloys, such as a metallic uranium 10wt% zirconium alloy. These fuels were used throughout the life of EBR-II and several lead test assemblies were irradiated in FFTF. Currently, several advanced reactor vendors have chosen metallic fuel as the preferred fuel form based on the EBR-II and FFTF experience. This class of fuels offer several potential advantages including simple fabrication processes, wider operating envelopes, clear irradiation histories, and greater flexibility in feedstock purity and potential alloy choices.

"Traditional" metallic fuel incorporates a solid fuel slug surrounded in sodium, and enclosed in a cladding tube. Although the traditional fuel has proven to be a robust fuel, advances in fuel design and fabrication methods have continued. Advanced geometries, such as annular and grooved fuel slugs have been proposed which do not require the sodium within the cladding tube, and other geometries are possible. At higher burnup levels, fuel-cladding chemical interaction (FCCI) limits the life of the fuel in reactor. Fuel alloy additions are being developed to reduce the amount of possible chemical interaction. Additionally, barrier layers, either applied to the fuel or the cladding tubes, which prevent contact of the fuel and cladding are also being investigated. These mitigations will extend the life of the fuels or increase safety margins utilized in the reactor design.

EBR-II fuel slugs were fabricated using a counter gravity injection casting method which utilized single use quartz molds. This process has been shown to be a robust casting method and has produced tens of thousands of acceptable fuel slugs. Other methods and techniques are also applicable to fuel fabrication that may be more suited to advanced geometries and reduce fuel losses and waste production. These methods include advanced casting techniques using re-usable molds and crucibles or continuous casting techniques which does not use traditional molds. Extrusion is also being investigated to produce fuels and is well suited to advanced geometries, as are other forming methods such as drawing, swaging, and machining (for laboratory scale testing).

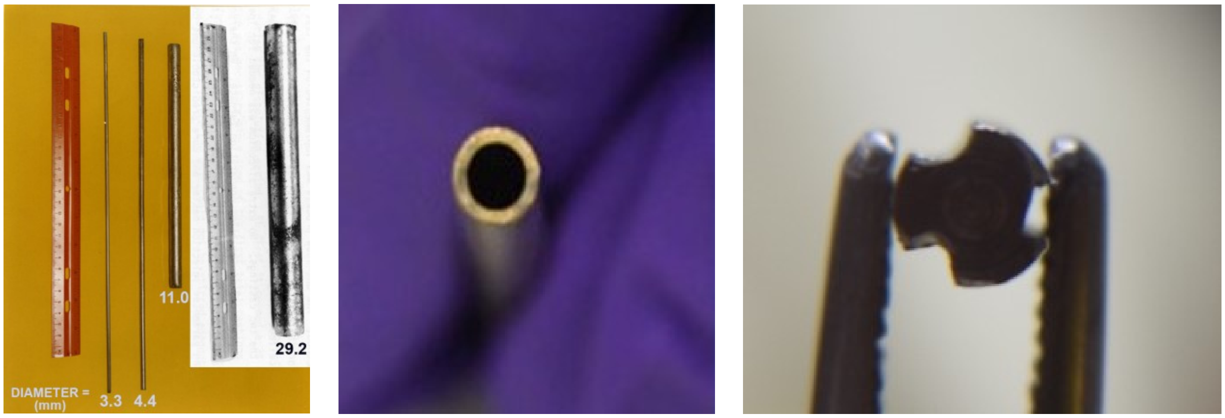


Figure C-2. Left) Counter-gravity injection cast fuel slugs. Middle) Annular cross section of extruded fuel. Right) Machined grooved fuel for testing purposes.

C-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 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 C-3). Design of efficient, low-loss fabrication processes is essential for success.

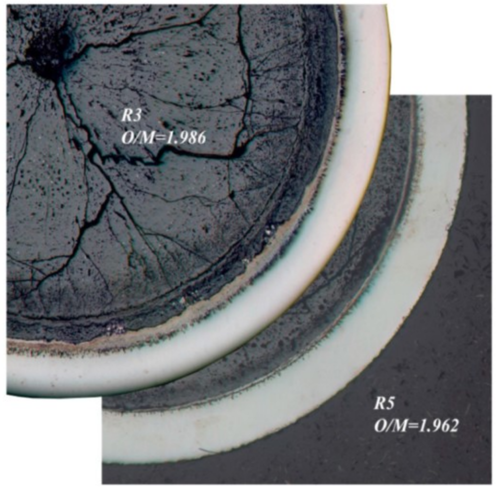


Figure C-3. Comparison of the effect of the oxygen-to-metal ratio (i.e., O/M) in minor actinide mixed oxide fuel. A lower oxygen-to-metal ratio results in reduced fuel-cladding chemical interaction.

C-1.1.4 High-Temperature Gas Reactor Fuel

High-temperature gas reactor concepts are based on tristructural isotropic (TRISO)-coated particle fuels (Figure C-4). 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.

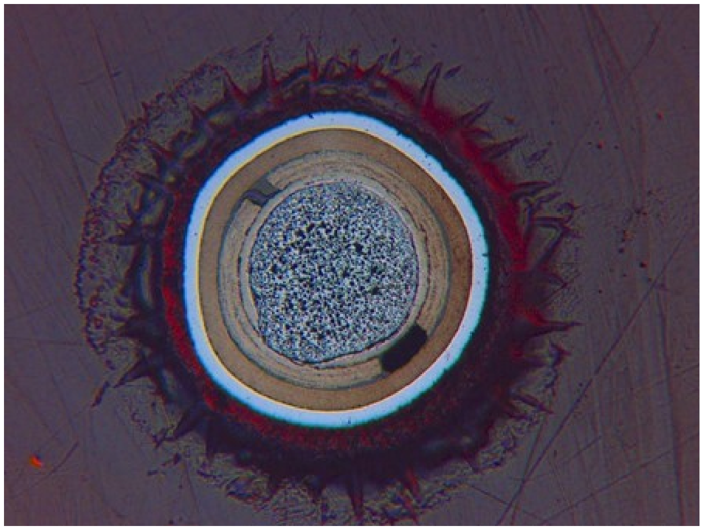


Figure C-4. Next-generation nuclear reactor fuels are designed to be more efficient and resistant to accident conditions. TRISO fuel contains a layer of silicon carbide that serves as the primary containment for radioactive material (center). Researchers have subjected TRISO fuel to extreme temperatures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

C-1.1.5 Molten Salt

INL has extensive experience with electro-chemical (or pyro-processing). This has led to a vast experience base with molten salts and working in a radiological and nuclear environment. With the increased interest in nuclear power technologies, interest in revisiting molten salts as nuclear fuel is also increasing. INL is partnering and discussing several molten salt fuel forms with numerous developers and the DOE. Currently, the largest funded molten salt reactor program is the Molten Chloride Reactor Experiment (MCRE). MCRE is a DOE ARDP funded joint program with Southern Company, TerraPower and INL. The molten salt synthesis part of this project is discussed below.

MCRE is a first-of-a-kind reactor experiment using highly enriched uranium (HEU) in the form of eutectic $NaCl$-UCl_3 as its fuel. Approximately 1.3MT of $NaCl$-UCl_3 fuel salt is needed for critical reactor operations. Synthesis of the quantity of UCl_3 required for MCRE has never been performed on the timeline required, and consequently, the synthesis process must be developed to meet the requirements of the project. Technological development of the fuel synthesis process is being performed in the Fuels and Applied Science Building (FASB) using depleted uranium. These Fuel Synthesis Scale Up (FSSU) experiments are intended to enable the design of the MCRE project’s Fuel Salt Synthesis Line (FSSL) such that it meets requirements for yield, scale, purity, and reliability. An example of a $NaCl$-UCl_3 salt ingot generated during FSSU experiments is shown in Figure C-5. Current progress in FSSU experiments allows for the specification of the majority of required FSSL long-lead equipment, such as furnaces and fuel salt containers. Further process optimization is still necessary to refine the requirements of the furnace internal components.

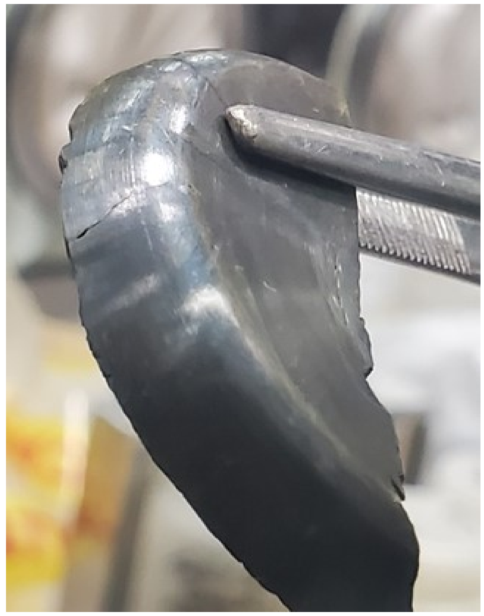


Figure C-5. A photograph of a consolidated NaCl-UCl_3 salt ingot collected during fuel salt synthesis scale-up experiments. This ingot is typical of gram scale experiments after consolidation.

