May 20, 2024

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Manager, Used Fuel Management Department

Ken Marsden
Fuel Cycle Science & Technology

Used Fuel Disposition and Used Fuel Recycling Activities

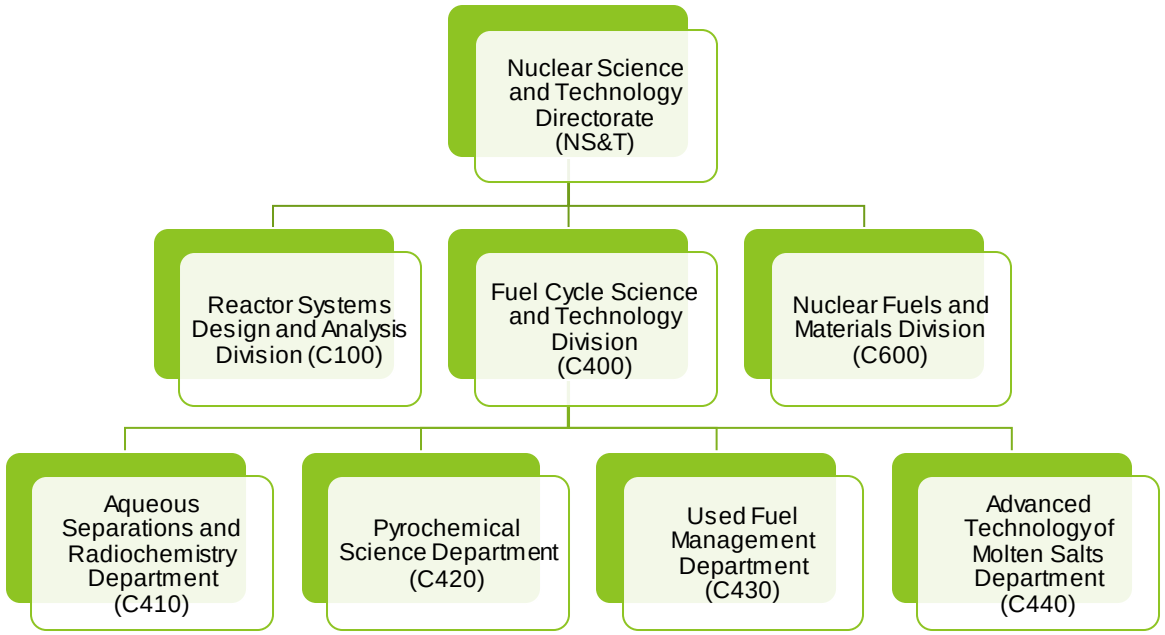
NSUF MSI User Development Workshop

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

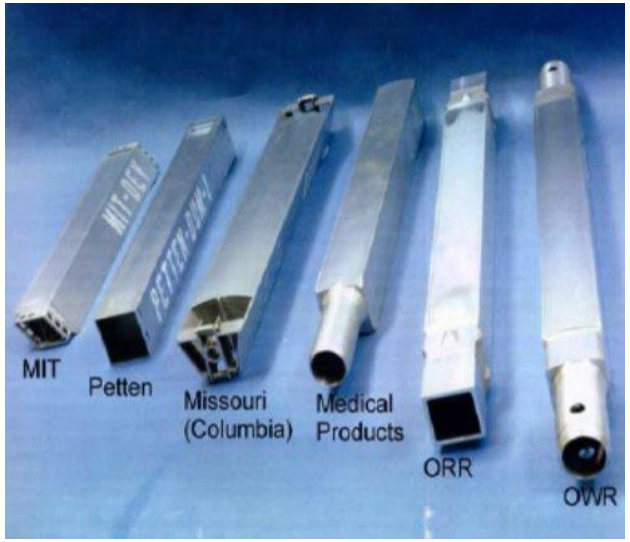
Outline

- Used Fuel Disposition
  - Used Fuel Management Department
  - Office of Nuclear Energy Projects
  - Office of Environmental Management Projects
  - Examples of Projects
  - Test Facility
- Used Fuel Recycling
  - Aqueous Separations and Radiochemistry, Pyrochemical Science, and Advanced Technology of Molten Salts Departments
  - Reprocessing Projects