The FSSL will consist of hardware required for chemical production of fuel salt using HEU metal feedstock, installed in the Multi-Function Glove Box (MFG). The fuel salt storage systems include Fuel Salt Containers (FSC) for transfers and handling of clean (unirradiated) fuel salt and shielded Irradiated Salt Containers (ISC) for handling radioactive fuel salt and fission products after reactor operations.

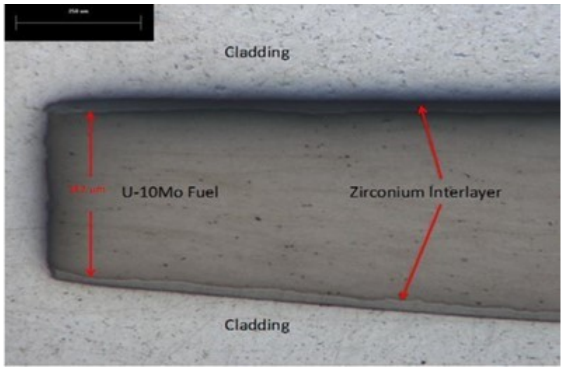
C-1.1.6 Support for the U.S. Commercial Reactor Fleet

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 is required to meet industry needs.

C-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 C-6). 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.



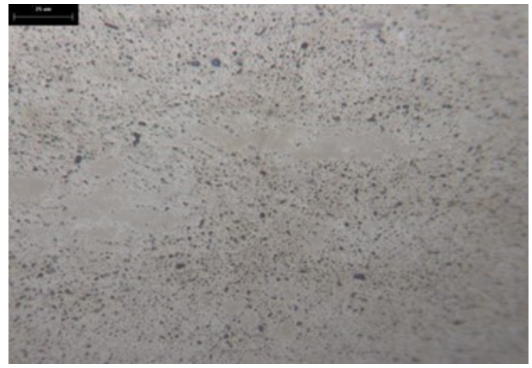


Figure C-6. An optical micrograph of an irradiated low-enriched uranium monolithic fuel plate showing laminated fuel structure (top) and fuel microstructure (bottom) after irradiation to a fission density in excess of 4.1×10^{21} fissions/cm^3, showing fission-gas bubbles within recrystallized regions, remnants of original grains, and precipitates.

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.

C-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. The NSUF program 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.

C-1.2 Experiment Assembly

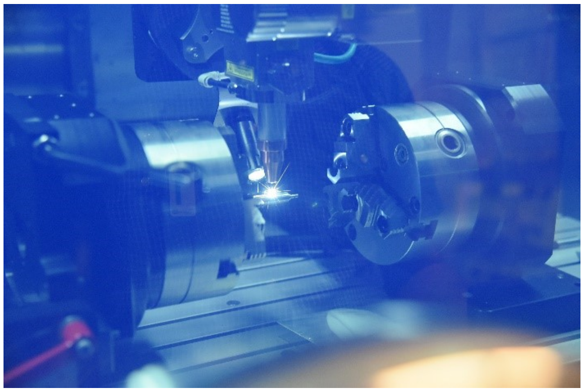
The current state of the national and international nuclear enterprise, and a renewed interest in nuclear energy, has fostered a significant increase in nuclear research related to fuel, cladding, and other in-core components and systems. This includes collaboration with industry, university, government, and international partners for a wide range of experiments. Gathering empirical data through irradiation testing is pivotal to understanding performance of these systems, collecting scientific and licensing support data, and validating modeling and simulation platforms. To satisfy these growing irradiation testing needs, MFC has a robust set of capabilities to support assembly and qualification of experiments.

As the landscape for nuclear research has evolved, experiments have also evolved in kind. This includes irradiation tests destined for ATR for steady-state testing, TREAT for transient testing, and other test reactors external to INL. The quantity of experiments has increased by an order of magnitude in the last 5 years, and is expected to continue to grow. Additionally, the complexity of many of these experiments has increased to accommodate the need for gathering in-situ data during irradiation instead of solely relying on PIE data for experiment performance evaluation. While drop-in style irradiation tests are still commonplace, there's now a growing demand for new test geometries and experiments ranging in size from inches to several feet and often include suites of novel instrumentation.

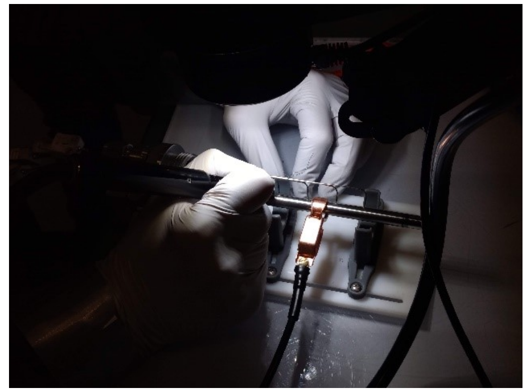
Experiment assembly capabilities at MFC have expanded over the last several years in response to these changes. FASB, EFF, and AFF are the primary radiological facilities used for assembly of fresh-fuel uranium bearing or material experiments, while FMF contains some basic capability to tungsten inert gas (TIG) weld transuranic-bearing capsules. All of these labs have varying and complementary capabilities that are exercised for assembly of experiments, although AFF has become more of a central location for experiment assembly given the set of equipment within the lab. Located in AFF, a custom-designed laser welder integrated within an inert atmosphere glovebox is the primary workhorse for welding experiment assemblies or sub-assemblies and opens the envelope for faster turnaround of testing novel design and materials (Figure C-7). Additional capabilities supporting experiment assembly include:

- The Weld Under Pressure System (WUPS), which allows for pressurization of experiment capsules up to 500 psi using nearly any inert gas
- Benchtop micro-TIG and resistance welding systems to allow for instrumentation installation in support of instrumenting irradiation tests
- The Experiment Vehicle Assembly (EVA) glovebox which serves as a large volume inert atmosphere suitable for mechanical assembly of capsules

As the number of industry partners and other entities looking to INL to perform irradiation tests increase, along with the ever-growing quantity and complexity of these experiments, it's expected that MFC will have to continue to grow its assembly infrastructure to respond to these evolving needs.



Inert atmosphere laser welding system in AFF used to seal a variety of test specimen materials and geometries



Micro-TIG welding system used for attachment of advanced instrumentation to experiments to allow in-situ data collection during irradiation testing

Assembly of an instrumented TREAT test (MARCH-SERTTA) designed to test PWR specimens to failure while gathering a significant amount of data from the instrumented assembly.

Figure C-7. Examples of capabilities in AFF for experiment assembly.

C-1.3 Nuclear Fuel Development Cycle Improvement Goals

Historically, nuclear fuel development has been empirical. The massive amount of atomic displacement damage the fuel microstructure sustains, along with changes in chemical composition during fission, complicate the understanding of microstructural evolution and the interaction between radiation damage processes, and challenge 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 to decrease 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.

C-1.3.1 Fabrication Process Improvement

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.

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 C-8). 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.

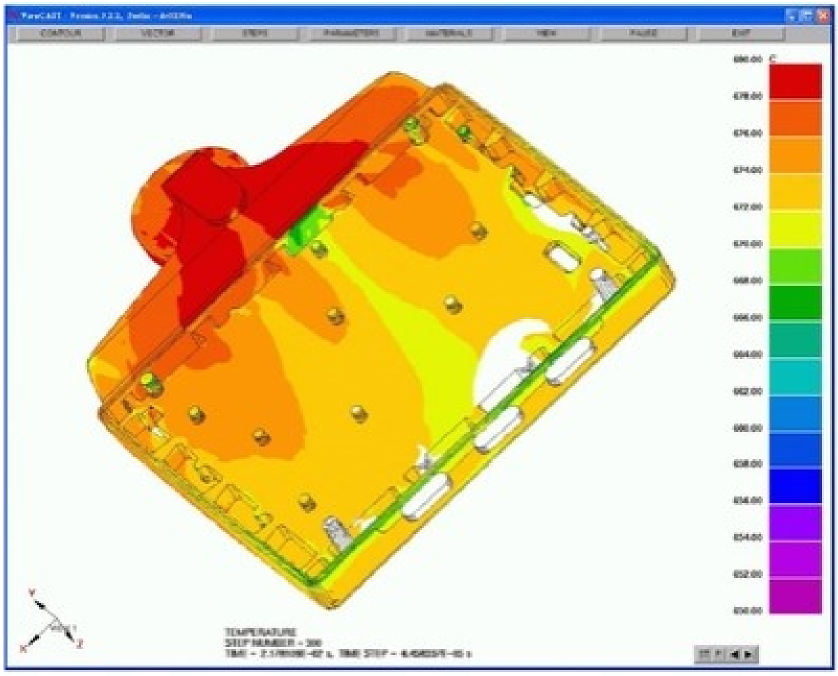


Figure C-8. Fabrication process modeling can be used to determine optimum casting mold geometry and thermal conditions, reducing time for development of advanced fuel fabrication technology.

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).

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[l] is currently being developed in other major technology sectors (Figure C-9).[m] 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.

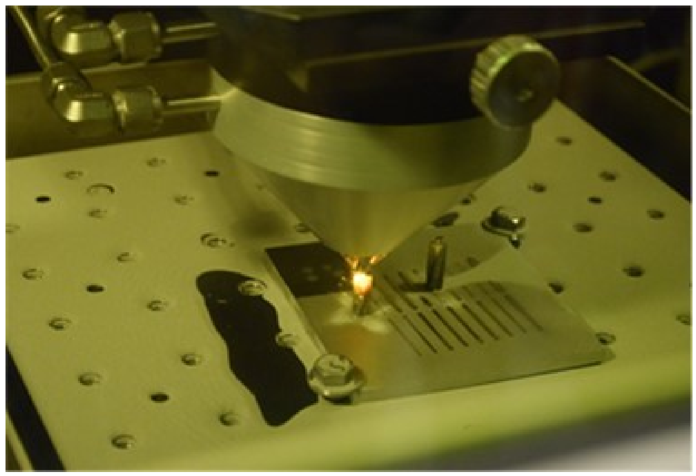


Figure C-9. Laser additive manufacturing is being developed and applied for use in the manufacturing of advanced materials, for example, turbine engine components. The method will be applied to the development of advanced nuclear fuels at MFC.

C-1.4 Proposed MFC Reactor Fuels Research Capability

Based on the tremendous potential value of advanced nuclear reactors, private-sector investment in nuclear innovation has increased in recent years. Currently there are dozens of U.S. companies pursuing advanced reactor concepts that are potentially safer, more efficient, and less costly than conventional nuclear reactors. In addition, DOE's national laboratories, other federal agencies, and universities are actively pursuing the development of next generation advanced reactor technologies. These new reactor technologies are dependent upon development, fabrication, testing, and qualification of new, innovative fuel concepts. Furthermore, fuel manufacturers are investigating new fuel designs for the operating light-water reactor fleet that allow higher fuel burnup and extension of core cycles from 18 to 24 months.

Most of the innovative fuel designs being investigated at present involve ^{235}U enrichment requirements that range between 5% and 20% (referred to as high-assay, low-enriched uranium [HALEU] fuel). However, the U.S. currently does not have a flexible domestic facility capable of developing and producing multiple simultaneous new forms of HALEU fuel on an engineering scale (hundreds of kilograms of material). Across the DOE complex, no flexible Hazard Category 2 nuclear facilities are available to support engineering-scale fuel development and manufacturing demonstration, and all

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

m. For example, http://www.geaviation.com/company/additive-manufacturing.html.

existing facilities are near capacity and are without space for new process development equipment. DOE-NE has ability at MFC to produce HALEU fuel, but only at research-scale quantities (typically less than a kilogram) and with little capacity to support concurrent projects. This existing capability is insufficient to meet most demonstration and process validation needs in practice. Furthermore, U.S. private industry has very limited capability to fabricate engineering-scale quantities of HALEU fuel that deviates from commercial light-water reactor specifications, and thus cannot address this need at present.

Effectively addressing the identified capability gap requires establishment of a reactor fuels research capability that provides flexibility and reconfigurability to accommodate concurrent development and engineering-scale fabrication of a wide range of fuel types. Establishment of the reactor fuels research capability will provide DOE and industry with the infrastructure necessary to support development, testing, and deployment of new reactor fuels needed for the demonstration of new reactor technologies, support of fuels research for the existing reactor fleet, and capacity to support existing research and test reactors. Development and testing of these fuels will provide real data that can be used to validate models, support fuel qualification, and bring new reactor fuels to market quickly, efficiently, and cost effectively.

C-2. FUEL CHARACTERIZATION

C-2.1 Engineering-Scale Examination of Irradiated Fuels

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

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[n] 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.

C-2.2 Scientific Understanding of Fuel Behavior

Fuel performance originates in events that occur at the atomic scale and it is important that atomic-scale damage processes be well understood. This understanding translates to control of the fuel microstructure, composition, fine-scale geometry, and interfaces to optimize the local response of fuel to the fission environment. It is further applied to the engineering-scale design of fuel elements and assemblies to compensate for material changes. For example, examination of the microstructure of U-10Mo fuel indicates that a stable nanoscale superlattice of fission gas bubbles forms during irradiation and remains stable to very high fission densities (Figure C-10). 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.

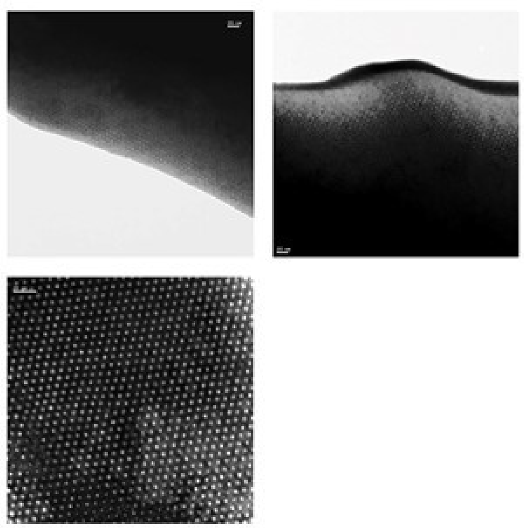


Figure C-10. Transmission electron microscopy images of an ordered array of fission gas bubbles in U-Mo fuel at high burnup. The ordered array of high-pressure gas bubbles provides a stable and efficient mechanism for storing fission gas (INL/EXT-10-20466).

n. 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.

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.

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 C-11). This knowledge allows development and validation of models that accurately predict local thermal conditions and mechanical properties throughout the fuel's life cycle.

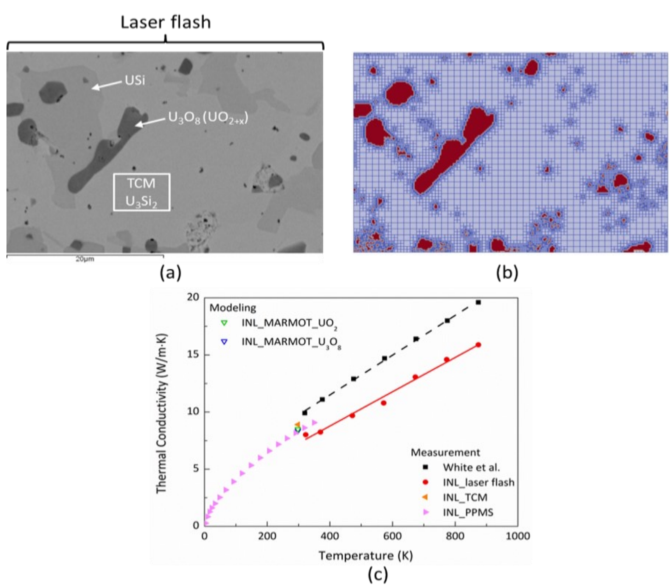


Figure C-11. Thermal conductivity measurements of U_3Si_2 using several methods comparing different length scales and a wide range of temperatures. (a) Scanning electron microscopy image of an U_3Si_2 sample, (b) reconstructed microstructure and mesh in MOOSE for MARMOT calculations, and (c) thermal 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.

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 C-12 is an example of TRISO compact and particle examinations with x-ray tomography from the IMCL versa microscope. This work helps isolate anomalous particles within compacts for further investigation with the advanced microscopy tools of IMCL.