Used Fuel Management Department

- The Used Fuel Management Department's focus is all kinds of nuclear fuel, like the nuclear fuel from commercial power reactors, research and test reactors, reactor experiments, Department of Energy (DOE) managed legacy fuels, new accident tolerant fuels, and fuels that are being developed to come from new advanced reactors and small modular reactors (SMRs).
- Our work with used nuclear fuel includes testing, characterization, monitoring, and packaging for storage, transportation, and disposal.
- We are involved in Consent-Based Siting (CBS), Technology Development, and Systems Analysis, as well as mechanical design and engineering structural, thermal, radiological, and criticality analyses.
- Our work is mostly funded by DOE Office of Nuclear Energy (DOE NE) and DOE Office of Environmental Management (DOE EM), but we do some work directly with the commercial nuclear industry and have some project with the Nuclear Regulatory Commission (NRC).
- We have partnerships with a number of different universities.



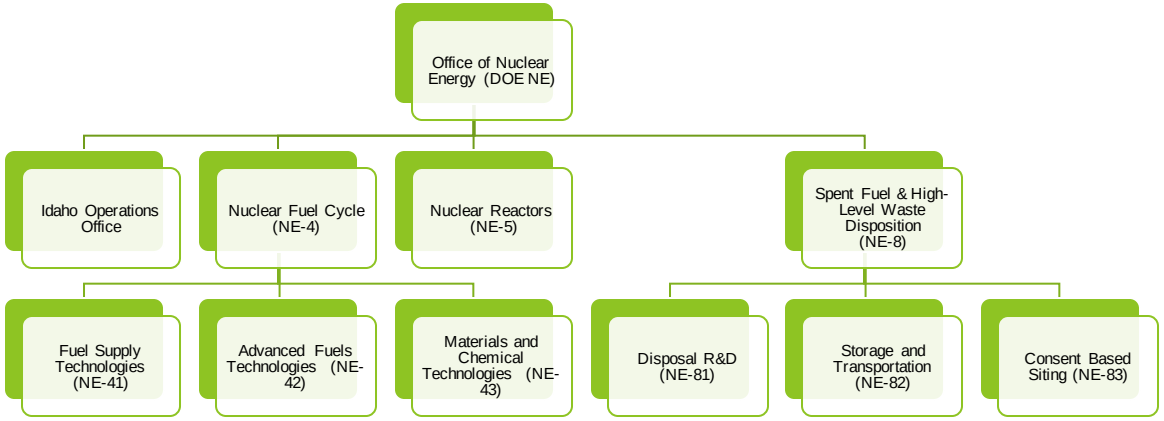
Research reactor fuel elements



CPP-603 fuel storage area

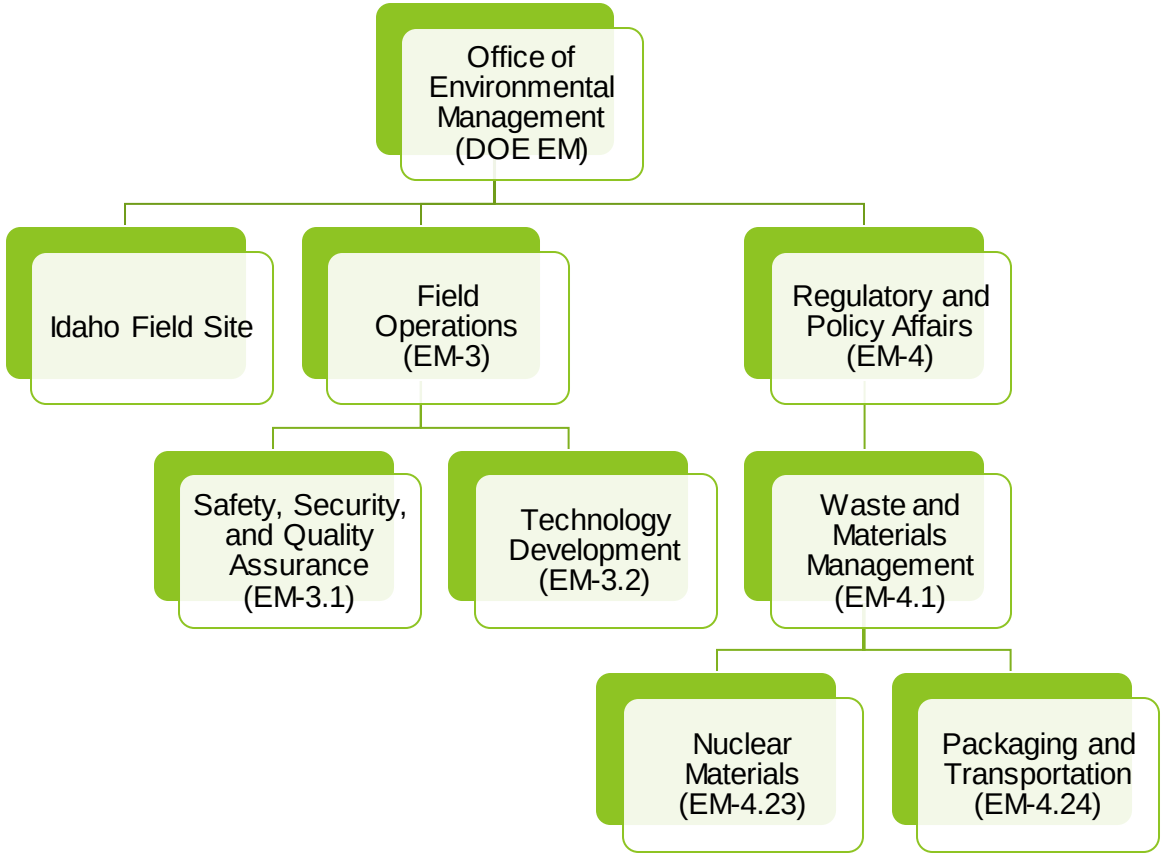
DOE Office of Nuclear Energy Projects

- Most of the Used Fuel Disposition research is funded by NE-8
  - NE-81 Disposal
  - NE-82 Storage and Transportation
  - NE-83 CBS
- Research on disposition of new advanced reactors and SMRs is funded by NE-8 and NE-5.
- NE-4 with the Idaho Operations Office is looking at disposition of the current test reactor fuels like from the Advanced Test Reactor (ATR).
- NE-41 is a new office and will focus on domestic HALEU supply
- NE-42 supports the Advanced Fuels Campaign
- NE-43 supports the Materials Recovery and Waste Form Management Campaign



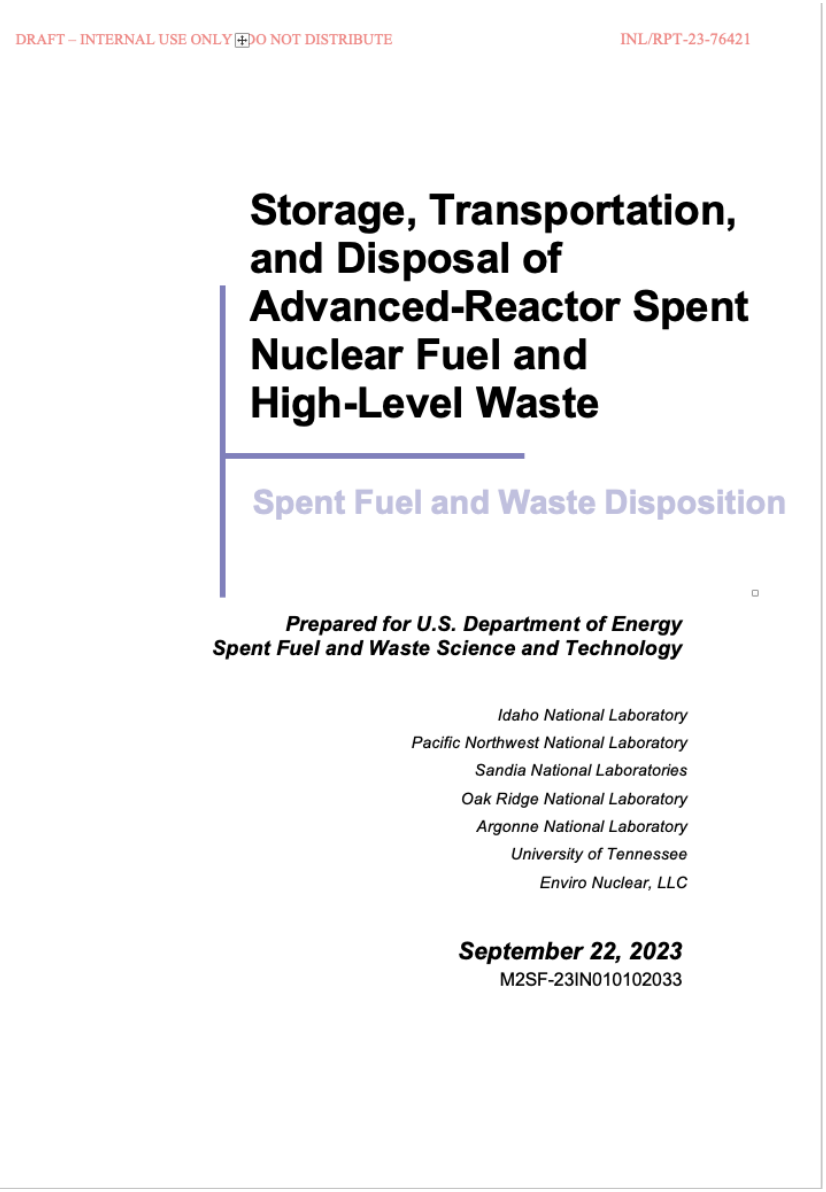
DOE Office of Environmental Management Projects