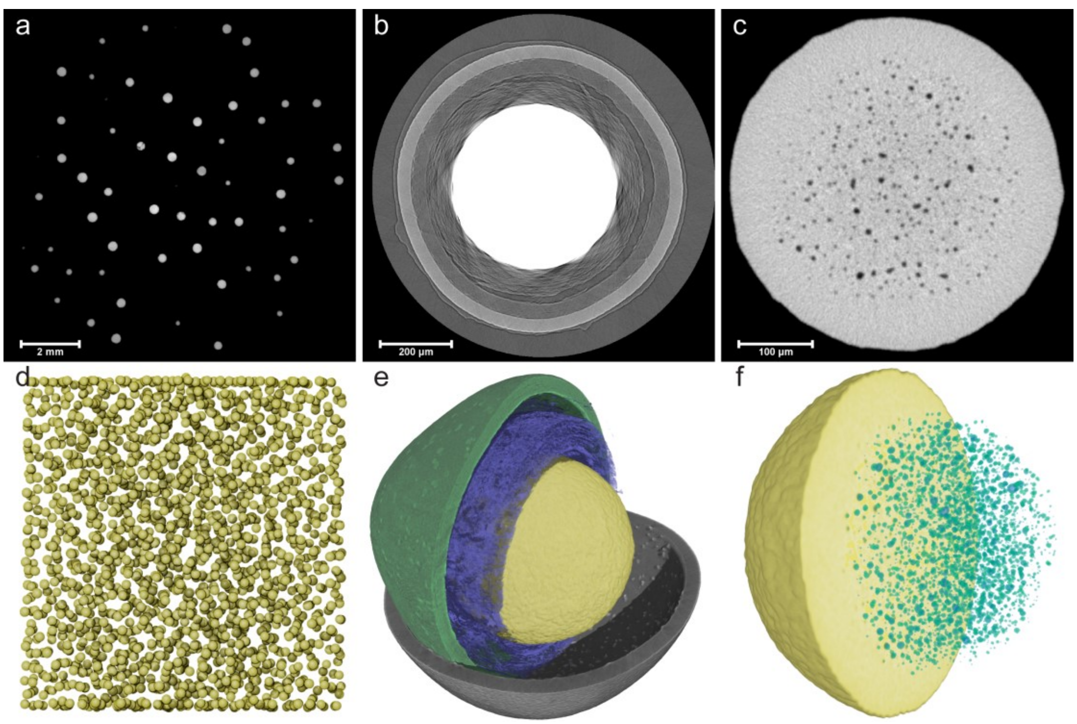


Figure C-12. Reconstructed cross-sectional images (i.e., slices) of a neutron-irradiated tristructural isotropic (TRISO)-coated particle fuel compact from the AGR-3/4 irradiation test (a) and a neutron-irradiated TRISO particle from the AGR-2 irradiation test, acquired at a low (b) and high X-ray energy range (c). A 3D rendering of the uranium oxycarbide (UCO) fuel kernels contained in the compact is provided in (d). A 3D rendering of the TRISO particle in (e) is a derived from a digital registration and merger of the low and high X-ray energy tomograms. The coating layers (SiC = gray, IPyC = green, buffer = blue, UCO = yellow) are digitally cropped to show subsurface features. A 3D rendering of the UCO fuel kernel, derived from the high X-ray energy range tomogram, is presented in (f). The rendering has been digitally cropped to show subsurface fission gas bubbles.

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 C-13) currently accepts small (i.e., less than 0.08-mm^3) samples of irradiated fuel produced using focused ion beam techniques. The use of national neutron and photon scattering facilities has the potential to provide very high-quality data, but with severely restricted access, very small sample size, and with the added complexity of nuclear material shipping. Development of neutron and/or x-ray scattering capabilities at MFC would provide the ability to rapidly acquire critical information about fuel and material evolution under irradiation with larger specimens, but at low resolution relative to national user facilities. A three-tiered approach is being pursued to develop the capability for routine access to neutron and photon scattering data:

- INL is partnering with Brookhaven National Laboratory to develop a capability that allows routine acceptance and analysis of high activity samples at the National Synchrotron Light Source-II. A preconceptual design and cost estimate for the MRE (Materials in Radiation Environment) beamline facility outside of the National Synchrotron Light Source -II ring have been completed. The Advanced Photon Source has also proposed a beamline to routinely accept and analyze radiological samples.
- Development of neutron scattering based on the NRAD as the neutron source. An initial demonstration has been made using a conventional goniometer. A wide-angle detector has been acquired for future use. 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. Collaborations are ongoing with LANL and ORNL to develop facilities capable of routine examination of nuclear materials at LANSCE (Los Alamos Neutron Science Center) and SNS (Spallation Neutron Source).

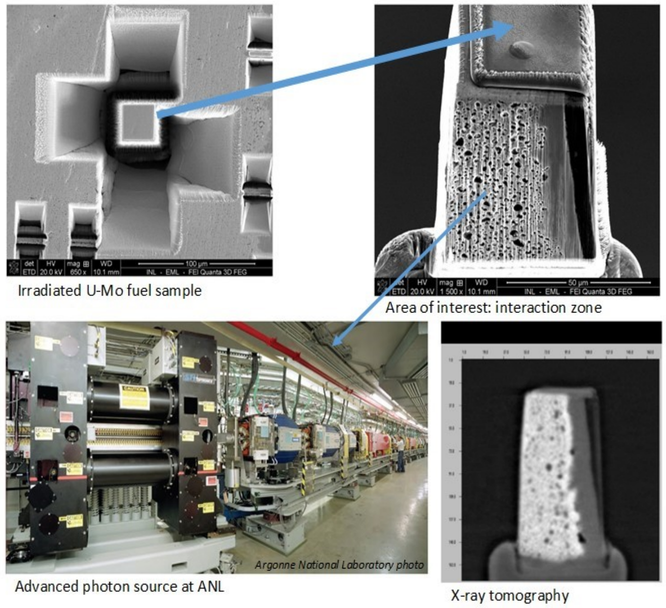


Figure C-13. Focused ion beam sample preparation at MFC allows INL staff to conduct fuel experiments at other national user faculties. An irradiated U-Mo fuel sample was prepared for characterization at the Advanced Photon Source at Argonne National Laboratory. Access to Advanced Photon Source beam lines 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.

- 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 linear accelerator (LINAC) or cyclotron electron sources. One company has entered commercial production, and several others have developed prototypes. The state of technology and reliability will be monitored as it continues to mature. These compact light sources offer greater ease of access, but at a penalty in x-ray brightness. Cost of an installed capability is estimated to be in the range of $30M, roughly divided between the instrument and the facility (or facility modifications) required to host it.

C-3. MATERIALS CHARACTERIZATION - RADIATION DAMAGE IN CLADDING AND REACTOR COMPONENTS

The DOE-NE mission requires significant fuels and materials research development, and testing capabilities to support the deployment of new nuclear innovations, life-extension, and long-term operation for both the existing reactor fleet, and new reactor concepts. Experimental programs in support of life-extension, fitness-for-service or materials development require testing cycles in one of two ways:

1. Ex-service or Surveillance Material Testing (Figure C-14)
2. Accelerated Irradiation Programs (Figure C-15)

Figure C-14. Experimental cycle for ex-service material surveillance programs.

Figure C-15. Experimental cycle for accelerated irradiation programs.

To deliver on the DOE-NE mission, both approaches to assess fuel and material performance are required. Performing experimental tests on actual plant materials is the ideal scenario for Nuclear Power Plant (NPP) operators to assess fitness-for-service and material degradation phenomena, but this is costly, time consuming, and it is not always feasible to remove certain components from a reactor before end-of-life. From the perspective of supporting material qualification programs, and supporting fundamental research activities, the concepts of pre-machining specimens for insertion in a test reactor for irradiation is an acceptable approach especially when coupled with modeling and simulation analyses, as there is no possible way of obtaining surveillance material under relevant conditions. Researchers need to contend with artifacts associated with accelerated irradiations, and non-prototypic environmental conditions (e.g., water chemistry, temperature, dose rate effects, thermal/fast flux, etc.). Therefore, adopting a strategy of assessing structural material performance using a combination of both ex-service material surveillance programs, and accelerated irradiation programs is an ideal approach to understand material aging phenomena.

With respect to supporting industry initiatives for long-term operation and life extension strategies, it is required to obtain, test and characterize material obtained from reactor harvesting (either during shut down or during decommissioning activities). These materials are crucial to validate approaches used from accelerated irradiation programs, and their characterization provides reactor utilities, regulators and ratepayers the confidence that reactor materials operate within proper safety margins and continue to behave as expected up-to and beyond reactor design end-of-life. This validation also provides credibility to the accelerated irradiation concepts as they pertain to material qualification programs for advanced reactor designs. Critical to success in this area is a capability for rapid development of materials, including fabrication, performance testing in a realistic environment, and characterization. INL and MFC are equipped with state-of-the-art experimental facilities for engineering scale testing of fuels (HFEF), in-core structural materials and environmental testing (SPL), and microstructural characterization (IMCL/EML) to deliver this mission.

C-3.1 Reactor Materials Research, Development, and Demonstration

To provide modern, advanced post-irradiation examination (PIE) capabilities for the scientific understanding of nuclear fuels and materials behavior at the microstructural level, INL is updating and expanding the Irradiated Materials Characterization Laboratory (IMCL) and constructing a new hot-cell facility, the Sample Preparation Laboratory (SPL). SPL is dedicated to investigating non-alpha, core materials and is scheduled for completion in FY 23 with radiological operations beginning in FY 25. These two facilities have been designed with advanced in-cell robotics, camera systems, and advanced data processing capabilities to enable high-throughput testing and analysis aimed to accelerate the development and qualification cycle of fuels and materials in support of advanced reactors. Together with HFEF, IMCL and SPL will provide a complete suite of capabilities for fuel and reactor component materials PIE, as illustrated in Figure C-16.

Structural materials research provides a fertile basis for collaborative scientific investigation by INL, other national laboratories, and universities/ industry partners. Irradiated reactor structural 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. The SPL external advisory committee consisting of Industry, National Laboratory and University partners will help establish the user base for this upcoming facility.

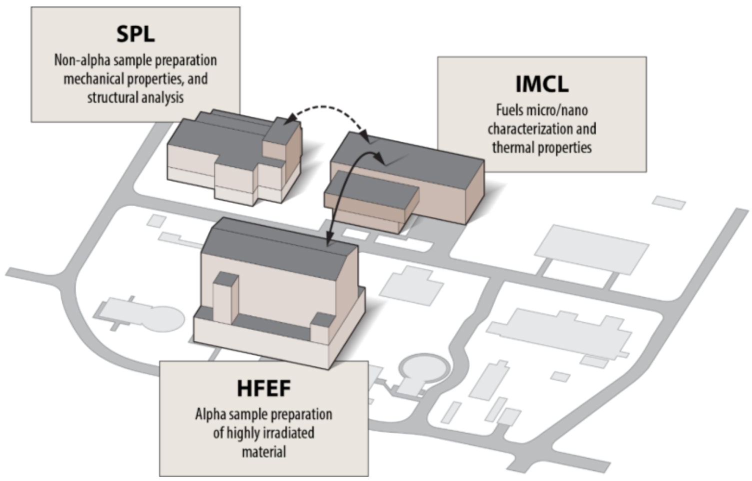


Figure C-16. SPL, IMCL and HFEF provide complementary capabilities.

To make characterization truly effective, efforts are also being taken to address the standardization of data collection and analysis techniques. Data is only valuable to a researcher if it has the right pedigree and is accessible. Standards on the data collected on nuclear materials are needed to ensure its utility throughout the community. This would be analogous to standards used by the American Society for Testing and Materials (ASTM), which have been implemented throughout the world in numerous industries. Data from failure and success can then be coupled with data analytics methods to improve the efficiency of data utilization. This methodology has been adapted in the design of both IMCL and SPL with the goal of streamlining the timely process of back-end analysis of experimental data acquisition.

C-4. FUEL RECYCLING AND NUCLEAR MATERIAL MANAGEMENT

Nuclear fuel cycles that increase uranium resource utilization and reduce high-level waste require a comprehensive recycling strategy. In general, all actinides important for resource utilization and waste management can be productively 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 pyrochemical methods, typically using electrochemistry and chemistry in a molten salt electrolyte.

C-4.1 Aqueous Recycling Research, Development, and Demonstration Focus Areas and Goals

C-4.1.1 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 of high-level waste requiring 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.

C-4.1.2 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 nonradioactive 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.

C-4.2 Pyrochemical Research, Development, and Demonstration Focus Areas and Goals

C-4.2.1 Pyrochemical Research Focus Areas

The terms pyrochemistry and pyroprocessing refer to a family of technologies involving high-temperature chemical and electrochemical methods for separation, purification, and recovery of fissile elements from used nuclear fuel. Pyrochemical technologies can be applied to oxide fuels and metallic fuels; however, the fissile elements are generally recovered as metals for fabrication of new fuels. Presently, pyrochemical technologies are being actively researched by the United States, Japan, France, Republic of Korea, China, India, and Russia. Research aims not only at the challenges of implementing the technologies for commercial-scale applications, but also effective safeguards methods and technologies for such facilities to the standards required by the International Atomic Energy Agency.

Pyrochemical recycling has some unique advantages as a recycling technology for used nuclear fuel. For example, molten salts are impervious to the radiolysis and thermal effects of used nuclear fuel, unlike aqueous organic solvents, allowing for the treatment of ‘fresh’ used nuclear fuel recently discharged from a reactor core. Effective neutron moderators are absent from these processes, providing distinct advantages for processing high-fissile content fuels and enabling compact processes in right-sized facilities. These processes allow effective group separation of re-usable actinide components from fission products, potentially significantly reducing high-level wastes. Opportunities also exist to use these technologies to recover useful products from a variety of high-residual value legacy used research fuels. Current MFC activities in this area include those mentioned in the following subsections.

Joint Fuel Cycle Study – MFC supports a jointly-funded pyrochemistry study with the Republic of Korea on the Joint Fuel Cycle Study’s Integrated Recycling 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 sufficient TRU has accumulated, these metals are recovered in a liquid cadmium cathode at an approximately 50:50 uranium:TRU ratio. The recovered uranium/TRU alloy has been used to make a series of recycled fuel samples for irradiation testing in ATR and subsequent PIE analyses in HFEF. Process testing in this research equipment is planned when additional irradiated commercial fuel is received at INL.

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 electrorefiner 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 for these corroded fuels.

Safe storage and disposition options for residual materials such as cladding hulls and process salts are being evaluated given the absence of a high-level repository. The current focus of these efforts is long-term storage options which provide the flexibility to accommodate multiple final disposition options.

C-4.2.2 Pyrochemical Research and Development Goals

Research in pyrochemistry 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 increase separation efficiencies, simplify processes, and improve technical readiness of these technologies for used fuel recycling scenarios.

Modeling and Simulation of Pyrochemical Operations – These theoretical-based efforts provide a means of assessing performance of process flowsheets with regards to the layout and performance of the individual unit operations, identify key opportunities, and extend knowledge to new recycling scenarios. Verification of performance requires experimentation and testing.

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 wastes from pyrochemical processes is a key component of determining the efficiency and viability of any proposed recycling 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. Development of simplified processes which can accommodate a broader spectrum of fission products is also a key activity, and MFC continues to lead in development of advanced waste forms.

C-4.3 Used Fuel Disposition

Understanding the behavior of used nuclear fuel during interim storage is required to extend the dry storage period while a permanent repository is being developed. Additionally, as commercial utilities pursue higher fuel burnup, information about the impact on 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.

C-4.4 Fuel Cycle Test Bed Facilities

INL configures fuel cycle test bed facilities to provide a modern, flexible RD&D test environment, that incorporate engineering and pilot-scale equipment, modeling, simulation, data science and cyber tools to address science and technology gaps. Advanced test beds allow INL to lead advanced reactor development, including SMRs, microreactors, liquid-fuel reactors, and TRISO-fuel development and to advance unique capabilities to address DOE legacy issues related to orphan SNM. All new fuel cycle test beds are design with the ability to demonstrate innovating safeguards and security concepts applicable to advanced reactors and their fuel cycles in support of national security objectives.

Stewarding RD&D test bed facilities is critical for INL to engage and train the next generation of fuel cycle, nonproliferation, and waste management experts. Fuel cycle test beds serve as user facilities that allow multiple programs and mission partner agencies to run experiments that explore scientific and technology issues, and develop the data needed to address technical questions associated with evolving fuel cycles.

C-4.4.1 Beartooth

To meet the challenges associated with the evolving nuclear fuel cycle, INL is developing a test bed capability called Beartooth, an aqueous processing platform for demonstrating new safeguards and security concepts applicable to advanced fuel cycle operations. This highly configurable transuranic glovebox contains all the necessary unit operations for dissolution, chemical separations, conversion, and off-gas treatment for SNM relevant to both existing and emerging fuel cycles (Figure C-17). The Beartooth test bed fills a complex-wide infrastructure gap and will be installed in the Fuel Conditioning Facility (FCF) at the Materials and Fuels Complex (MFC), with construction completion anticipated in FY-23. Beartooth will be capable of processing plutonium, enriched uranium (HALEU and HEU), thorium, and other SNM, as well as handling trace minor actinides and fission products. Beartooth will also leverage a real-time digital replica (digital twins) for aqueous processes in combination with machine learning and artificial intelligence approaches to demonstrate new safeguards and security concepts applicable to advanced fuel cycle operations in support of national security and commercial objectives.