- Idaho Field Site Office is looking at disposition of Used Fuel under their management (mostly through their cleanup contractor) working with NE-8.
- EM-3.2 funds research in a number of areas that are supportive of Used Fuel Disposition.
- EM-4.23 funds the tracking of all the DOE-managed SNF.
- EM-4.24 is supporting NE-8 work for transport of Used Fuel.



Examples of Projects

- **Advance Reactor Support**
  - Multi-laboratory team evaluating the feasibility, characteristics, and operations for the back-end (storage, transport, and disposal) of advanced reactor fuel cycles.
  - Integrated Project Team (IPT) titled Back-End Management of Advanced Reactors (BEMAR).
  - Nuclear Energy Agency Panel on Extended Storage and Transportation of Spent Fuel and Radioactive Waste from Current and Future Reactor Technologies.
  - TRISO Back-End Phenomena Identification and Ranking Table (PIRT).


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INL/RPT-23-76421

Storage, Transportation, and Disposal of Advanced-Reactor Spent Nuclear Fuel and High-Level Waste

Spent Fuel and Waste Disposition

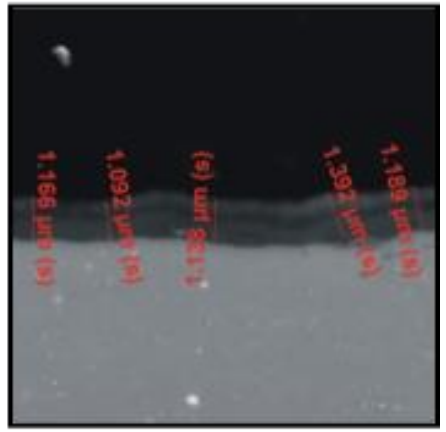
Prepared for U.S. Department of Energy
Spent Fuel and Waste Science and Technology

Idaho National Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratories
Oak Ridge National Laboratory
Argonne National Laboratory
University of Tennessee
Enviro Nuclear, LLC