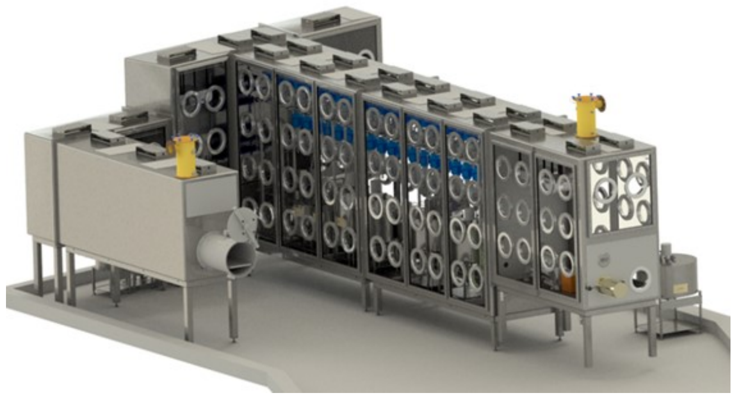


Figure C-17. Conceptual rendering of the Beartooth test bed

Head-end processing and chemical separations equipment will be chemically compatible with multiple techniques that may be encountered in advanced fuel cycles (e.g., hydrofluoric acid or other corrosive mineral acids and salts) processing of SNM. Chemical separations capabilities include a reconfigurable 40-stage CINC V02 annular centrifugal contactor system along with associated cold chemical and effluent reagent tankage and pumps. Evaporation and modified direct denitration are utilized for solidification of SNM, with options to utilize precipitation and calcination methods as well. Dedicated off-gas treatment equipment including condensers, scrubbers, high-efficiency particulate absorbing (HEPA) filtration, and significant instrumentation/sampling capabilities are also included to enable fundamental scientific understanding of source term characterization to meet proliferation detection and assurance objectives. Beartooth has dedicated glovebox space for plutonium processing, with available footprint to incorporate additional unit operations as research need arises. Furthermore, the process will be highly instrumented to complement digital twin and AI/ML approaches, with real-time monitoring of both process parameters and physical/chemical/radiological parameters during operation. Control system cyber capabilities are also an integral part of the test bed.

Lastly, challenges associated with an aging workforce and fuel cycle infrastructure domestically underscore the importance of test beds not only to address evolving research needs, but to develop and maintain U.S. expertise in the nuclear fuel cycle and nonproliferation. Beartooth is being designed, built, and operated by early career staff under the supervision of experienced staff to develop and retain expertise in nuclear chemical processing. Beartooth will ultimately be leveraged across the national laboratory complex and end user community to establish an enduring capability for advanced fuel cycle processing operations.

C-4.4.2 MSTEC

Molten salt fuels are a central design element for several advanced nuclear reactors. The proposed fuel salts for MSRs vary in neutron spectrum, enrichment, fissile isotopes, chemical and thermodynamic properties, and composition. These variations in fuel salt chemistries require a variety of characterization instruments to provide key data sets for molten salt reactor development, design, and deployment. To fill this need, the DOE-NE funded NRIC is deploying the Molten Salt Thermophysical Examination Capability (MSTEC) test bed at INL as a one-of-a-kind platform to design, demonstrate, license, and operate MSRs. As shown in Figure C-18, MSTEC is a 22-foot-long shielded argon glove box with adjoining fume hood specifically designed for characterization of irradiated and actinide bearing molten salt systems. MSTEC will be located within FCF at MFC and will be ready for use in 2024.

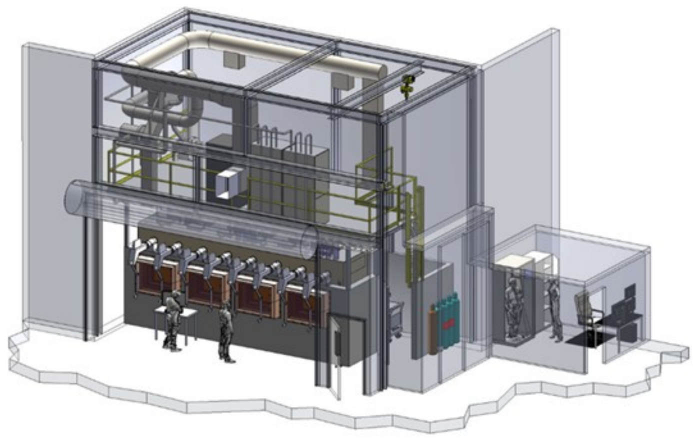


Figure C-18. Conceptual rendering of the MSTEC test bed

The main objective of MSTEC is to provide users with the characterization equipment and infrastructure to produce high fidelity data needed to design, demonstrate, license, and operate MSRs as well as to advanced fuel cycle research. A secondary goal of MSTEC is to develop human capital necessary to produce this high-fidelity data. MSTEC is being designed, built, and operated by early and mid-career staff to develop and retain expertise in molten salt processing and characterization. The infrastructure and equipment in MSTEC will provide high temperature characterization capabilities for irradiated and actinide bearing salts which are currently nonexistent in the DOE national laboratory complex. Additionally, MSTEC will allow for the study the interaction of fuel/coolant with structural materials, generate data sets needed to design and license MSRs, provide data to aid in long-term storage or disposal solutions, allow for development and validation of multi-physics models and simulations, and provide a technology platform for developing competency for the nonproliferation mission.

MSTEC is designed to accept, handle, examine, disassemble, size reduce, and repackage samples delivered via a shielded container, and permits use of compressed gases (H_2, HCl, Cl_2, F_2, HF, and NF_3) contained in lecture bottles for salt purification and synthesis. MSTEC is equipped with a well furnace providing up to a 1,000°C environment for salt synthesis, electrochemistry, corrosion, and other general long-term molten salt experiments using irradiated molten fuel salt. The characterization instrumentation included in MSTEC includes analytical instrumentation for measuring viscosity, density, thermal conductivity, specific heat capacity, weight loss as a function of temperature and vapor pressure, and temperature-dependent dimensional changes in solids and liquids. In addition, MSTEC can accommodate new and versatile experiments that can be integrated into excess power receptacles and feedthroughs.

C-4.4.3 Sustainability Test Bed – Modern Waste Management Capabilities

INL is developing waste management test bed capabilities at MFC to address some of the challenges associated with legacy and newly generated waste streams, specifically mixed low-level waste (MLLW) and TRU waste, to support the laboratory's enduring mission. Those capabilities include:

- Geomelt – a thermal treatment system that will operate in the Fuel Conditioning Facility and will be used to treat radioactive liquids and activated debris by mixing the waste and transforming it into a glass monolith which will meet off-site disposal waste acceptance criteria
- Pyrolysis – a thermal treatment technology that will remove hazardous characteristics to make the waste acceptable for shipping, storage, or disposal.
- Drum Assay – The Universal Drum Assay Segregation System (UDASS) is a new non-destructive assay system that will be used as a screening tool commencing in FY-22 to discriminate between transuranic (TRU) waste and low-level waste (LLW) with improved characterization capability.

The new sustainability test bed RD&D environment will provide scientists and engineers with the opportunity to develop better more stable waste forms for final disposition in support of advanced reactor development, including SMRs, microreactors, liquid-fuel reactors, and TRISO-fuel development and to advance unique capabilities to address DOE legacy issues related to orphan SNM. Stewarding RD&D test bed facilities is critical for INL to engage and train the next generation of fuel cycle and waste management experts.

C-5. TRANSIENT IRRADIATION TESTING

The TREAT facility (Figure C-19) 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 helping advance the state of nuclear energy science and technology. TREAT capability for testing LWR fuel is now more important following the 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:

- 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, to properly screen and evaluate fuel designs and the materials used in them. These tests are used to identify a range of fuel performance characteristics that can be used to guide fuel design and advanced reactor design.
- Considered in design of a new reactor system that will utilize a given fuel system, a development program is implemented 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 (or underpin the design criteria and regulatory assessment). A fuel qualification program is executed to demonstrate as-designed fuel performance under design basis conditions, validating the design criteria and operating limits for fuel rods and assemblies produced by industrial processes.
- In addition to supporting the specific missions of DOE-NE, the capabilities resident in the transient testing facility support 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. TREAT capability also is available to support forensics, nuclear attribution, and component testing for NNSA.

Figure C-19. Test vehicle being loaded into the TREAT reactor for transient testing of a new fuel design.

C-5.1 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, Pressurized Water Reactor (PWR) conditions, and flowing hydrogen conditions typical of nuclear thermal propulsion reactors for space applications. These vehicles will provide the conditions needed for fuel design evaluation and qualification testing.

C-5.2 HFEF Transient Testing Infrastructure

Transient testing of irradiated fuel requires incorporation of highly irradiated fuel into an experiment assembly at HFEF prior to transport to TREAT. Interpreting results of transient testing requires disassembly of TREAT test vehicles to extract the test fuel for PIE at HFEF. Preparing, operating, and dispositioning test loops with appreciable quantities of contaminated sodium and pressurized water is a key part of DOE's transient testing capability. A description of the transient testing PIE capability needed to support basic and complex transient testing is provided in INL engineering documents.[o]

o. K. Davies, *"Evaluation of HFEF capability to Support TREAT Restart,"* TEV-3093, November 7, 2017; Daniel Crush, "*Equipment and Infrastructure to Support the Mk-IIIR Sodium Loop Cartridge (NLC)*," TEV-4357, February 24, 2022; "*HFEF Infrastructure to Support the TREAT Sodium Loop Cartridge (NLC)*," August 27, 2021.