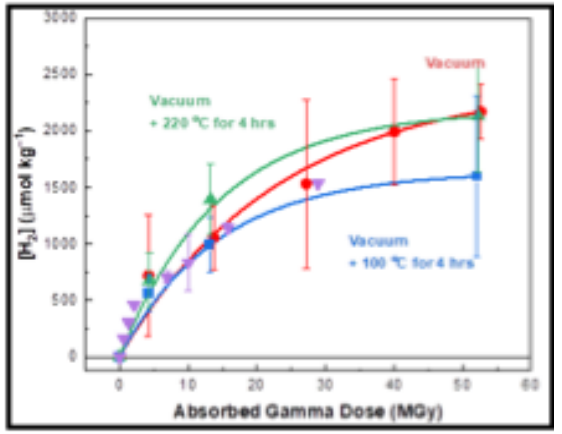
September 22, 2023
M2SF-23IN010102033

Examples of Projects

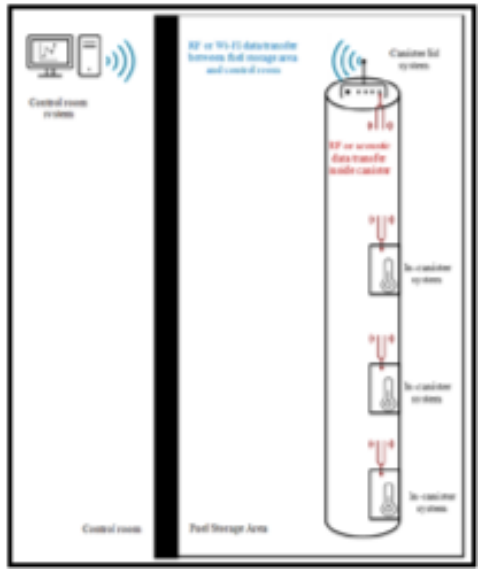
- **DOE-EM SNF Technology Development (TD) Program and TD Projects**
  - Work on various projects for aluminum spent nuclear fuel (ASNF) (concepts to load, dry, and close canisters;
  - Dry storage configurations;
  - Hydrogen and oxygen in storage canisters, oxide layer thickness, and pressure and flammability safety of ASNF);
  - Helical guided ultra-sonic wave DOE SC technology readiness level assessment; and
  - Development of a HFIR dry storage pilot.



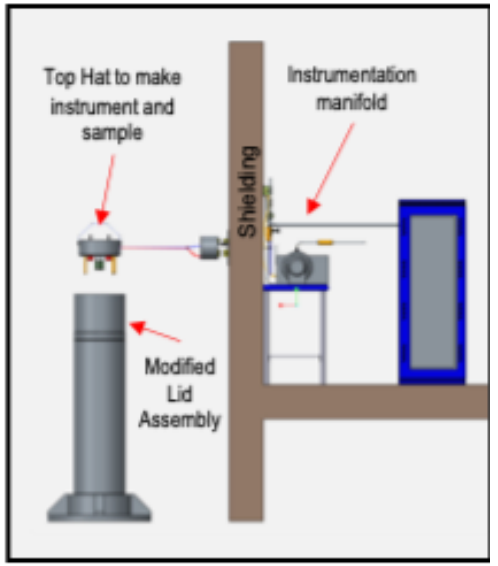
ASNF Oxide Layers



Radiolytic Gas Generation



Remote Canister Monitoring System



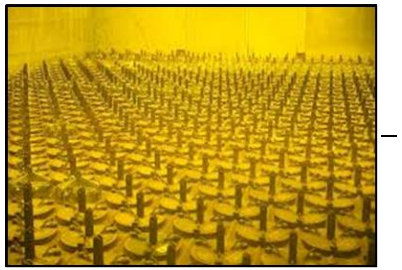
HFIR Dry Storage Pilot

Examples of Projects

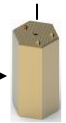
- Road-Ready Packaging Demonstration Project
  - Joint NE-8 (NE-81 and NE-82) and EM (Idaho Field Site and TD)
  - Place DOE-managed SNF in a Road-Ready Dry Storage Configuration



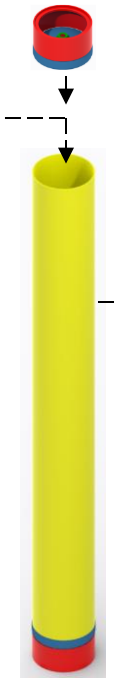
CPP-2707 Cask Pad
(Outdoor Fuel Storage Facility)



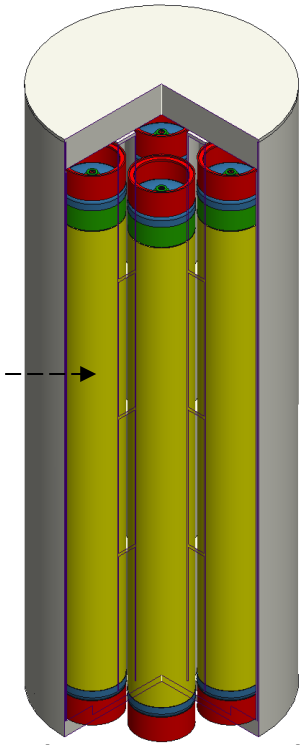
CPP-603 IFSF
(Irradiated Fuel Storage Facility)



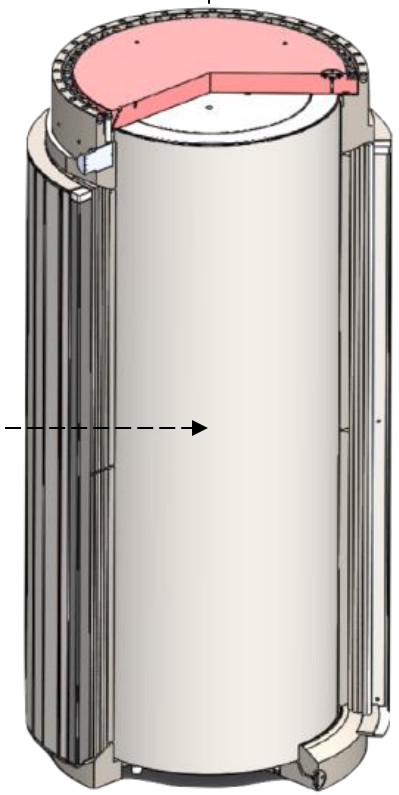
FSV
(Fort Saint Vrain)
Fuel Element



DOE Standard Canister



Mult-Purpose Canister

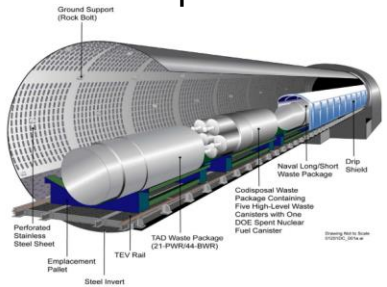


Cask for Storage

FUTURE – NOT PART OF PROJET



Transportation



Disposal

Test Facility

- **Remote Packaging Demonstration Facility**
  - The West 1 lab in the Idaho Engineering Demonstration Facility (IF-657) has been set up to perform cold demonstrations of packaging technology for used nuclear fuel.
  - The lab is set up to test and qualify remote equipment for welding, non-destructive examination, machining/repair, helium leak testing, conditioning, canister loading, and canister handling

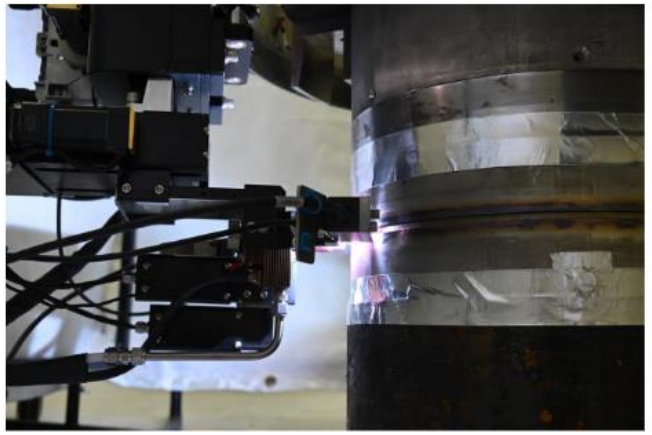




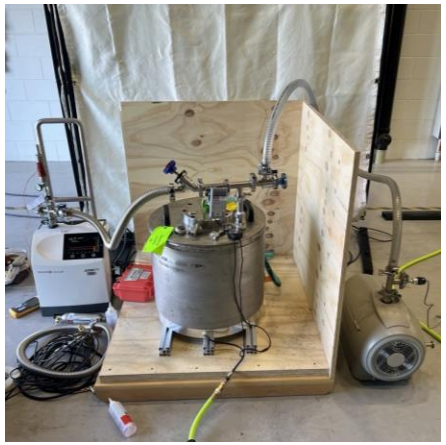
Closure system welding user interface in operation



Circumferential Weld Platform installed on canister simulation hardware with weld coupon