C-5.3 Test Rod Instrument Application

A shielded experiment handling cell, (named the Experiment Preparation and Inspection Cell, or EPIC) preferably collocated at the TREAT facility, is needed for applying instrument sensors to re-fabricated LWR fuel rods. EPIC would include the capability to install instrument sensors onto test rods refabricated from shortened pre-irradiated LWR fuel rods (and perhaps fast reactor test rods at some time in the future). The refabrication effort will be performed at HFEF and the process will complete with instrument installation performed at the collocated facility at TREAT. Both these capabilities will provide functions necessary for ATR and TREAT to help fulfill the mission served by the Halden Test Reactor, which was recently shut down. The facility that could be used to house the instrument installation capability is the TREAT Experiment Support Building (TESB), a repurposed TREAT warehouse, which will undergo facility upgrades to house TREAT test train assembly and low-activity experiment disassembly and examination and to prepare for potential installation of EPIC.

C-5.4 Narrow Pulse Width for Prototypic LWR Transients

Power pulse widths, defined as the full width at half maximum (FWHM) of time-dependent reactor fuel power, 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 simulate Light Water Reactor (LWR) RIAs more accurately, pulse-width narrowing capability is needed for TREAT. Incorporating a He-3 injection system will shorten the pulse width to as low as 40 ms making it possible to simulate PWR RIAs.

C-5.5 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.

C-5.6 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 allow insertion 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.

C-5.7 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 detection and 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. This information is used to assess fuel behavior during a transient and to assess implications and consequences of fuel failures. 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 prepared, but installation has been deferred due to limited available funds. 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 Fuel Motion Monitoring System 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.

C-5.8 Neutron Radiography

Neutron radiography capability is collocated at TREAT providing in-process, non-destructive irradiation examination capability for experiment campaigns of multiple planned transients including multiple specimen irradiations. With simple movement of a test vehicle from the TREAT core to the adjacent neutron radiography stand, neutron images of the experiment configuration inside the vehicle can be obtained for assessing experiment effects and determining the next steps for an experiment (e.g., whether to expose an unfailed fuel specimen to another transient to determine failure thresholds). The in-process radiography can provide data for tuning the subsequent transients in the irradiation campaign without waiting for detailed 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. Radiograph processing capability was recently updated to digital format, and further digital improvements are possible. The development of a new collimator is under way to increase the resolution of the system to better inform experiment campaigns though TREAT radiographs will not approach the capabilities of NRAD at HFEF. NRAD will still be used for high-resolution neutron radiography.

C-6. RADIOANALYTICAL CHEMISTRY

The radioanalytical chemistry competency at MFC underpins several of MFC's other core competencies, providing expertise and resources to perform

- chemical and isotopic characterization that includes shielded cells for chemical analysis,
- state-of-the-art methods for analysis of fuels and materials up to Hazard Category 3 limits,
- transuranic (TRU) thermophysical property measurements, and
- development of bench-scale methods for aqueous reprocessing technology.

Radioanalytical chemistry capabilities are embedded primarily within the Analytical Research Laboratories Division, whose strategic objectives are to

1. Conduct analytical chemistry on nuclear fuels and materials in support of INL research programs and outside customers including advanced nuclear fuel design, nuclear waste management, and nuclear nonproliferation
2. Conduct analytical chemistry on environmental samples for regulatory compliance
3. Provide data analyses on samples that meet or exceed the requirements of the customer
4. Develop cutting edge chemical methods to meet the growing analytical challenges of the nuclear fuels community
5. Provide modern instrumentation and subject-matter expertise for analyses in the areas of radionuclide separations, mass spectrometry, elemental analysis, and radio-analytical measurement (counting)
6. Foster development of scientific and operational talent.

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.

C-7. 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. Leadership in the area of space nuclear power utilizing nuclear reactors has been a growing area of interest for the INL and NASA.

C-8. 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 C-20).

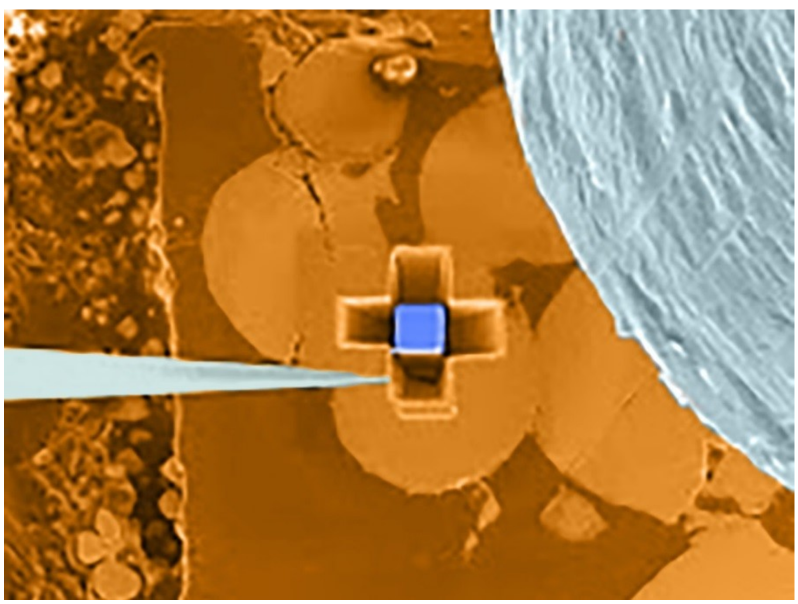


Figure C-20. INL researchers have demonstrated a new sample preparation technique that makes it easier to examine irradiated fuel at the nanoscale. The new technique uses an ion beam to mill material sections that are just tens of nanometers thick. A platinum layer (i.e., the blue square) protects the 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

C-8.1 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*,[p] 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[q] 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.

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p. "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).

q. "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).

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.[r]

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

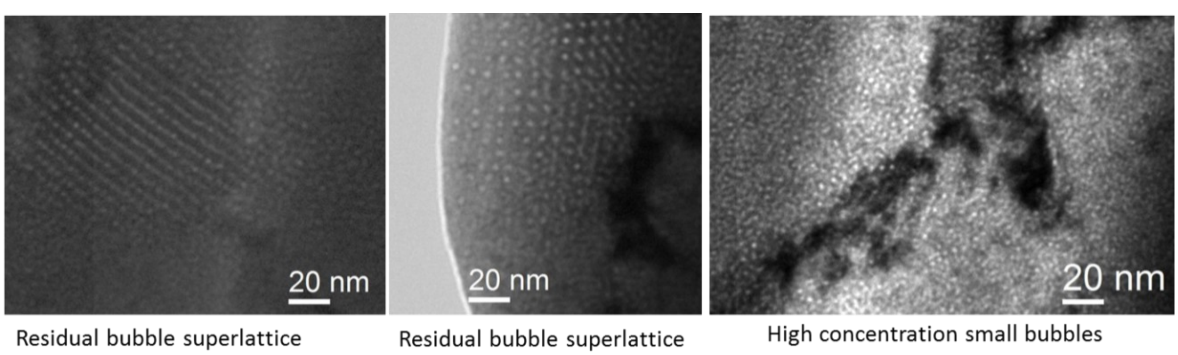

Figure C-21. Examination using transmission electron microscopy shows that the unusual fission gas bubble superlattice that forms in U-Mo fuel during irradiation and is retained to ultra-high burnup.

r. "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).

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.

C-8.2 Focused Basic Research Goals

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

C-8.2.1 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 of 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 to provide 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.

C-8.2.2 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[s] that the unusually low thermal conductivity and its unique temperature dependence, which have been a mystery since the beginning of the nuclear era, is related to resonant spin-phonon interactions. These collective phenomena suppress the thermal conductivity and lead to many intriguing 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 (≤ 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 C-22) 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

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

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 focused ion beam (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.

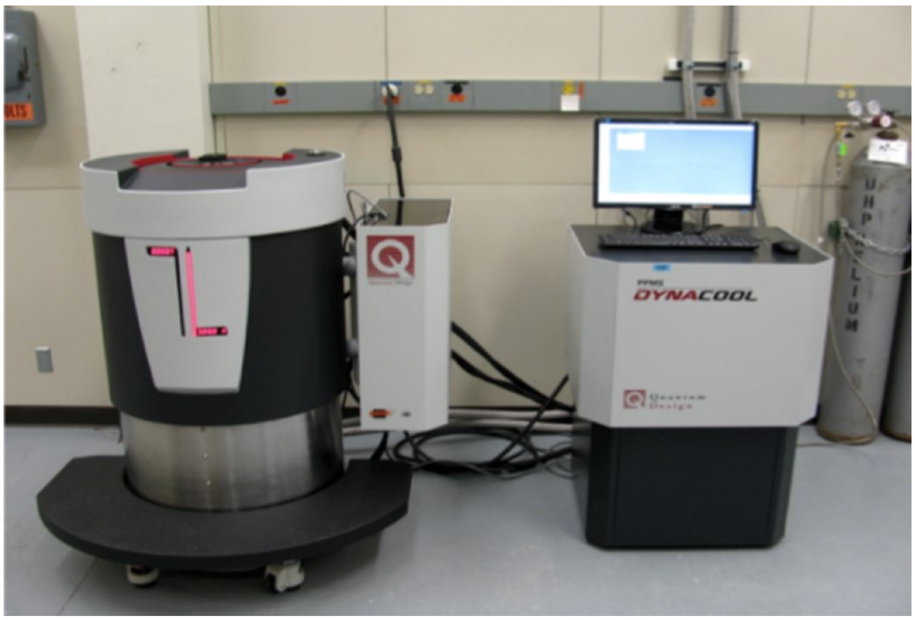

Figure C-22. Physical Property Measurement System (DynaCool-9, currently installed at the INL Idaho Research Center). Availability of this capability in IMCL has resulted in unique capability for understanding the fundamental properties of the actinides and actinide-bearing ceramics and alloys.

C-9. Isotope Production

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).

C-9.1.1 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 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 accelerated 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.

C-9.1.2 Cobalt-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-SC.

C-10. 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 and plutonium content of advanced LWR fuels for current generation nuclear reactors; Non-destructive assay techniques, both passive and active, are desired to determine ingoing spent-fuel inventories to head-end fuel processing techniques, and residual fuel hold-up in waste streams, such as residual fuel in cladding
- Applying predictive algorithms integrated with process models and measurements to assess SNM the magnitude of SNM processing, or deviations from declared operations and inventories
- In partnership with NE programs develop engineering-scale demonstration facilities that are designed to test advanced process monitoring instrumentation for nuclear safeguards and accountability, and remote monitoring technologies and prediction algorithms to detect and assess the magnitude of undeclared nuclear fuel processing or conversion activities

- Offering world-class training courses for domestic and international students to learn about the nuclear fuel cycle and methods and best practices for safeguards
- Expand the use of INL's demonstration facilities to training the next generation of nuclear and chemical engineers, chemists and nuclear physicists.

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 International Atomic Energy Agency, 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.

C-10.1 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 advanced detection methods for characterizing and monitoring the transportation of plutonium, uranium and spent fuel between irradiation facilities, used nuclear fuel storage cooling ponds, dry-cask storage containers and fuel processing facilities.
- 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.

C-10.2 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.

Appendix D

Flow Down of DOE-NE Goals and INL S&T Initiatives to MFC Critical Outcomes

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Appendix D

Flow Down of DOE-NE Strategic Goals and INL S&T Initiatives to MFC Critical Outcomes

The MFC Five-Year Mission Strategy is driven by the DOE-NE strategic vision and the INL S&T initiatives. In the DOE-NE Strategic Vision issued in January 2021, five goals are identified to address challenges in the nuclear energy sector, help realize the potential of advanced technology, and leverage the unique role of the U.S. government in spurring innovation. Of these five goals, four are directly supported by the MFC Critical Outcomes (Section 6), as shown in Table D-1. The MFC Critical Outcomes also directly support three of the five INL S&T initiatives, as shown in Table D-2.

Table D-1. DOE-NE Strategic Goals Supported by MFC Critical Outcomes.

MFC Critical Outcome	DOE-NE Strategic Goal			
	Enable continued operation of existing U.S. nuclear reactors	Enable deployment of advanced nuclear reactors	Develop advanced nuclear fuel cycles	Maintain U.S. leadership in nuclear energy technology
Enable & accelerate demonstration, testing, and deployment of advanced reactors		X		X
Fabricate innovative nuclear fuels for demonstration reactors, and advance technologies for used fuel treatment		X	X	X
Perform irradiation, analysis & testing of fuel and materials for nuclear applications	X	X		X
Provide components and/or technology for radioisotope power generation				X
Fulfill environmental stewardship commitments			X	X

Table D-2. INL S&T Initiatives Supported by MFC Critical Outcomes.

MFC Critical Outcome	INL S&T Initiative		
	Nuclear Reactor Sustainment and Expanded Deployment	Integrated Fuel Cycle Solutions	Advanced Design & Manufacturing for Extreme Environments
Enable & accelerate demonstration, testing, and deployment of advanced reactors	X		
Fabricate innovative nuclear fuels for demonstration reactors, and advance technologies for used fuel treatment	X	X	
Perform irradiation, analysis & testing of fuel and materials for nuclear applications	X		X
Provide components and/or technology for radioisotope power generation	X		
Fulfill environmental stewardship commitments		X	

Appendix E

Acronyms

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Appendix E

Acronyms

AFF	Advanced Fuels Facility
AGR	Advanced Gas Reactor
AI	Artificial Intelligence
AL	Analytical Laboratory
ARCS	Automatic Reactor Control System
ARL	MFC Analytical Research Laboratories
ARDP	Advanced Reactor Development Program
ATF	Accident-Tolerant Fuel
ATR	Advanced Test Reactor
BWR	Boiling Water Reactor
CAES	Center for Advanced Energy Studies
CAPIE	Characterization and Advanced Post Irradiation Examination
CRADA	Cooperative Research and Development Agreement
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DOE-SC	DOE Office of Science
DOME	Demonstration of Microreactor Experiments
EBR-II	Experimental Breeder Reactor-II
EDL	Engineering Development Laboratory
EES&T	Energy & Environment Science and Technology (directorate within INL)
EFF	Experimental Fuels Facility
EFRC	Energy Frontier Research Center
EML	Electron Microscopy Laboratory

EPIC	Experiment Preparation and Inspection Cell
EV	Electric Vehicle
FASB	Fuels and Applied Science Building
FAST	Fission Accelerated Steady-state Test
FCCI	Fuel-Cladding Chemical Interaction
FCF	Fuel Conditioning Facility
FFNMM	Fuel Fabrication and Nuclear Material Management
FFTF	Fast Flux Test Facility
FMF	Fuel Manufacturing Facility
FOA	Funding Opportunity Announcement
FSSL	Fuel Salt Synthesis Line
FSSU	Fuel Synthesis Scale Up
FY	fiscal year
GAIN	Gateway for Accelerated Innovation in Nuclear
GASR	Gas Analysis and Sample Recharge system
HALEU	High-Assay Low-Enriched Uranium
HEU	Highly-Enriched Uranium
HFEF	Hot Fuel Examination Facility
HPI	Human Performance Improvement
HVAC	Heating, Ventilation and Air Conditioning
ICP	Inductively Coupled Plasma
IFM	Idaho Facilities Management
IMCL	Irradiated Materials Characterization Laboratory
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IPL	Indirect Priorities List funding
IRPT	Integrated Resource Planning Tool
LA	Laser Ablation
LANL	Los Alamos National Laboratory
LC	liquid Chromatography

LDRD	Laboratory-Directed Research and Development
LIBS	Laser-Induced Breakdown Spectroscopy
LOTUS	Laboratory for Operation and Testing in the United States
LWR	light water reactor
MARVEL	Microreactor Applications, Research, Validation, and Evaluation
MCRE	Molten Chloride Reactor Experiment
MFC	Materials and Fuels Complex (location and directorate within INL)
ML	Machine Learning
MMRTG	Multi Mission Radioisotope Thermoelectric Generator
MOOSE	Multiphysics Object Oriented Simulation Environment
MRPP	Material Recovery Pilot Plant
MS	Mass Spectrometry
MSTEC	Molten Salt Thermophysical Examination Capability
MW	Megawatt
NASA	National Aeronautics and Space Administration
NEUP	Nuclear Energy University Program
N&HS	National & Homeland Security (directorate within INL)
NNSA	National Nuclear Security Administration
NRAD	Neutron RADiography reactor
NRIC	National Reactor Innovation Center
NS&T	Nuclear Science and Technology (directorate within INL)
NSUF	Nuclear Science User Facilities
NZ	Net Zero
OMI	Operations Management Improvement
ORNL	Oak Ridge National Laboratory
PCAT	Primary Coolant Acceptance Test
PEMP	Performance Evaluation and Measurement Plan
PIE	Post-Irradiation Examination
PPMS	Physical Property Measurement System

PWR	Pressurized Water Reactor
RCL	Radiochemistry Laboratory
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RIA	Reactivity Insertion Accident
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generator
SCO	Strategic Capabilities Office (Department of Defense)
SNF	Spent Nuclear Fuel
SNM	Special Nuclear Material
SPL	Sample Preparation Laboratory
SPP	Strategic Partnership Project
SSPSF	Space and Security Systems Power Facility
S&T	Science and Technology
TCM	Thermal Conductivity Microscope
TETI	Thermal Energy Transport under Irradiation
TIG	Tungsten Inert Gas
TLC	Technical Leadership Council
TOF	Time of Flight
TREAT	Transient Reactor Test Facility
TRIGA	Training, Research, Isotope, General Atomics
TRISO	TRistructural ISOtropic
TRU	TRansUranic
UCO	Uranium oxycarbide
UN	Uranium mononitride
US	United States of America
VTR	Versatile Test Reactor
ZIRCEX	ZIRConium removal prior to EXtraction
ZPPR	Zero Power Physics Reactor Facility