Circumferential Weld Platform during remote weld process



Prototype Bell Jar Leak Test Assembly

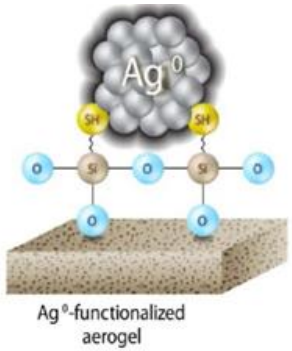


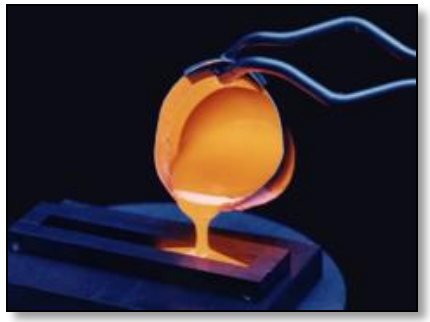
Bell Jar Bench Leak Test

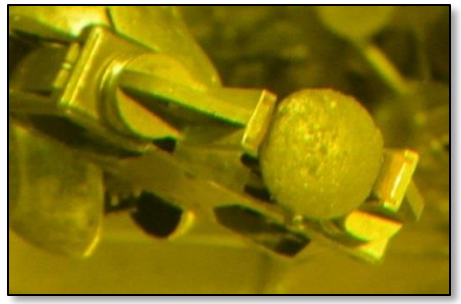
Used Fuel Recycling

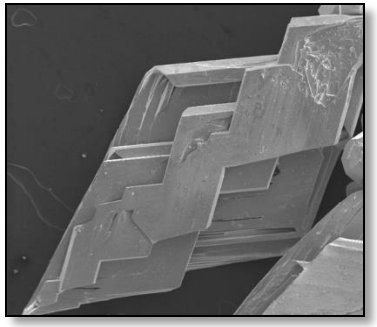
- Most aspects of used fuel recycling research and development within the DOE-Office of Nuclear Energy are pursued within the Material Recovery and Waste Form Development (MRWFD) Campaign.
- Activities are funded and led through the Office of Chemical and Materials Technologies, NE-43.











Role of MRWFD in the NE Portfolio

Similar to most NE Technical Activities, Supporting Advanced Reactors is also a priority for MRWFD

- MRWFD prepares recycling options for the range of expected advanced reactor fuel types.
  - Oxide fuels are more likely for incremental designs.
  - However, recent ARDP selected reactors use TRISO, metal, and salt fuels.
- Although there are many reasons to recycle, economics is an important consideration.
  - Often smaller advanced reactor concepts utilize HALEU.
  - Recent study showed economic breakeven near 7% end-of-life enrichment (although economics of waste avoidance are difficult to quantify absent a defined repository).
  - Discharged HALEU fuels or federally-owned HEU greatly impact the economic perspective.



Role of MRWFD in the NE-4 Portfolio

Over-Arching Goals

- Recover HALEU materials for advanced reactor fuel fabrication development needs
- Address nuclear fuel recycling challenges for advanced reactor designs
- Establish technical bases to support future U.S. recycling deployment
- Maintain capabilities and knowledge in nuclear chemistry for a range of nuclear applications

Program Focus Areas

- EBR-II Fuel Treatment
- Chlorination Decladding Processes (including Zr recycle)
- Advanced Aqueous and Vapor Phase Separations
- Molten Salt Chemistry & Processes
- Off-Gas Capture and Waste Form Development
- Salt Fuel Synthesis

Major Focus Areas

Accelerated EBR-II Processing	Acceleration of HALEU production to meet near-term metallic advanced reactor fuel needs
Chlorination Decladding	Evaluation of chemical decladding techniques for Al and Zr, including options for zirconium recycle
Advanced Aqueous & Vapor Phase Separations	Development of improved recycling options, including advanced voloxidation and direct extraction, alkaline-side aqueous processes, and fluoride volatility
Molten Salt Chemistry & Processes	Investigation of key science and technology issues for application of electrochemical recycling techniques for advanced reactor fuel cycles
Off-Gas Capture & Waste Form Development	Development of economic options for recycling off-gas management and salt-derived waste forms to meet U.S. regulations
Salt Fuel Synthesis	Planned program for development of scalable synthesis processes

Aqueous and Vapor Phase Technologies

Mission: Develop simplified aqueous and vapor phase separation processes to lower the cost of recycling and reuse of used nuclear fuels while maximizing the recovery of useful products and minimizing geological wastes

Goals:

- Improve our fundamental understanding of aqueous and vapor phase processes to simplify and optimize flowsheets
- Develop integrated processes to improve the overall economics, reduce emissions and minimize wastes and integrating safeguards by design
- Supports U.S. nuclear industry, technology developers, and small businesses in the development and deployment of recycle and reuse technologies

Recent Emphases – Aqueous and Vapor Phase Technologies

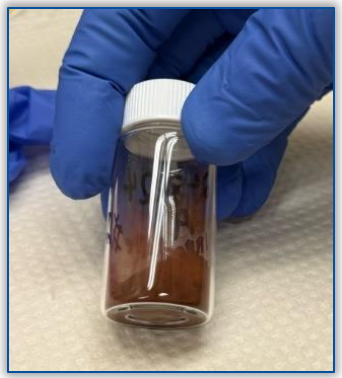
- Advanced voloxidation to produce a fine powder allowing the dry removal of tritium, iodine, carbon-14, and noble gases and reducing the overall cost by 7%
- Direct dissolution of ε-UO3 from advanced voloxidation into an organic phase
- Alkaline-side aqueous processes
- Fluoride volatility methods for recovery of uranium and facilitating re-enrichment



Traditional aqueous-organic solvent extraction processes



UF_6 crystals condensed during fluorination separation studies



Epsilon-phase UO_3 formed by low temperature NO_2 voloxidation

Molten Salt Chemistry & Processes

Mission: Develop pyrochemical separation and conversion technologies for recycle and reuse of used solid fuels, and for preparing and treating molten salts fuels

Goals:

- Develop advanced electrochemical processes
- Expand fundamental understanding of salt chemistry to simplify and optimize flowsheets
- Improve overall economics with technology improvements and simplified flowsheets
- Develop integrated facility design requirements and design concepts
- Integrate safeguards by design in RD&D

Recent Emphases – Molten Salt Chemistry & Processes

- Enhanced TRU recovery techniques with improved separation factors for Ln
- Management options for residual oxides and oxychlorides in chloride processes
- Expansion of waste reduction techniques, such as crystallization as a base salt purification technique
- Novel process enhancements to simplify or eliminate unit operations
- Process adaptations to expand process applicability, e.g. TRISO and fluoride systems



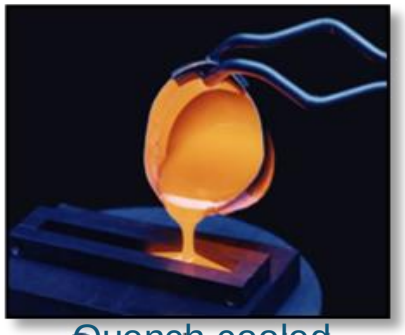


Recent Emphases – Off-Gas Capture and Waste Form Development

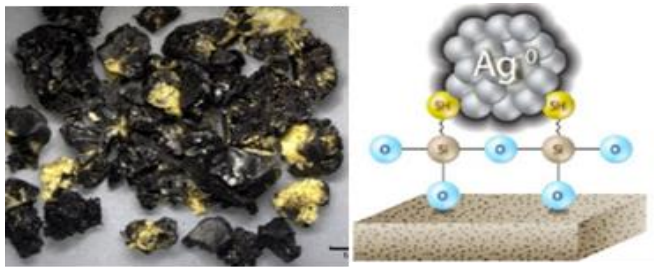
Mission – Design and develop off-gas and waste form processes tailored to treat the exhaust from a wide range of fuel cycle processing technologies

All recycling applications require off-gas and waste form management

- Developing and demonstrating advanced waste forms for salt waste streams
- Developing options for iodine capture and immobilization
- Developing and optimizing sorbent material for traditional and advanced fuel cycles



Quench-cooled sampling of phosphate glasses



Silver-loaded aerogel, an iodine sorbent



Studying long-term efficiency of an iodine sorbent

Recent Emphases – Chemical Decladding

Developing options for recovery of U-235 from federally-owned, high value used nuclear fuel to produce HALEU

- Evaluating decladding of zirconium- and aluminum-based UNF at pilot scale in the Material Recovery Pilot Plant (MRPP) using ZIRCEX
- Developing low temperature chlorination technique based on dissolution using S_2Cl_2





Recent Highlights – Accelerated EBR-II Processing

- HALEU as metal from EBR-II is a near term feedstock available to support fast-spectrum advanced reactor concepts
- Processing of EBR-II driver fuel will continue until all driver fuel is processed
  - Facility at 24-hour operations as of February 2024
  - 1750 kg HALEU available in metallic reguli form (~5500 kg recovered total)
  - Availability of 5 MT as reguli planned by mid 2020s



Recovered U metal



Large metallic ingot



New graphite crucible



New Multi-function furnace



Low dose rate, small size HALEU metal regulus



Idaho National Laboratory

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